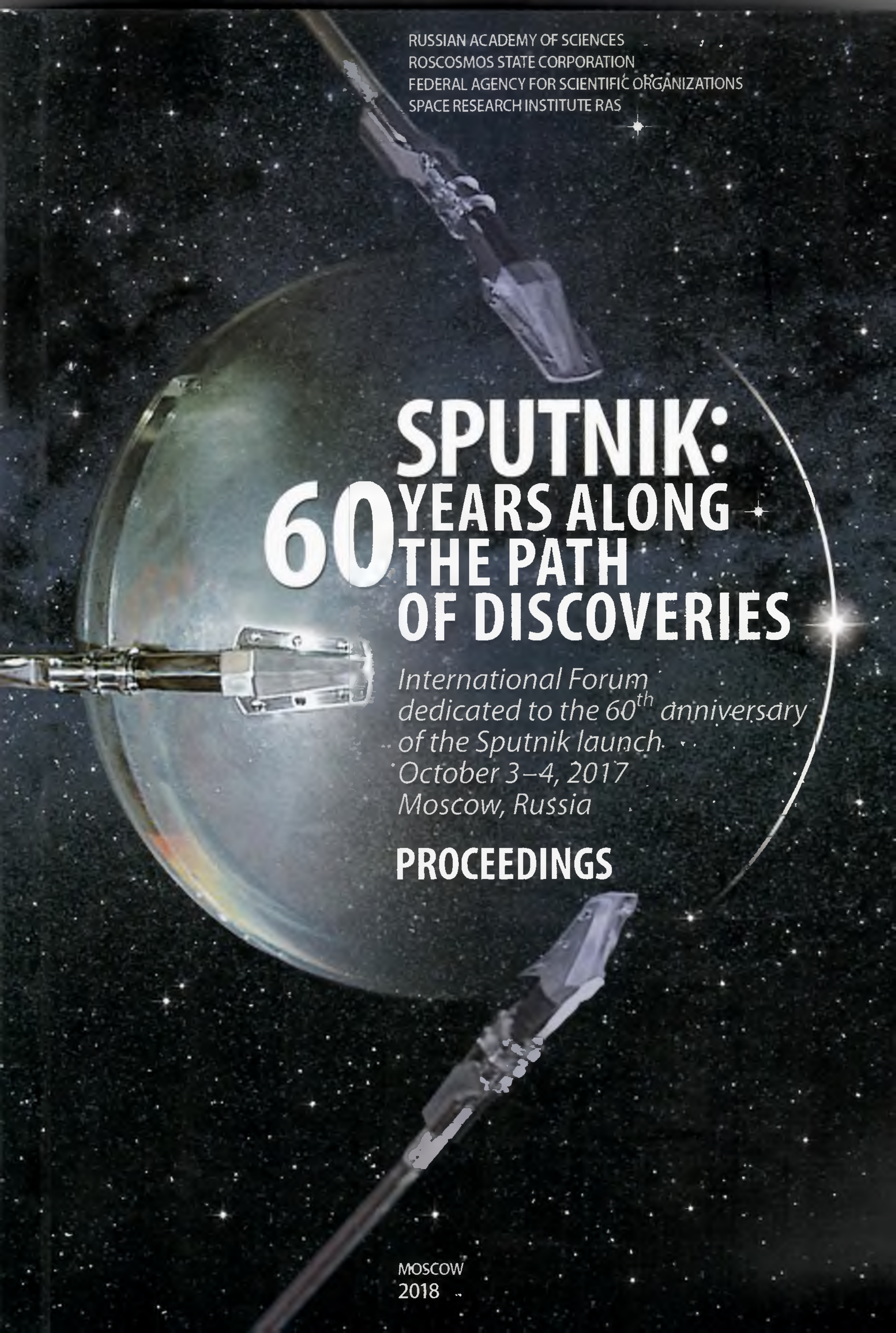

RUSSIAN ACADEMY OF SCIENCES
ROSCOSMOS STATE CORPORATION
FEDERAL AGENCY FOR SCIENTIFIC ORGANIZATIONS
SPACE RESEARCH INSTITUTE RAS

SPUTNIK: 60 YEARS ALONG THE PATH OF DISCOVERIES

International Forum
dedicated to the 60th anniversary
of the Sputnik launch
October 3–4, 2017
Moscow, Russia

PROCEEDINGS

MOSCOW
2018

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The present volume contains the papers, based on the talks given at the International Forum "Sputnik: 60 Years Along the Path of Discoveries" (October 3–4, 2017, Moscow), and abstracts of the talks, given at the associated International Symposium "Studies of the Moon, planets, and small bodies of the Solar system with the help of spacecraft" (October 5–6, 2017, St. Petersburg).

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GREETINGS TO THE ATTENDANTS OF THE INTERNATIONAL FORUM “SPUTNIK: 60 YEARS ALONG THE PATH OF DISCOVERIES”

SELECTED RESULTS OF SPACE RESEARCH AND EXPLORATION IN THE FIRST 60 YEARS

INTERNATIONAL SYMPOSIUM "STUDIES OF THE MOON, PLANETS, AND SMALL BODIES OF THE SOLAR SYSTEM WITH THE HELP OF SPACECRAFT" BOOK OF ABSTRACTS

FOREWORD

October 4, 1957 the launch of Sputnik 1 marked the beginning of the Space Age of humankind.

To commemorate the event Space Research Institute of the Russian Academy of Sciences (IKI) hosted an International Forum "Sputnik: 60 Years Along the Path of Discoveries".

The speakers of the Forum examined the evolution of our ideas about the Earth, Solar system, other stars, galaxies, and the Universe over the recent six decades. The main fields and issues of modern space research were covered in the talks, given by prominent experts in the field of space science.

The Forum was supported by Russian Academy of Sciences, State Space Corporation Roscosmos, Federal Agency for Scientific Organizations of Russia. We are especially grateful to LSR Group for their invaluable help in many our activitites for the promotion of space science and Russian achievements in space.

The present volume is not a proceedings *sensu stricto*. It does not represent all the talks and, on the other hand, it includes additional material not presented at the Forum. The style of the contributed articles may also deviate from classical scientific discourse, as their main aim was to embrace our overall advancement in different regions of vast space science, which — to the idea of the organizers — would be the due homage to Sputnik and the people who made it. We are deeply grateful to the authors, who did not only contributed the papers, but shared their visions and attitudes and ultimately created multifaceted picture of space as we know it now.

The 60th anniversary of Sputnik 1 in 2017 coincided with the year of another anniversary — 100 years from Russian October Socialist revolution on 7 November 1917 (that year it was 23 October Julian date). While the necessity of Soviet revolution is still highly disputed, the paramount significance of Sputnik 1 launch for the humanity as a whole is acknowledged and praised all over the globe. People from many countries celebrate the event every year during the World Space Week, declared by the United Nations in 1999.

At IKI, Space Science Days, an annual meeting, is held every year to mark the beginning of the Space Age and to promote awareness of the history and current status of space exploration and research within scientific community and general public.

The Forum in 2017 follows this annual tradition and bears a legacy of two earlier international Forums, organized also by Russian Academy of Sciences and supported by other organizations:

- "Collaboration in Space for the Peace on the Earth", 1987
- "Space: Science and Challenges of the XXI century", 2007

We hope to carry on the tradition of decadal overview of what was achieved and what is yet to be done in space exploration and research.

GREETINGS TO THE ATTENDANTS OF THE INTERNATIONAL FORUM “SPUTNIK: 60 YEARS ALONG THE PATH OF DISCOVERIES”

Arkady V. Dvorkovich

Deputy Prime Minister of the Russian Federation

Dear friends!

I congratulate you on the 60th anniversary of the launch of the Earth's first artificial satellite.

This event led to the beginning of the space age, inspiring many people to do science, and brought to the creation of a completely new field of activity. I am referring not only to rocket and space industry, not only to new spacecraft and space instruments, but also to the space applications in a wide range of industries and everyday life.

Fundamental science and the Academy of Sciences played a decisive role in the development of this new industry. Everyone knows the name of Sergei Pavlovich Korolev, the founder of Russian rocket engineering. Together with him, Mstislav Vsevolodovich Keldysh, mathematician, academician, and president of the Academy of Sciences, stood at the origins of aeronautics in our country during the so-called "golden age of science" of the 20th century.

Thanks to Mstislav Vsevolodovich the first space programs were conceived after the launch of Sputnik. The systematic approach was the basis for many remarkable achievements. Among them are programs of Moon and planetary studies, systems of Earth remote sensing satellites, space communication systems, brilliant program of manned space travel. Their results are used by scientists and society.

Astronautics is one of the most sophisticated industries, which continues to be the «driving force of progress» for science and technology.

Last week, the elections of the president of the Russian Academy of Sciences were held. I hope that the Russian Academy of Sciences will actively state the problems and propose effective methods for space projects realization in our country in the nearest future and in a long-term period.

I wish you successful and fruitful work!

Igor A. Komarov

Director General, Roscosmos State Corporation

Dear colleagues, dear friends. I am glad to welcome you today at this representative international forum on the very eve of the 60th anniversary of the beginning of the space age, the launch of the First artificial Earth satellite.

Space Research Institute of the Russian Academy of Sciences, which hosts the Forum, and Roscosmos have long and good relations. We work together in space exploration programs, on experiments aboard the International Space Station, on the study of planets and small celestial bodies. I am confident that our cooperation will continue successfully in the future.

Sixty years ago, an event occurred that marked a new era in the development of mankind — the beginning of the exploration of space. Our country, then called the Soviet Union, was the first to launch an artificial Earth satellite. It was quite small: only 58 cm in diameter and weighed just over 80 kg. He transmitted a very simple radio signal, famous "*beep… beep… beep*" which became known to the whole world.

Then it was close to impossible to imagine the real significance of this scientific and engineering breakthrough, which fruits would it bring to all mankind. It marked the beginning of both space exploration and manned programs, which develop today. The International Space Station is perhaps the most vivid and positive example of international collaboration in space for the sake of achieving common goals. Moreover, today we cannot imagine life without satellite navigation systems, communication, remote sensing of the Earth. All this goes back to that date sixty years ago, when even those people who made Sputnik could not probably understand what results their work would ultimately result in.

It is also probable that today we cannot appreciate the long-term consequences, which can follow scientific research conducted by the Russian Academy of Sciences in the field of space activities, one of the most advanced and interesting areas in the life of mankind. But one thing is certain: that both society and the state will always give the closest attention to the exploration and development of outer space. This was confirmed by the recent forum of space agencies, which took place last week in Adelaide in the framework of the International Astronautical Congress, within which, it seems to me, a very serious step was taken.

In particular, it confirmed that both Roscosmos and NASA are ready for and understand the need for step-by-step cooperation, starting with joint work in low Earth orbit and evolving to a near-moon station, followed by research on Mars.

It is very important that this program has open infrastructure, and not only the ISS member countries, but all other countries will be invited to it. For the first time representatives of China participated in the discussion of the future lunar station, as well as representatives of countries that are now entering the space club. This trend is very important. We all understand that there are no borders in space, the dangers that emanate from outer space threaten the whole Earth, and the results we receive should serve the benefit of all mankind.

I am convinced that the work carried out by the Russian Academy of Sciences and the Space Research Institute in the near future will be embodied in specific space projects, which we will support and develop for our part. I wish the participants of today's Forum success in discussing very important projects for all of us and once again I congratulate you on the upcoming holiday — the 60th anniversary of Sputnik launch and the opening of the space age of mankind.

Alexander M. Sergeev

President, Russian Academy of Sciences

I am glad to welcome the participants of the International Science Forum, dedicated to the 60th anniversary of the first Sputnik launch. It is significant for me that today it is the first time I am speaking to a scientific assembly in a new position. Several days ago, I was elected President of the Academy of Sciences. Therefore, I would ask you to excuse me if I do not completely follow the etiquette, as I will express mostly my thoughts in view of the forthcoming anniversary date.

Without any doubt, the event, that happened sixty years ago, is considered to be great on a human scale as well as on the country scale. It seems to me that the event, which happened sixty years ago, has ensured that for the last six decades we have been living without great wars. Actions that were taken to strengthen the country's defense capability maintained and continue to maintain peace today on our planet. This is one of the paradoxes of the 20th century.

Then, we know that scientific discoveries and achievements can be different. It happens that when something has been done, it is usually predicted that this discovery will change the world, give us eternal youth or whatever good you may imagine. However, after some time it becomes clear that the hopes are greatly exaggerated. But the launch of Sputnik, and the access of mankind into space, which followed, become more and more significant with time. This is the sign of a great achievement. New and new consequences and new applications are found, which could not be imagined in the time it was made.

These new unexpected applications in space activities, new opportunities for the economy and people's lives prove that this area is constantly developing. Numerous international collaborations that space research provide are very important for maintaining both scientific cooperation and the peace in general. It is enough to remember that the International Space Station faced many very rapid changes in relations between countries. Nevertheless, I think that it is much to the credit of this common “space house” that we still feel ourselves connected with each other. This is the reason to say “thank you” to the space.

And finally, I want to say about the collaboration of the Academy of Sciences with Roscosmos State Corporation. This is an example of a very deep and well-structured interaction. First of all, I want to recall the agreement between the Roskosmos State Corporation and the Russian Academy of Sciences, which has been signed recently, and the work of the Space Council of the Russian Academy of Sciences. Nowadays our Academy is going through difficult times, and the fact that the most important council on the most important problem is headed by the Academy is very important.

Colleagues, I would like once again to congratulate you on the anniversary of this great event and on my part I assure that the new management of the Academy of Sciences will give the highest priority to cooperation with Roscosmos State Corporation and further work on space exploration. Thank you!

Grigorii V. Trubnikov
Deputy Minister of Education and Science of the Russian Federation

Dear colleagues!

On behalf of the Ministry of Education and Science of the Russian Federation, I convey to you my most sincere congratulations on the 60th anniversary of the launch of the Earth's first artificial satellite.

The Space Age in the history of humanity began on October 4th 1957 at 22 hours 28 minutes and 34 seconds Moscow time. On that very day the Earth's first artificial satellite (PS-1) was launched from the Scientific Research Test Range No. 5 of the Ministry of Defense of the USSR, later named as Baikonur Cosmodrome.

Many scientists were engaged in the development of the first artificial satellite, headed by Sergey Korolev — the founder of the practical astronautics.

People all over the globe watched the flight of the Earth's first artificial satellite. Any radio amateurs anywhere in the world could get the satellite's signal. The launch affected the US prestige and was completely at odds with the perception of the technological backwardness of the Soviet Union.

The launch of the PS-1 had a great scientific significance. One of the most important discovery was that atmospheric density at the orbital altitude was determined, which lead to the development of the satellite deceleration theory and contributed to the further development of the astronautics.

The launch of the first satellite was said to be similar to the discovery of America by Christopher Columbus in the middle age.

I would like to congratulate everyone on the 60th anniversary of the launch of the Earth's first artificial satellite and wish the further blazing development.

Mikhail E. Shvydkoy

Special Representative of the President of the Russian Federation
for International Cultural Cooperation

Distinguished Assembly,

It is a great honour for me to speak to you today at the 60th anniversary of the launch of the first Earth satellite.

The fact that a person from a completely different area attends this eminent gathering may seem odd. However, the interconnection between space and art, more specifically Sputnik and art is undeniable, and so are the changes in public consciousness that had taken place in the USSR and beyond following the launch of Sputnik.

I suppose that there was no more important thing for the USSR, except the victory in the Great Patriotic War, than the victory over Earth's gravity. This achievement defined our mind in various ways. It is not even that after the launch of Sputnik people wrote about apple trees blossoming on Mars. The event gave birth to a new understanding of human freedom. Mankind got free from gravity, from the seemingly inseparable ties to the earthly existence. This degree of freedom was unknown until the Sputnik reached Earth's orbit. Konstantin Tsiolkovsky once wrote that the most difficult thing is to make the first step, to overcome atmospheric density and enter orbit. It seemed to him that coping with the gravity of the Sun would be much easier afterwards.

Indeed, this very first step was the defining moment. People's noble dream about overcoming the gravity of being came true. Of course, despite the fact that these words are mostly metaphorical, it is not only an artistic image. Actually, it is about a giant leap into the unknown.

At the same time, space projects are not associated with any threat to our planet unlike nuclear projects, for instance. No offense to my colleagues working in the area that in many respects was equally important. However, space gives us a pure sense of creativity without risks for the existence of people on the Earth.

As Fyodor Dostoevsky brilliantly wrote, "show a Russian schoolboy a sky map, and he will give you back the map next day with corrections on it". The desire to "correct a sky-map" is enduring among Russians, and that is what led to the launch of Sputnik. This quality is essential because through mistakes we achieve new levels of the understanding of human existence.

I would like to reiterate that scientific discoveries are inseparable from discoveries made in art. They might appeal to eternity, but still they change us as humans. In that respect, I believe you are lucky to be in quite an enviable situation. Whatever problems today might be considered in the Academy of Sciences, people able to think freely about eternity are outstanding.

I convey you my best wishes on occasion of this important anniversary!

Lennard A. Fisk

President, Committee on Space Research (COSPAR)

I very much regret that I am not able to be with you today to celebrate the 60th anniversary of the launch of Sputnik, the event that released humankind to explore and to utilize the vast opportunities that are available to us in space. An event that ushered in the space age, which has given us vast knowledge about our Solar system and the Universe beyond and which has created the infrastructure of our civilization in space, which has led to the development of our global intertwined economy.

I was in high school in 1957 in New Jersey and I marveled when Sputnik orbited over my house. My country, the United States, had a very frenzied response to Sputnik in particular, to Sputnik 2 which was launched in November of 1957 with the payload of 5 hundred kilograms and a live dog. Our pride was hurt, our security was threatened. The Soviets had better missiles than we had. When finally the US launched its first satellite in January 1958, a number of actions were taken to increase the technological capability of the United States. Perhaps, the most significant for many of us was the encouragement given to students to pursue careers in science, and math, and in engineering, which resulted in a vast increase in the technological workforce of the United States.

With the United States and the Soviet Union in space, international organizations were created to ensure that space will always remain a peaceful domain. COSPAR, the organization, of which I am a President, was formed in 1958 for the purpose, in part, of providing a venue, where Soviet and Western scientists could meet and share scientific discoveries at the height of the Cold War. The United Nations Committee on the Peaceful Use of Outer Space was also formed in 1958 that led eventually to the Outer Space Treaty of 1967, which has now been signed by 83 nations.

And so as we celebrate the launch of Sputnik, we should also celebrate the many events that took place so quickly after Sputnik and placed our civilization on the inevitable irreversible path to becoming a true space-faring civilization.

We should also celebrate how far we have come since the launch of Sputnik. We have sent spacecraft to every planet. We have orbited many. We have landed on a few. We have observed the Universe across the electromagnetic spectrum. And we marvel at the majesty and the mysteries of what we have discovered. We have placed human on the Moon; we have humans living and working in low-Earth orbit.

We have observed the Earth from space, and from that global prospective we are able to manage Earth and predict its future. We have assembled the global weather forecasting system, based on observations of satellites of many nations.

We are aware that the space environment of Earth can present hazards to our technological civilization and we are working to forecast those hazards.

We locate ourselves by global positioning satellites, we communicate through the vast infrastructure of communication satellites in orbit, all in an effort to build a more connected world with a global intertwined economy that serves the well-being of all our people.

And it all began with the launch of Sputnik on October the 4th, 1957. Who would have thought in 1957 how quickly and how completely the space age would develop to where it is indispensable to our society and essential to our future?

You should be justifiably proud of the launch of Sputnik. Celebrate it, but also celebrate what you began, the space age, from which humanity has ever more benefited. Thank you very much!

Mikhail M. Kotyukov

Director, Federal Agency of Scientific Organizations

Dear colleagues!

On behalf of the Federal Agency for Scientific Organizations, I gladly welcome all the participants of the International Forum “Sputnik: 60 Years along the path of discoveries”!

The anniversary on October 4 is one of the most significant dates in the Russian and world history. If we remember 1957, we must admit that it is thanks to the launch of the first satellite and the achievement of equilibrium and parity of the global state our country did not only ensure six decades of its peaceful development, but also faced off the main threat to the existence of all mankind. We will always remember and be proud of the great feat of Sergei Korolev, Mstislav Keldysh, Igor Kurchatov, and all other Soviet scientists and designers.

Today’s anniversary is special; here we will talk about the results of the whole decades of space exploration. For the last 60 years, space technologies have passed from their original intent to the stage of the rapid development. In the moment, they provide telecommunications and control systems, Earth studies, prospective materials, and exist in all areas of high-tech activity. It is even impossible to imagine present and future development of our civilization without space. I will say more: during these 60 years, it became evident that the ongoing transition of humanity from the Earth to the open space has greater impact on the history of our planet than even the appearance of living organisms on the land after the ocean.

“Sputnik Day” is widely celebrated by the international community; various events are organized in its honor in the framework of World Space Week, which includes this Forum. Representatives of many institutes of the Federal Agency for Scientific Organizations take part in it and actively participate in space research and implementation of the Federal Space Program of Russia. We are proud that these institutions have made a significant contribution to the implementation of many space projects, and we will do our best to assist with this work.

The program of the Forum includes both fundamental and practical issues that become more and more urgent. We are talking not only about Earth studies using space data and possible responses to the climate change, but also about space weather, space debris problem, prospective projects for the other planetary bodies exploration, and even space threats.

Every year in October the Space Research Institute of the Russian Academy of Sciences holds “Space Science Days”, summarizing the “results of space activities of the year”. It is remarkable to notice that after the scientific session, a great number of associated events will be organized for the public, students, and pupils, who will continue space studies.

I wish the goals set by the organizers of the Forum are achieved and the Forum becomes a source of inspiration for those, who are involved in space studies, as well as for professionals and amateurs of astronautics, researchers, and those who now starts their life in science

SELECTED
RESULTS
OF SPACE
RESEARCH
AND
EXPLORATION
IN THE FIRST
60 YEARS

Lev M. Zelenyi
Space Research Institute,
Russian Academy of Sciences,
Moscow, Russia,
Chairman of the Programme
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SPUTNIK: 60 YEARS ON THE ROAD OF DISCOVERIES

On October 3–4, the entire world, including the Russian Academy of Sciences, marked the sixtieth anniversary of the launch of the first artificial Earth satellite, *Sputnik 1*, as it is called abroad. From this day, and even from the exact time of 22:28:34 on October 4, 1957 in Moscow, the space age of mankind can be measured: and in everyday life, in science, in culture, in the whole world outlook of mankind, the cosmos now plays a huge role.

Today, when space is talked about, we mean a whole multi-branched "bush" of phenomena, directions, and fields of activities: from theoretical cosmology — unthinkable without the data of modern astrophysical observatories — to the launching of commercial communications satellites, which do not have a direct relationship to science. Still, in the public consciousness, space is probably associated with scientific research and natural excitement *par excellence*, since cosmic researchers "by necessity" study extreme phenomena and states of matter.

In this article, an attempt is made to make a very short and cursory survey of the main trends in modern space research. Aspects of this will be described in more detail in other papers in the collection. The review aims to provide a brief historical sketch of the circumstances in which Sputnik was launched.

1. A DREAM, A THEORY, A REALITY…

Long before the Great October Socialist Revolution, described by John Reed as *Ten Days That Shook the World*, a philosophical trend emerged in Russia, called "Cosmism" or "Russian Cosmism". Its ideas were not unique; similar trends can be observed in other countries as well, but it was perhaps in Russia that this movement was most pronounced.

The Russian cosmists comprised Nikolai Fyodorov, Nikolai Morozov, academician Vladimir Vernadsky (to some extent), Alexander Chizhevsky, and, of course, Konstantin Eduardovich Tsiolkovsky. He was the one whom today we would call a visionary — he outlined the future of mankind, proceeding from the assumption that humanity would not stay on the Earth forever. At the same time, he dealt with technical issues, became one of the founders of practical cosmonautics and was one of the first to talk about artificial Earth satellites. It were his works, which called to space many people from the generation of Sergey Korolev and his elder colleagues. In the 1920s and 1930s they began to develop Soviet Union rocket engines, being in fact just enthusiasts. One shall recall the GIRD team (Group for the Study of Reactive Motion), led in the 1930s by Friedrich Zander. Its members became the main developers of Soviet missile technology. Jokingly, they renamed their organization the "Group of Engineers Working For Free", which has the same acronym in Russian as GIRD.

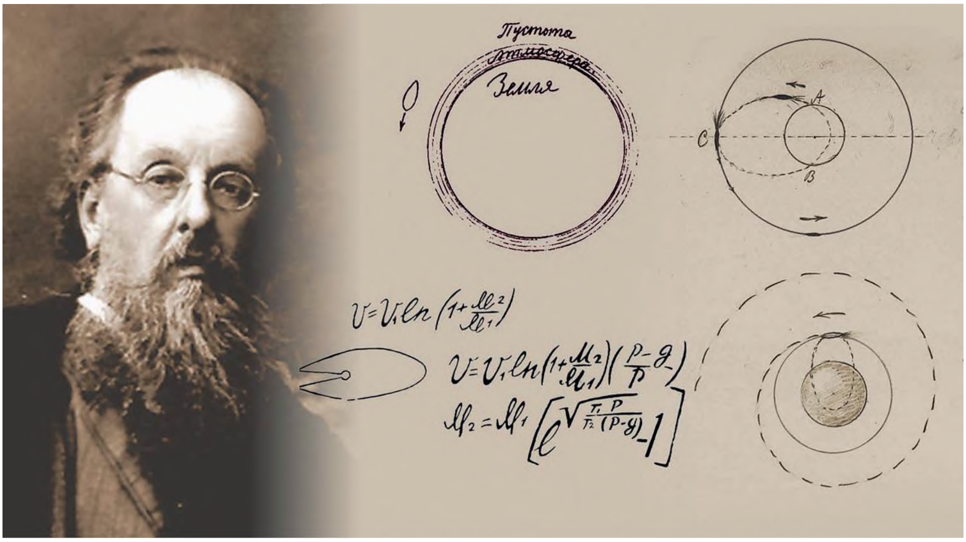


Fig. 1: Tsiolkovsky's formula and the scheme of motion of an artificial Earth satellite

In addition to K. E. Tsiolkovsky and S. P. Korolev, whose roles are well known, it is necessary to recall Mstislav Vsevolodovich Keldysh, mathematician, academician, vice president and president of the USSR Academy of Sciences, who provided the mathematical needs of the newly emerging missile industry. While the name of S. P. Korolev was never mentioned in media ("chief designer" was used instead), M. V. Keldysh was a much more public figure, although up to a certain point his scientific role in the development of cosmonautics also remained known only to the initiated: newspapers referred to the anonymous "main theoretician of cosmonautics". Collaboration of these two great people gave much to science, but, unfortunately, we learned about this only after they passed away.

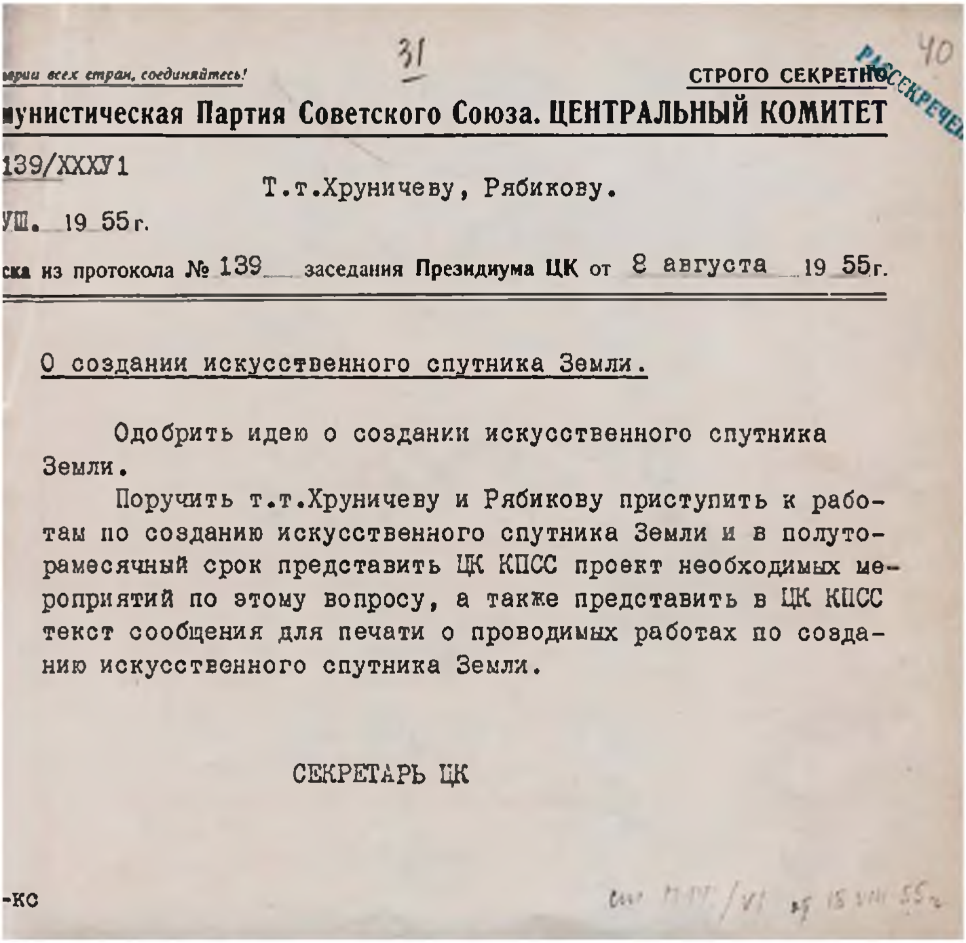
M. V. Keldysh was a mathematician, S. P. Korolev was an engineer. What about physics? Physicists also took part in the development of Russian cosmonautics, although in a somewhat curious way. It is known that rockets were developed to provide the means for delivering nuclear devices to the territory of a "potential enemy"; the best physicists of that time were mobilized to create the actual nuclear weapons (just as it was in the US also).

The history of the Soviet Nuclear Project is well known. A major role there (specifically, in the creation of a thermonuclear bomb) was played by academician Andrey Sakharov. Three times Hero of Socialist Labour, and later one of the main dissidents and opponents of Soviet government, he recorded in his memoirs that in the 1950s he was engaged in the work on calculations of parameters of thermonuclear devices.

Fig. 2: Mstislav V. Keldysh and Sergey P. Korolev

Fig. 3: Andrey D. Sakharov and Igor V. Kurchatov

In particular, he estimated the mass of the thermonuclear charge, to which the mass of the rocket should be "adjusted". According to his initial calculations, the charge should have been very heavy, about 5 tons, and it was for such a mass that S. P. Korolev began to design a rocket, the famous R-7. Later, however, it turned out that the mass required in Sakharov's calculations had been greatly overestimated; but the rocket had already been made, and its capabilities were enough to send the first satellite into space, and then the spaceship of Yuri Gagarin.



31

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РАССЕКРЕЧЕ

ории всех стран, соединяйтесь!

СТРОГО СЕКРЕТНО

унистическая Партия Советского Союза. ЦЕНТРАЛЬНЫЙ КОМИТЕТ

139/XXXУ1

Т.т.Хруничеву, Рябикову.

УШ. 19 55г.

ска из протокола № 139 заседания **Президиума ЦК** от 8 августа 19 55г.

<u>О создании искусственного спутника Земли.</u>

Одобрить идею о создании искусственного спутника Земли.

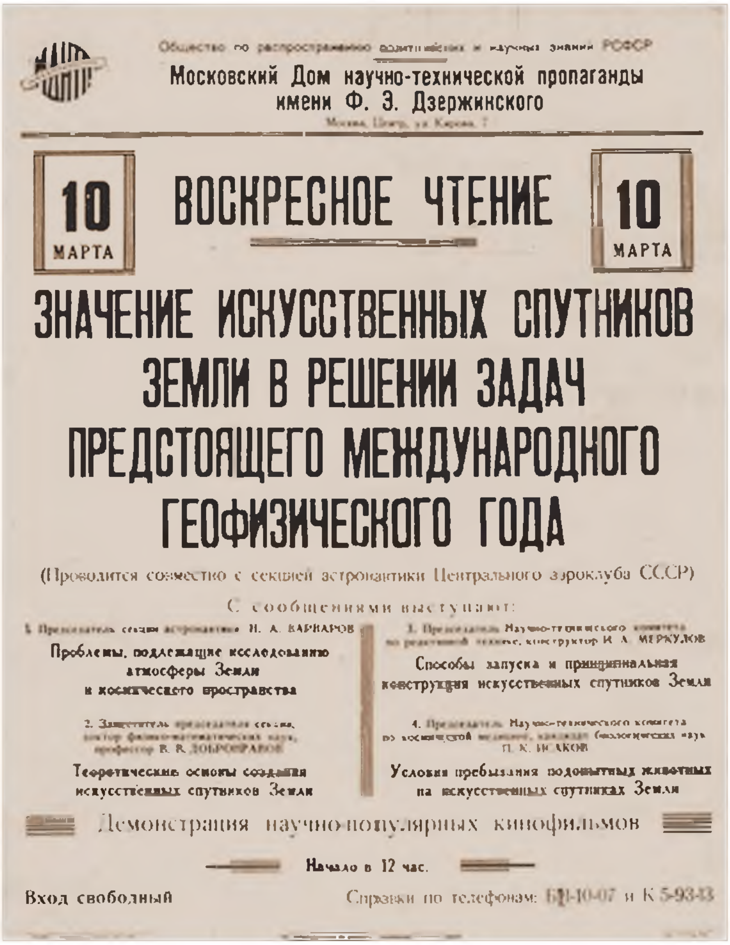
Поручить т.т.Хруничеву и Рябикову приступить к работам по созданию искусственного спутника Земли и в полуторамесячный срок представить ЦК КПСС проект необходимых мероприятий по этому вопросу, а также представить в ЦК КПСС текст сообщения для печати о проводимых работах по созданию искусственного спутника Земли.

СЕКРЕТАРЬ ЦК

-КС

Fig. 4: Resolution of the Central Committee of the Party on the creation of the first artificial satellite of the Earth. Moscow, August 8, 1955. Russian State Archive of the Modern History, F.3, List 47, File 272, Page 40. Copy

As it turned out later, the R-7 was especially useful for cosmonautics. And Boris Chertok, the "right hand of Korolev", also writes about this: *I cannot judge to what extent Andrey Sakharov personally defined the design of the charge, but, of course, exactly what Sakharov was doing required the creation* *of just such a powerful rocket as we developed under the code R-7. So the name of Sakharov should also be mentioned in the history of astronautics!* Even an error made by a brilliant person can give a useful result! The first successful launch of the R-7 rocket was made in August 1957, just a few months before the launch of Sputnik 1.



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10 МАРТА

ВОСКРЕСНОЕ ЧТЕНИЕ

10 МАРТА

ЗНАЧЕНИЕ ИСКУССТВЕННЫХ СПУТНИКОВ
ЗЕМЛИ В РЕШЕНИИ ЗАДАЧ
ПРЕДСТОЯЩЕГО МЕЖДУНАРОДНОГО
ГЕОФИЗИЧЕСКОГО ГОДА

(Проводится совместно с секцией астронавтики Центрального аэроклуба СССР)

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по реактивной технике, конструктор И. А. МЕРКУЛОВ

Способы запуска и принципиальная
конструкция искусственных спутников Земли

4. Председатель Научно-технического комитета
по космической медицине, кандидат биологических наук
П. К. ИСАКОВ

Условия пребывания подопытных животных
на искусственных спутниках Земли

Демонстрация научно-популярных кинофильмов

Начало в 12 час.

Вход свободный

Справки по телефонам: БД-10-07 и К 5-93-43

Fig. 5: Advertisment of a popular Sunday lecture “Importance of artificial Earth satellites for the upcoming International Geophysical Year” on March 10, 1957 in the Moscow House for promotion of science and technology. Circulation 200 copies. 1957. Russian State Archive of the Scientific and Technical Documentation, F.31, List 15, File 86

All this work was done for national defense and was “top secret”. But in 1955 the Soviet Union had already begun to pursue a course of openness. On the personal initiative of the Secretary General Nikita Khrushchev, it was decided that the USSR would participate in the International Geophysical Year (IGY) program in 1957–58 and, in particular, would launch an artificial Earth satellite with “scientific equipment for studying the physical properties of near-Earth space". This was exactly the moment when the political and defense interests coincided with scientific goals.

In one of the documents there is a clause: *...to allow the Academy of Sciences to conduct preparatory work, in an open manner, for the involvement of radio amateurs and astronomers of voluntary societies and observatories to monitor the flight of the satellite.* In other words, from the very beginning, space activities were understood in the context of international cooperation and the promotion of science.

But it seems that no one took seriously the announcement that the USSR was going to launch an artificial Earth satellite as part of IGY, because our country was still in a very difficult economic situation after the end of the Great Patriotic War — World War II. In the US they also prepared for a launch, so the world community was waiting for results to come from across the ocean as the most probable variant.

The main instrument of Sputnik 1 was a radio transmitter emitting the famous *beep-beep-beep...* signals. It was made by Konstantin Gringauz, who was to become an employee of the IKI (which did not yet exist), and it was actually Gringauz whose hand touched Sputnik last.

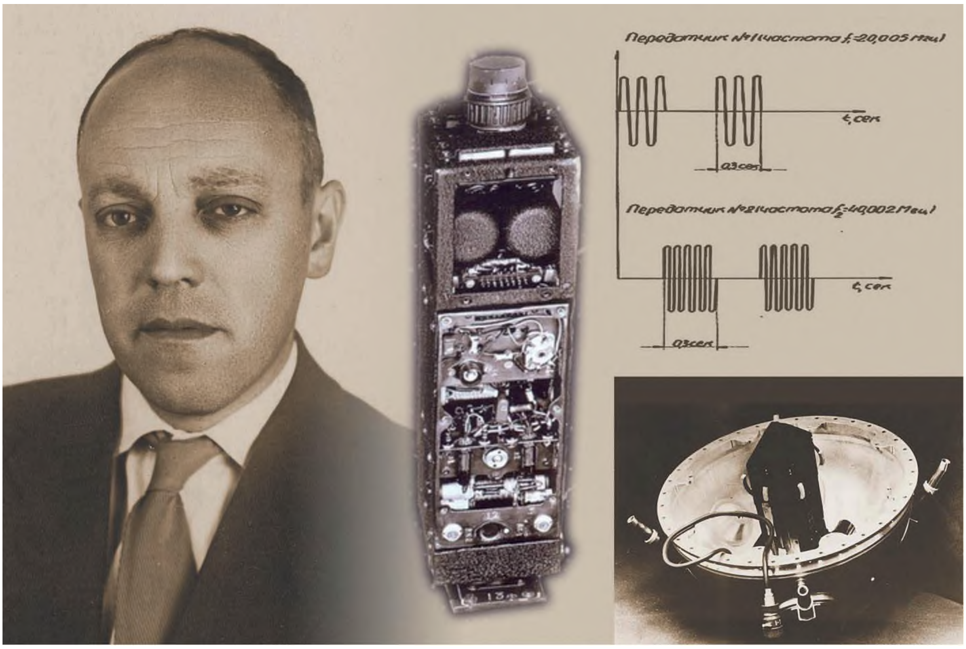


Fig. 6: Konstantin Gringauz and the famous radio transmitter aboard Sputnik 1. Graphics show the signal emitted in two different frequencies. Russian State Archive of the Scientific and Technical Documentation, F.107, List 4, File 2 and F.24, List 59, File 12

So, the “space race” was launched. In the USSR, a heavy spacecraft with a large package of scientific instruments was developed. Scientific program was headed by the Academy of Sciences; the vicepresident M. V. Keldysh was then the chairman on the special Commission on the Object ‘D’, which was the “nickname” for the spacecraft. But this spacecraft was not ready by the autumn of 1957, and there wasn’t time to wait — information was received that the US spacecraft (the future *Vanguard*) was ready for launching. Therefore, already by mid-1957, it was decided to postpone the planned launch of the heavy scientific spacecraft (it was launched later, on May 15, 1958, as Sputnik 3), and instead to make a “simple” spacecraft weighing only some tens of kilograms. This idea of Korolev’s was approved by the Communist Party’s Central Committee.

So, Sputnik 1 was launched on October 4, 1957 from Kazakhstan, and it remained in orbit for several months, until in January 1958, it burned up in the atmosphere after performing 1400 revolutions.

Fig. 7: R-7 launches Sputnik 1

The TASS report was published in *Pravda* the very next day, but it was nothing special — the material was but one among many columns. Apparently, the Soviet government was not yet fully aware of the importance of this event. In contrast, the international response on the same day was striking. The satellite was on the front pages of the largest foreign publications. The media extolled the “achievement of the Russians” and mocked the United States.

Someone immediately composed a satirical poem:

"Oh little Sputnik, flying high
With made-in-Moscow beep,
You tell the world it's a Commie sky
and Uncle Sam's asleep"

But our American colleagues (at that time, however, still rivals) did not sleep of course; they, too, worked hard and earnestly. Inside the US missile industry there was also a kind of competition, only here, between the Army and the Navy; two spacecraft were actually made, and after the success of the USSR, the priority was given to the project led by Wernher von Braun (*Explorer 1*), which the US government initially did not really want, favouring project *Vanguard*.

The launch of the second Earth satellite, sent into space on November 4, 1957, a month after Sputnik 1, was now extensively covered by the Soviet press. The government now understood the tremendous role of space exploration propaganda, and the following years have become "golden" for space science, when our predecessors did not experience financial constraints, as long as they were able to make progress. Nikita Khrushchev was a great space enthusiast; he was personally involved in the planning of all launches and should be given credit for his very important role in initiatiating our strong space science.

Sputnik 2 was also famous for taking the dog Laika, the first living creature, into space. Earlier there were numerous launches with dogs and other animals, but they were done with geophysical rockets, which returned to Earth. That was the way space medicine and biology had begun.

The Academy of Sciences joined the "space theme" practically from the very beginning. It has been said above that the instruments for would-be Sputnik 3 were created in the institutes of the Academy of Sciences and Moscow University. The data of the first two satellites were analyzed by the staff of these institutes. The documents, concerning scientific research in space, were signed by M. V. Keldysh, S. P. Korolev, and A. N. Nesmeyanov (the latter was then the president of the Academy).

Finally, on May 15, 1958, Sputnik 3 (which had had to be the first) was launched, carrying heavy and very substantial "scientific" payload. It carried aboard twelve scientific instruments to measure the pressure and ionic composition of the atmosphere, the concentration of positive ions and electrons, the strengths of electrostatic and magnetic fields, the intensity of the corpuscular radiation of the Sun, and the recording of micrometeorite impacts.

A few months before it, the first US satellite (*Explorer 1*) was launched on January 31, 1958 in the United States; its chief scientist was James Van Allen. The main scientific result and the first discovery of the space age, which had both scientific and propaganda value, was the discovery of the Earth's radiation belts, the domain in near-Earth space where charged particles with very high energies are captured. With this result, the epoch of "great space discoveries" began. For details, please, refer to the paper by Mikhail Panasyuk "Radiation in space: dramatic ways of Soviet and American pioneers of space exploration".

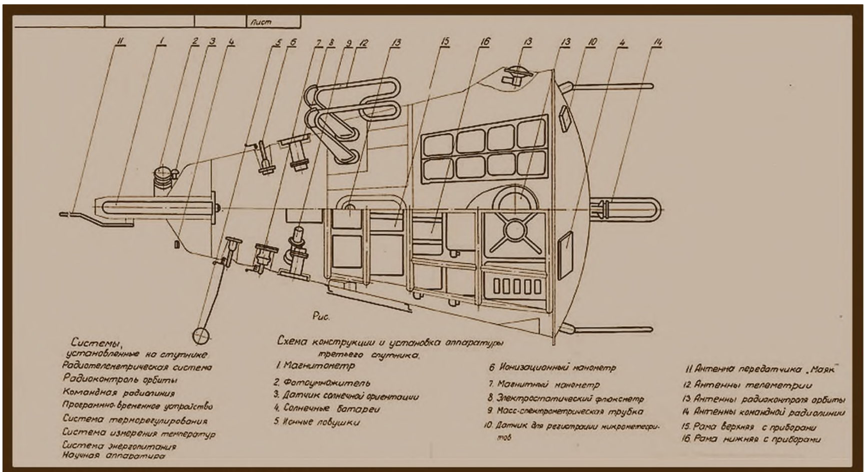
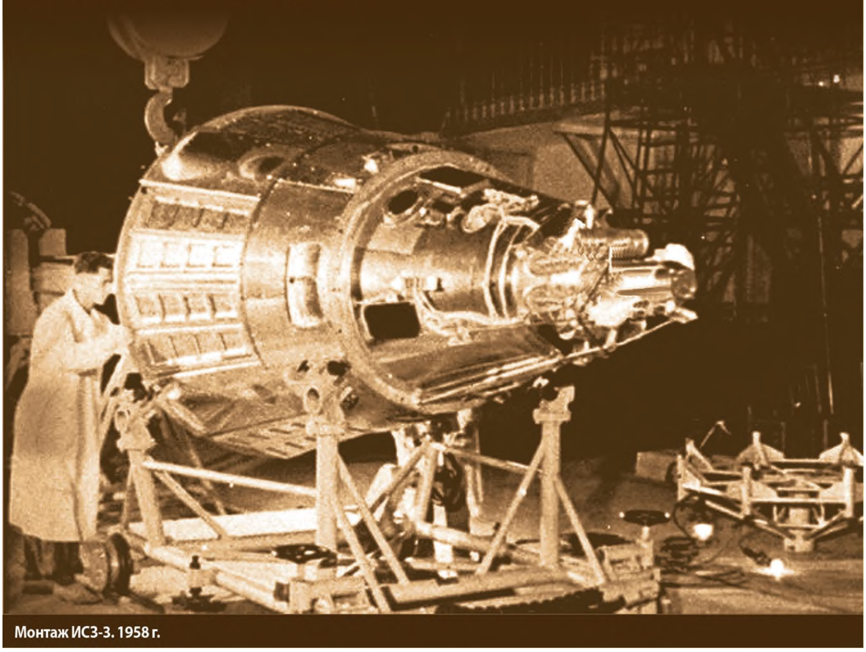


Схема конструкции и расположение аппаратуры ИСЗ-3



Монтаж ИСЗ-3. 1958 г.

Fig. 8: Top: Structural diagram and instruments' mounting aboard Sputnik 3. [1958]. Drawing. Blueprint. Ink. Bottom: Sputnik 3 assembly. [1958]. Documentary shot. Russian State Archive of the Scientific and Technical Documentation, F. 107, List 4, File 4 and K244-01-28 respectively

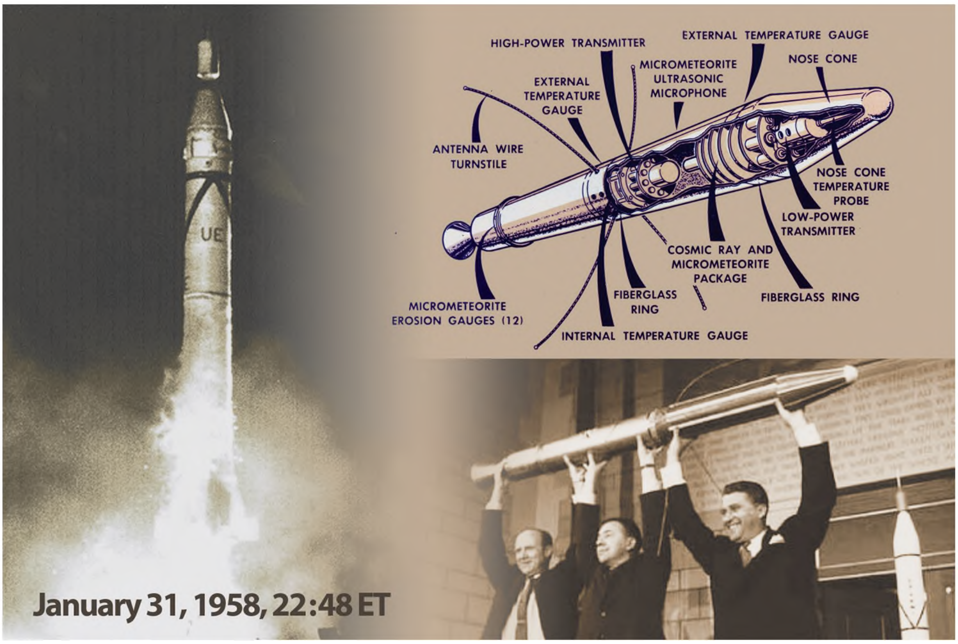


Fig. 9: Left: *Explorer 1* launched by *Juno 1* booster. Top right: *Explorer 1* instruments. Bottom right: William Hayward Pickering, James Van Allen, and Wernher von Braun display a full-scale model of *Explorer 1* at a news conference in Washington, DC

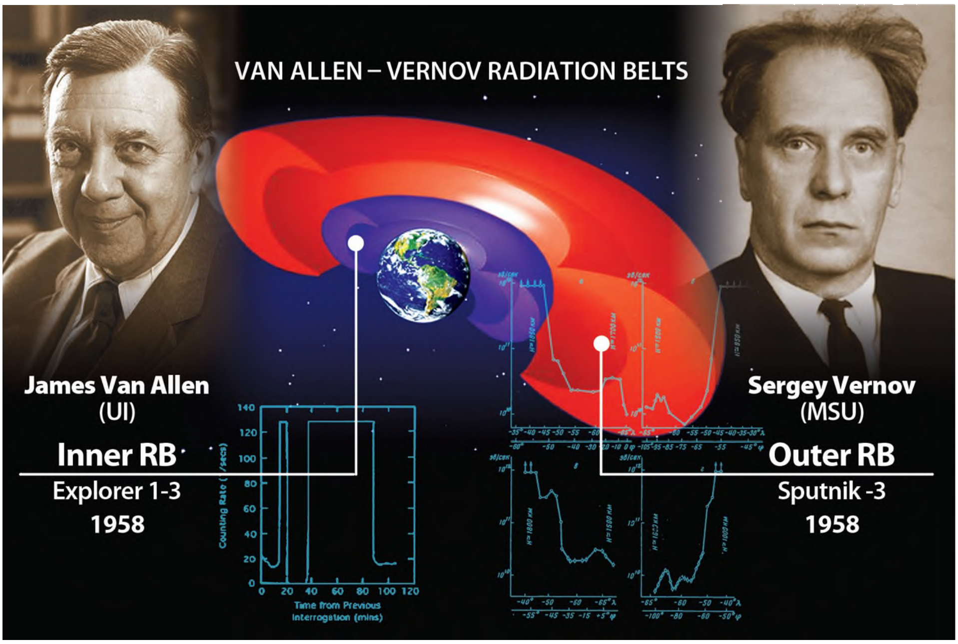


Fig. 10: Two pioneers of space science: James van Allen (USA) and Sergey Vernov (USSR)

So Sputnik became a part of everyday life, an important part of culture. Scientific readings were devoted to the science from the first spacecraft, many people took to the streets to observe how the sky was traced by a small man-made star. The very word "Sputnik" began to live a life of its own and, turned into a common noun, entered without change into many languages. In English, a lot of words appeared on the basis of "Sputnik". So, for example, a spacecraft, the launch of which ended in failure, began to be called *flopnik* and *kaputnik*. Not all neologisms have entered the language, but there is one example, which now is cultural heritage — the word "beatnik". It was coined by journalist Herb Caen in an article in the *San Francisco Chronicle* of April 2, 1958. He added the Russian suffix "-nik" to the English expression "Beat Generation" to name that part of the youth who behaved antisocially and did not accept the traditional cultural values of the United States.

The sequence of further launches is traced in many sources: almost immediately flights to the Moon began, designers started working towards expeditions to Mars and Venus, physicists thought about the study of near-Earth space; preparations for the first manned launch were in full swing, and the flight of the dogs Belka and Strelka was a triumphant, as the first living beings to return from a spaceflight.

In parallel, the leaders of both the rocket industry and the Academy have deliberated about the organization of space research. On May 5, 1963, in his letter to the "directive bodies", M. V. Keldysh, by now president of the Academy of Sciences, proposed establishing (within the USSR Academy of Sciences) of the Joint Institute for Space Research, whose main task would be the systematic study of outer space. Two years later, on May 15, 1965, the USSR Council of Ministers established the Space Research Institute of the USSR Academy of Sciences. A year earlier, the Institute for Biomedical Problems was founded, also within the Academy, and now it is the leading organization for the medical support of human space flights and biological experiments in space. Large space programs were developed that provided for the systematic exploration of the space, and soon space science turned into what it means today — it's a whole "bouquet" or "bush" of directions, which includes not only physics, but also chemistry, geology, biology, mathematics, and computer science. And observations in space, in turn, have become for these disciplines a source of new discoveries, which, had we stayed Earth-bound, we might not have even guessed at.

2. ALL THE COLOURS OF THE UNIVERSE

In one of Flammarion's works an anonymous engraving was published, depicting a medieval monk who pierces the top of the heavenly vault and sees a completely different world — another sky and another Earth. Sputnik played just such a role for us. Thanks to it, people gained a new idea of cosmos.

For example, in each range of electromagnetic radiation, from radio to gamma rays, there are interesting processes. It is very important to look at the universe through this whole spectrum. But before space launches we could not do this, since the atmosphere and ionosphere absorb almost all the radiation coming from space (which is certainly fortunate for the inhabitants of the Earth). Of the full range, we are only able to see from 0.3 μm to ~1.5 μm (the region up to 8 μm consists of a number of narrow transmission bands), and only part of the radio-wave bands: from 1 mm to 15–30 m.

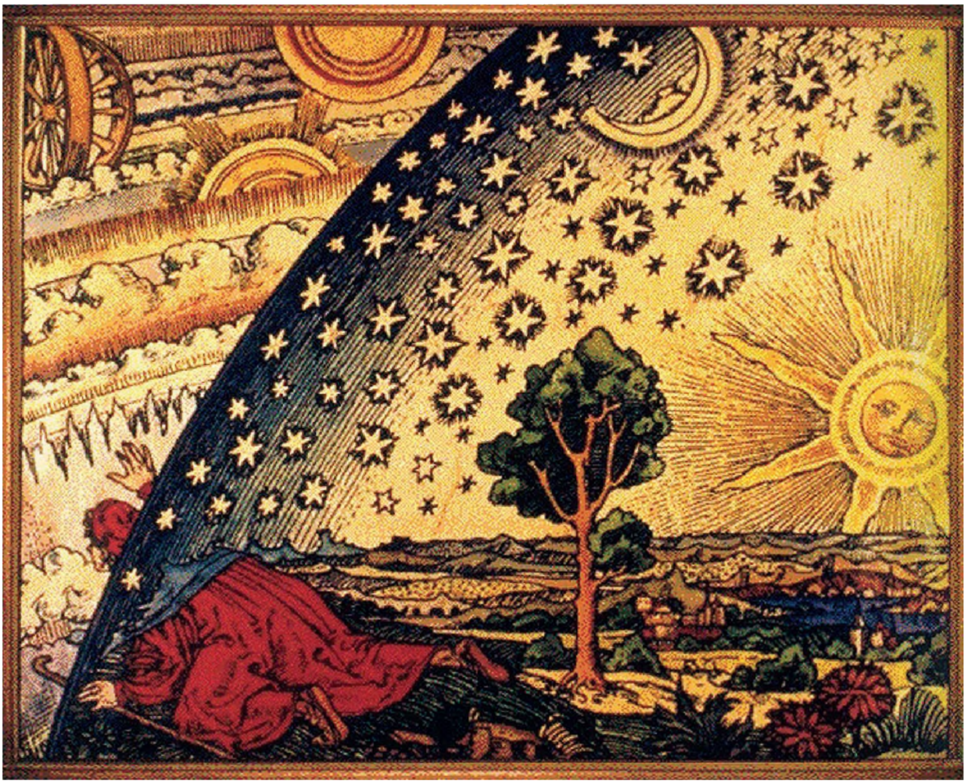


Fig. 11: Anonymous engraving from the work of C. Flammarion *The Atmosphere: Popular Meteorology* in 1888

The same applies to charged particles — the Earth's magnetic field has a very strong effect on their propagation. From the point of view of living organisms, this is fortunate, because such high-energy particles are dangerous to us; but for science this means that a whole huge complex of phenomena becomes unavailable to the scientists on Earth.

Discovery of space showered us with a cornucopia of breakthroughs. Much of what was theoretically predicted became possible to "touch" and "feel". So it was with the radiation belts of the Earth: the regions of "captured radiation" near space bodies with a magnetic field were considered even before the commencement of flights into space. Or the streams of “solar wind”, the existence of which was indicated by a number of phenomena.

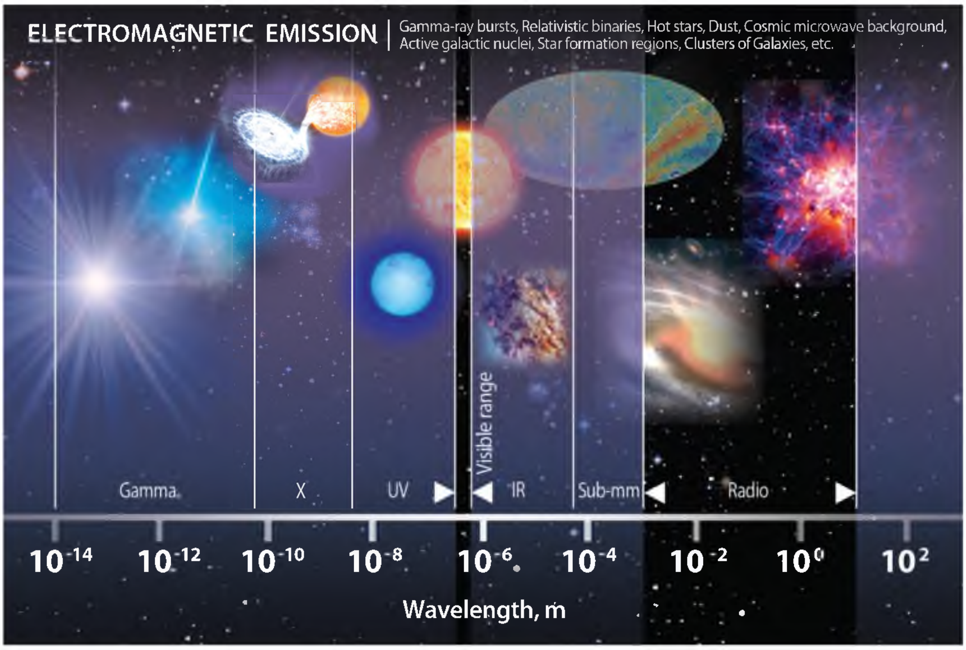


Fig. 12: The plot shows “transparency windows” (not shadowed) across the electromagnetic spectrum, which are available for astronomers on the Earth. One may see that these are quite modest part of the whole range. To see the Universe in other wavelengths, one should go beyond the atmosphere

But there were also surprises. The “loudest” was probably the discovery of “dark energy” at the end of the 20th century, the nature of which is still difficult to comprehend, but the scale is shocking: its contribution to the balance of matter and energy in the universe is about 75 %. The second surprising and unexpected observation is associated with the discovery of exoplanets and exoplanetary systems, many of which turn out to be very unlike the Solar system. This substantially changes the idea of how such systems could be formed.

In cosmonautics itself, that is, manned flights into space, there have also been changes. Gradually, man has adapted to a fairly long stay in space. Yuri Gagarin’s ship made one revolution around the planet; recently cosmonauts and astronauts returned from an expedition, which lasted for almost a year and a half. Space is hostile to man, but the efforts of physicians have managed to neutralize the negative impact of the space environment on man, at least in the near-Earth orbit. However, one must be prepared for the fact that longer human flights in interplanetary space, even to the Moon, not to mention Mars, will meet tremendous difficulties.

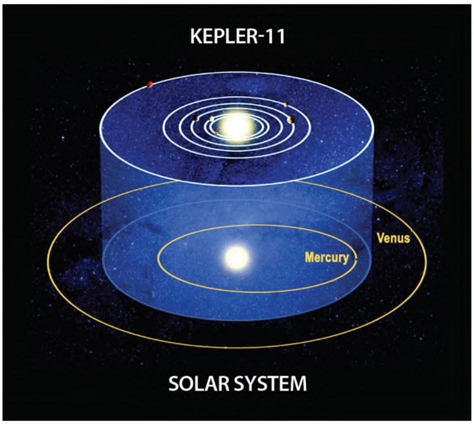


Fig. 13: Striking difference: exoplanetary system Kepler-11 has six transiting planets, whose orbits are closer to the star than that of Venus to the Sun. Image courtesy NASA/Tim Pyle

Summarizing, we can say today that now we are far better aware of how much our very existence is connected not only with our planet, but also with the outer space: from a person's adaptivity to the numerous cycles of solar activity to the hypothesis that all water or part of it was brought to Earth by comets.

Even brief overview of the most important results achieved during the first 60 years of the space age would require a book more voluminous than this one. I should admit, that my overview suffers from numerous omissions, but they can be excused by its modest purpose. On the one hand, I want to show how much space technology has influenced our ideas about the world; on the other hand, I want to present those issues and tasks that the scientific community sets for itself today, highlighting primarily the projects of the Russian space program.

With regard to studies in different spectral ranges, the simplest example here is the Sun. If we look at it through optical instruments, then in general we see a fairly calm picture, which is only sometimes blotted by sunspots and protuberances. But our star looks completely different in the radio, X-ray, and ultraviolet ranges: we will see a lot of active regions, flares, and other phenomena reflecting turbulent processes on the surface of the star. For more details on solar research today I refer the reader to the paper by Roger-Maurice Bonnet.

The same thing happens with observations of other stars and galaxies: if we use only optical and radio telescopes, the most energetic events will be obscured. For example, young hot stars shine in the ultraviolet range. In the infrared range, one can observe objects hidden behind cosmic dust, as well as the dust itself, which in the Galaxy serves as a "building material" for the planets. X-ray and gamma-ray astronomy allows us to see hot gas in clusters of galaxies, to observe compact relativistic objects: neighborhoods of black holes, X-ray pulsars — rotating neutron stars. More about the advancements of modern astrophysics may be found in the paper by Sergey Sazonov and Mikhail Revnivtsev.

The space program of Russia provides for a series of observatories under the common "umbrella name" SPEKTR, which are designed to study the universe in different ranges.

Fig. 14: SPEKTR series of space astrophysical observatories

The first satellite of this series is *Spektr-R* or *RadioAstron* project, successfully launched into space in 2011. Even though it works in the radio band, which is accessible from the Earth, space technology allowed a record increase of the base for operation in the so-called interferometric mode. As a consequence, we could improve the angular resolution dramatically. The length of the base, when the spacecraft is as far from the Earth as possible, is comparable with the distance to the Moon. The prospects for the development of this method, and the results already obtained from *RadioAstron* project are outlined in this collection by Nikolay Kardashev and Yuri Kovalev.

The next spacecraft, *Spektr-Rentgen-Gamma* (to be launched in 2019 as a joint Russian-German mission) will carry on a survey of the universe in the X-ray and gamma-ray ranges (the assumed energy range is 0.3–10 keV and 5–30 keV using a two-telescope observatory). The main objectives of the project are to find all the massive clusters of galaxies in the observed Universe, as well as the active supermassive black holes in the nuclei of distant galaxies.

Having this data, we may study the processes of evolution of the Universe and the role played in it by the “dark energy” (its action can be observed precisely in the mass distribution).

Finally, the space observatory *Spektr-UV* or the *World Space Observatory-Ultraviolet* (WSO-UV) will operate in the ultraviolet range. The launch is planned to take place around in 2024. In particular, it will be possible to observe physical processes on young hot stars, the physics of the formation of stars and star clusters.

3. MANY (UN)INHABITED WORLDS?

A real researcher, of course, always wants to switch from remote observations to direct experiments. While we cannot reach distant or even close stars (except of course the Sun), completely new worlds open up even in our Solar system. *In situ* experiments have greatly altered our understanding of how the planets formed in the vicinity of the Sun and what happened to them in the several billion years of the existence of the Solar system.

We should start from the closest sphere: in fact, our first natural satellite, the Moon. Flights to the Moon became the next object of the space race after the launch of the first spacecraft and the first manned flight. Many Soviet and American spacecraft explored it, and each country achieved much. The Soviet Union was the first to photograph the far side of the Moon, carried out three successful sample returns from the Moon, and sent to the surface two successful long-lived automatic lunar rovers. The United States carried out six manned missions to the Moon within the famous *Apollo* program, proclaimed by President John F. Kennedy. The irony for scientists is that the success of the *Apollo* missions and samples delivery exhausted the interest of politicians in the Moon. The “race” was over, and with it the launches of research craft to the Moon, initially in the USSR, but also in the US. When interest in our satellite became extinct, attention was paid to the study of near-Earth space and manned flights, where great achievement was the work of the *Mir* station, which in many ways has determined the present success of the International Space Station (ISS).

Back to the Moon. At the beginning of the 21st century interest again flared up, and this was due to the research of *Lunar Prospector* (USA), and later of the first *Chandrayaan* (India), which showed that the surface of the Moon is not uniform. Namely: the polar regions are very different from the equatorial regions. This, in principle, is true for all planets, but specifically in the polar regions of the Moon, the presence of frozen water under the surface was detected — and this was not expected; rather, there was a notion that the Moon should be completely “dry”. The presence of water was later confirmed by studies from the American spacecraft *Lunar Reconnaissance Orbiter*, on which the Russian neutron telescope LEND was installed. This instrument investigated the distribution of hydrogen in the upper layer of the lunar soil, and showed that in some places the content of water can reach several percent by mass.

There are several models explaining the presence of ice on the Moon. One of them connects this with the active bombardment of the surface by comets. The remnants of their nuclei are preserved in shaded craters at the poles, where solar light does not reach, as if in an eternal “refrigerator”. This is of interest, since in such ice, prebiotic compounds can survive if they are present in comets.

A review of the most important results of the first stages of the study of the Moon and the formulation of promising problems can be found in the present volume (see the paper by James Green and Carle Pieters “Geological Evolution of the Terrestrial Planets: 60 Years of Exploration and Discovery”) and in the earlier article by Carle Pieters “The Inspiring 50++ Years of Lunar Exploration”*. Below, I briefly outline the main provisions of the Russian lunar program for the coming years.

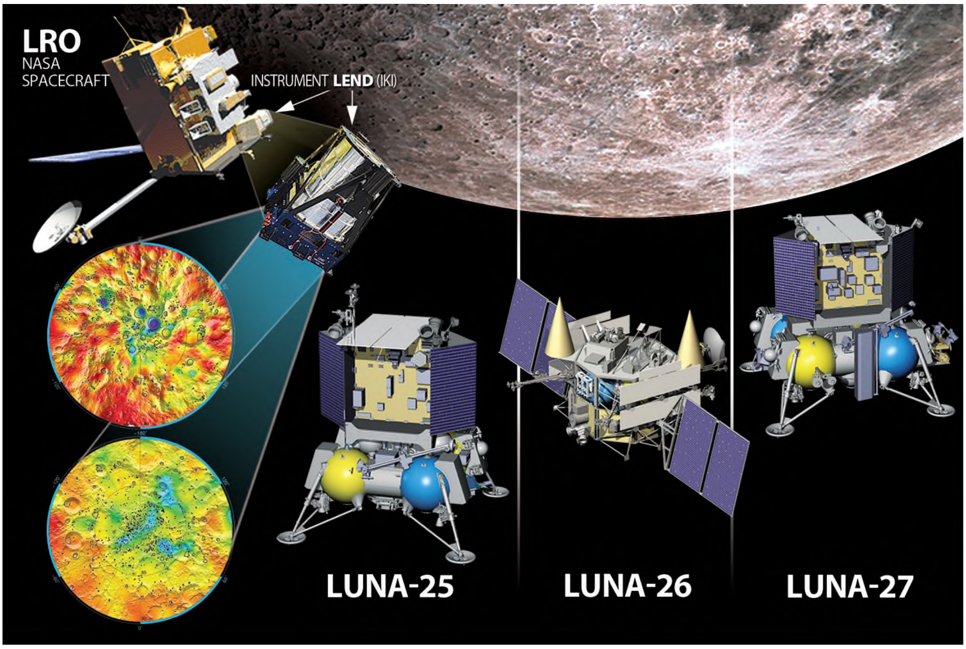


Fig. 15: IKI’s LEND instrument aboard NASA’s *Lunar Reconnaissance Orbiter* and the future sequence of Russian lunar missions: in search for volatiles

In its present state, the Russian lunar program is aimed at studying more precisely the polar regions of our satellite. Work is now underway on landers *Luna-25* and *Luna-27* — the count of mission numbers follows *Luna-24*, the

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* In “Space Research Institute in Times of Change, Glimpses of the Past and Visions of the Future”, Moscow, IKI, 2016

last project of the Soviet lunar program that brought lunar regolith to Earth in 1976. *Luna-26* is an orbiter. The next task, which is now being discussed, is sample return from polar regions of the Moon. However, in this case, it is not so much the soil itself that is important as are the volatiles in it, and their delivery to the Earth in an "intact" form becomes a difficult technical task.

Project of a manned space station near the Moon is being discussed, which could become a prelude to the full-scale development of the Moon as a test site for research, and perhaps even of some technological goals. In September 2017 an agreement was signed between Roscosmos State Corporation and NASA on the construction of a near-Moon habitable station in a highly elliptical orbit called the *Deep Space Gateway* (Igor Komarov, the head of Roskosmos, specifically mentioned this in a welcome speech to the Forum participants published in this compilation) (After October 2017, the project was renamed and is currently known as the Lunar Orbital Platform-Gateway (LOP-G). The development is led by the ISS partners: ESA, NASA, Roscosmos, JAXA and CSA for construction in the 2020s. — *Ed.*).

Russia is not alone in these plans. By 2023, it is expected that India, China, and South Korea will send their spacecraft to the Moon. Europe, Japan, and the United States are also interested in exploring the Moon and developing the infrastructure for human flights.

The second object of the Solar system of hypothetical interest for development, though in a much more distant future, is Mars. Unfortunately, science still does not know whether there is life on Mars. Attempts to search for life in past years, as we now understand, were doomed to failure, because the methods of research were not sufficiently refined. Nevertheless, some encouraging facts were found.

More than a decade ago, water, or rather ice, was discovered on Mars beneath the surface both in the polar and equatorial regions. But the most interesting discovery of the last two decades is that methane has been discovered in the atmosphere of Mars in an amount not exceeding several particles per billion. As is known, this gas fairly quickly — over several hundred years — decomposes under the influence of solar ultraviolet light. Therefore, we can conclude that its stock in the atmosphere is somehow being replenished. One of the very tempting hypotheses to explain this discrepancy is biological activity. To explain this phenomenon, the joint Russian-European project *ExoMars* is now underway, which includes two missions. The first has already begun. In March 2016, the year it was launched, the probe *Trace Gas Orbiter* (TGO) successfully entered the calculated orbit around Mars and gradually moved into an orbit designed for detailed studies of the atmosphere. In 2018, its nominal mission began.

During the flight, TGO instruments made some measurements, and the first results relate to the doses of radiation that were received in that time. These measurements were carried out by the Lyulin-MO module (Bulgaria and Russia) in the Russian FREND neutron spectrometer. These are very important data, since cosmic rays is one of the main threats to a manned flight to Mars.

For the second phase of the mission the task for the IKI and the Lavochkin Association (IKI main industrial partner) is to prepare a landing platform with a large number of scientific instruments. It will deliver a rover to the planet, made by the European Space Agency, and then it will start working as an autonomous research station.

ExoMars is designed to work until about 2022–23; the instruments will probably be able to work longer. But now we are already thinking about the continuation of these studies — in particular about a return to Phobos. This small body in the Solar system, a satellite of Mars, is of interest to us primarily because it consists of the "primordial matter" of the Solar system, which has not undergone exogenous changes since the formation of the planets. Unfortunately, previous missions to Phobos have not yielded results in this respect, although the *Phobos* spacecraft sent to Mars in 1988 managed to make quite interesting measurements from orbit. Data — a large number of images from different angles and distances — were obtained to construct a high-precision theory of Phobos' motion. The plasma shell of Mars was studied, and in particular the rate of erosion of the planet's atmosphere under the influence of the solar wind was estimated with the help of an ion spectrometer. This process is directly related to the loss of water by Mars in the course of evolution.

The next stage, which has not yet taken place, is to retrieve some soil from Phobos: in 2011, the automatic interplanetary station *Phobos Sample Return* was lost after launch. We plan to fulfill the tasks assigned to it in the project *Boomerang*.

The most ambitious task today, from the point of view of technology, is first of all the sample return from Mars. This is much more difficult than from the Moon, because of the relatively large mass of Mars. It is impossible to do with one spacecraft — it is necessary to reload the samples at Martian orbit to a return spacecraft. A large international cooperative effort is already gathering around this project, in which Russia also intends to participate.

Finally, the planet Venus, often called the "the Earth's twin sister". It is almost the same size as Earth, and has very similar internal structure. Prior to the beginning of the space age, it was often (especially in fantastic literature) presented as a variation on the theme of the early Earth, with impenetrable jungle and diverse biota — remember *Jump into the Void* by A. Belyaev or *The Land of Crimson Clouds* by the Strugatsky brothers? But the reality turned out to be quite different. On Venus, a self-induced and large-scale greenhouse effect emerged. The pressure reached almost 100 atmospheres with a surface temperature of almost 700 degrees Kelvin: that is, before us, in the literal sense of the word, was a red-hot hell.

The number of successful missions to Venus are many. First studies were made by the American space probe *Mariner 2* (1962) from the transit trajectory, and the first measurements in its atmosphere were carried out by the Soviet station *Venera-4*. For more than thirty years of research in the 20th century (the last expedition to Venus was the US *Magellan* in 1989–94), it was possible to study the composition of Venus' atmosphere in general and the features of its circulation, to investigate the sites for possible probe landing areas, to perform radar surveys of the surface, and to study its interaction with the solar wind.

The Japanese orbiter *Akatsuki* is currently studying Venus, and most recently in orbit around the planet there was *Venus Express*, a station of the European Space Agency (ESA), whose scientific payload included three instruments with Russian participation. It worked from April 2006 until the end of 2014, and gave scientists valuable data about the atmosphere of the planet. In particular, the ozone layer was discovered for the first time, and the atmospheric circulation at different altitudes was investigated. The processing of these data continues today.

Today, Venus researchers are facing several global issues. First, it is important to understand why the greenhouse effect on our neighboring planet has reached such incredible proportions. Second, what happened and is happening inside Venus is interesting — how this planet was formed and why, like Mars, it lacks intrinsic magnetic field. Finally, to understand how the incomparably more complex "climate machine" of the Earth is operating, it is important to understand how the climate machine of Venus and Mars works.

But Venus, in contrast to Mars, has a very dense atmosphere and a thick cloud layer, so to study the surface landers are necessary. Unfortunately, "hellish" conditions on the planet make it very difficult to build a long-living probe. The solution might be the use of a balloon or a flying platform or other similar craft that will not rest directly on the surface.

Venus is interesting not to us only, but also to researchers from the United States; and relatively recently, a joint science definition team of Russian and American scientists was created to discuss joint issues in the study of Venus. The basis is taken to be the Russian project *Venera-D*, consisting of an orbiter and a lander modules, to which a few other elements can be added. We are currently discussing the composition of the scientific equipment needed to solve the tasks assigned to the mission, and are considering the possibilities of its implementation. This is a wonderful example of international cooperation, albeit in a difficult political environment.

In recent decades, great attention has been paid to the study of small bodies in the Solar system — primarily asteroids, but also comets. A huge success was the recent project of the European Space Agency *Rosetta* to study the comet 67P/Churyumov-Gerasimenko. The mission itself is named after the Rosetta stone: just as it served as the key for Champollion to decipher Egyptian hieroglyphs, the hopes were that the mission would provide the key to understanding the origins of life for scientists.

While it is dificult to judge the success of this aim, it is obvious that the results of this two-year study (2014–16) gave very, very much to science. For example, it became clear that Comet 67P/Churyumov-Gerasimenko came to us from fairly close regions, whereas Halley's comet, which in 1986 was investigated in particular by the Soviet *Vega* spacecraft, came from a far more distant Oort cloud, the very existence of which (while still hypothetical) has many supporting arguments. The key to understanding this was the comparison of the composition of comets, in particular the ratio of deuterium to hydrogen.

In space research in recent years, the separate worlds of Mercury and the giant planets Jupiter and Saturn, as well as their satellites, have not been forgotten. A brilliant overview of our acheivements with regard to available technology is given here by Dr. James Green. The philosophical question that can now be asked is: what new knowledge did we finally acquire?

In the past, the idea of a zone of possible habitability — that is, a zone where the energy of the Sun is sufficient to allow the existence of water in a liquid state, and in which life can originate — was fairly modest. In fact, it consisted only of the Earth and partially of Mars. But thanks to new data, it is known that the satellites of the giant planets also have liquid water, which in this state is supported by heating due to tidal forces, so that the habitable zone can extend quite far beyond the Martian orbit. Oceans of liquid salty water were discovered on three of the Galilean satellites of Jupiter, and on Enceladus, a satellite of Saturn. Conditions there seem to be far from favorable for living organisms, but bacteria exist even in those places on Earth where life would seem to be impossible. And some experiments with terrestrial extremophile bacteria have shown that such organisms can survive in conditions similar to Martian ones.

In this regard, strong "intellectual impetus" was gained by the discovery of exoplanets. Now their number reaches several thousand, and among them there are quite a lot similar to the Earth. But we still cannot answer the question whether life exists there. Nevertheless, this dream can become a powerful driving force for new and exciting findings.

4. PLASMA LABORATORY IN SPACE

Information about other planets and life in the Universe are perhaps the most understandable of the results that were obtained thanks to Sputnik. However, space exploration is not limited to planetray studies or star observations; and if we talk about the most important discoveries after Sputnik, then one of them was the discovery of the Earth's magnetosphere — the region where the behavior of charged particles is controlled by the magnetic field of our planet. This was achieved in the very first years of space research. At the same time, numerous global structures produced by the interaction of the solar wind with the Earth's magnetic field within and around the magnetosphere were discovered — the magnetic tail, the magnetopause (the boundary of the magnetosphere), collisionless shock waves that decelerate the supersonic solar wind, etc.

The advancement of this line of research is duly covered in the present volume (see the paper by Chris Russell "Space and planetary magnetism: from 1958 to the present" and the one by Rosine Lallement, which extends our perspective even further to other stars).

The concept of the magnetosphere appears to be a very productive one, and it later turned out that the global magnetosphere structure is similar for many planets — Mercury, Saturn, Jupiter — taking into account their different dimensions; and not only in them: the magnetospheres are formed around many astrophysical objects (e. g., neutron stars). Thus, by exploring near-Earth space, one can get an idea of the processes that occur in other and usually very distant objects. When we speak of planets, we have in mind something more like "geographical" discoveries; but when we speak about space plasma, we are now talking about physics — about new phenomena and processes that are difficult to observe in the laboratory, but for which space grants number of unique opportunities to a researcher.

There are several fundamental processes that are explored in space, but which are also important for both astrophysical plasma and for hot plasma confinement in future thermonuclear fusion power-plants. Among the most important of them are magnetic reconnection, collisionless shocks (this term was introduced by academician Roald Sagdeev, the second director of the IKI), and wave-particle interactions.

Recently, phenomena related to manifestations of strong nonlinearity have been actively studied. Earlier, the more widespread theory was the quasi-linear one, which includes weak turbulence, when different modes of oscillations have different phases and interact weakly with each other. But the interactions between these different modes and their effects were often found to be much stronger. Actually, such weak turbulence is observed quite rarely.

For example: in the magnetosphere, strong nonlinear waves were found inside the so-called boundary layers at the boundary of the magnetotail plasma sheet. Nonlinear structures were identified already in a completely different area — the internal magnetosphere in its radiation belts — due to strong nonlinear interactions of waves and particles. In other words, studies of the magnetosphere provide very important data for fundamental nonlinear physics. Thus, space is gradually becoming a real laboratory.

Near-Earth space allows us to run another type of experiment in which we are able to observe the response of surrounding plasma on active, human-made perturbations (i.e. electron beams).

Such active experiments were very popular in 1960s and 1970s but the time has now come to revisit the problem. Much more sophisticated experiments are possible now than it was in earlier years. This should improve our understanding of both the principal physical plasma processes and the interrelationships of the magnetosphere, ionosphere, and atmosphere.

An excellent example of such an active experiment was the Soviet-French project ARAKS (1975) on the artificial injection of electron beams and plasma jets into the ionosphere from two rockets launched from the island of Kerguelen in the Indian Ocean, where a magnetic field line starts to end near the city of Arkhangelsk in Russia. The multitude of accompanying effects, which occured during such active interventions in the magnetosphere and ionosphere, were thoroughly investigated and analyzed. Similar experiments are now planned, which already are at a new and higher level of refinement.

An interesting and partly paradoxical situation is that such studies in space help to solve problems of thermonuclear fusion. In particular, the reconnection of magnetic fields plays an important role in the space environment, when the force lines of one magnetic field "connect" with the force lines of another (for example, the solar wind and the Earth) and then re-unite in a different combination (see the paper by Jörg Büchner "60 Years of Space Research — 70 Years of Magnetic Reconnection" in the present volume).

The properties of the reconnection layer arising at the boundary of two space plasmas are qualitatively similar to those of the outer boundary layer that appears during the confinement of the hot (in future thermonuclear) plasma in a tokamak. In both systems, confinement is supported by strong currents, flowing through hot plasma. A comparison of the dimensionless parameters of these systems shows that what is observed in outer space is close to what is observed in thermonuclear facilities. It is these dimensionless parameters that are important for the theory.

If we talk about the evolution of cosmic experiments in the magnetosphere, it must be emphasized that the general tendency is a transition from large scale studies to smaller and smaller. In the 1990's projects *Geotail* (Japan/USA) and the multisatellite INTERBALL (an international project; the leading country Russia) were implemented. Within the framework of the second, two "satellite plus subsatellite" pairs were launched into space, and carried out investigations in the auroral and tail regions of the magnetosphere. That was the key to understand many global plasma processes in the Earth-Sun relations.

The next stage of development dates back to the 2000s. The joint European-Chinese project *Cluster* II (4 probes) and *Double Star* (2 probes) have already tried to study magnetospheric plasma processes on a smaller, so-called, kinetic scale, determined by the Larmor radius of ions.

The newest achievements in this area belong to the US project *Magnetospheric Multiscale* mission, or MMS (4 probes), which is already investigating the processes on the smallest, electron scale. And this is very important, because all the phenomena that occur in this environment are multiscale, but in the terrestrial laboratory it is not always possible to study many of them because of the finite size of any, even the smallest, probes placed in laboratory facility.

To assist the experimenters, these are now joined by specialists in the field of computer modeling. Today, magnetohydrodynamic modeling has reached hitherto unimaginable heights. With its help, it is possible to simulate the processes that result from the ejection of coronal mass (solar plasma), then its propagation over the interplanetary space, and, finally, the emerging processes inside the Earth's magnetosphere.

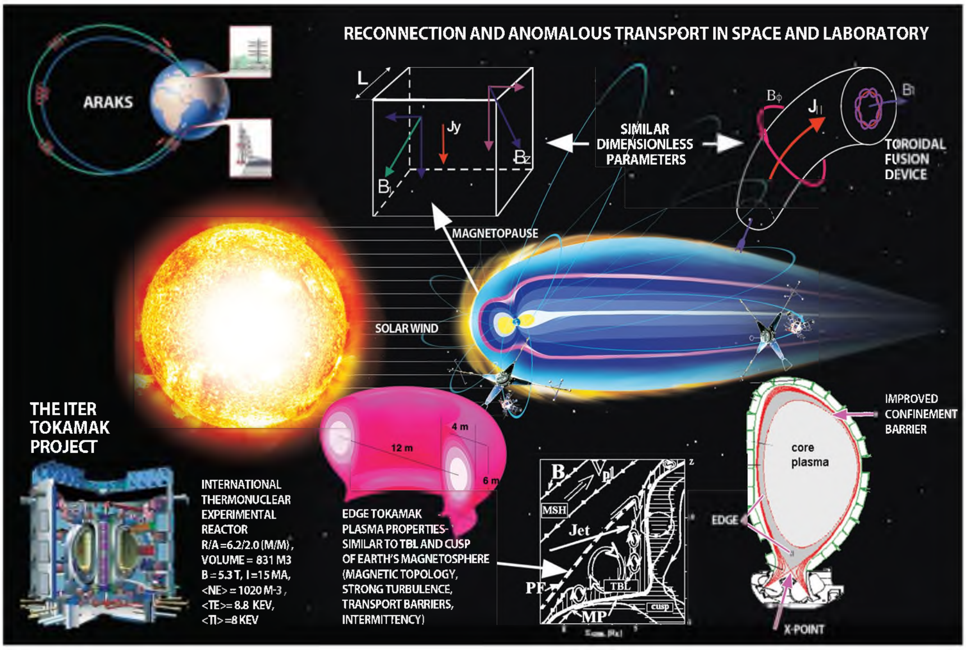

Fig. 16: Various phenomena in space and laboratory plasma

From this we can move now to the new field that is called "space weather" — a combination of factors associated with the impact of outer space on the biological and technological systems of the Earth. The very concept of "space weather" arose thanks to space research. On the other hand, unfavorable "weather conditions" in space are dangerous first of all for satellites and cosmonauts in orbit, and in "especially severe cases" for electrical networks, as well as pipelines on Earth. Thus, these studies are critical to the maintenance of our modern technosphere both on Earth and in space. Some of the problems are covered in the paper by Ji Wu "Space weather: history and current status" in the present book.

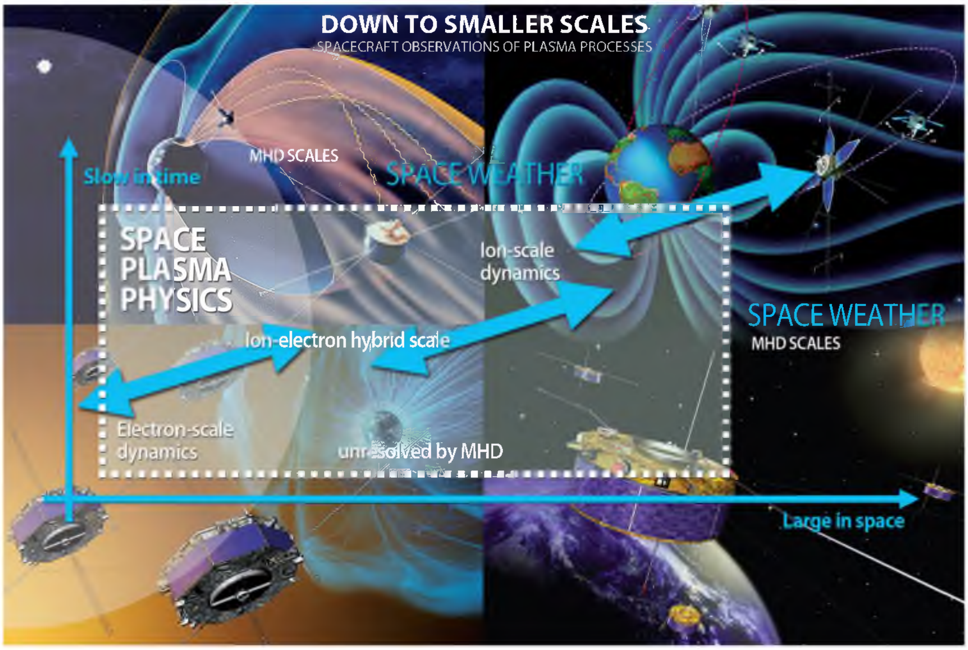

Fig. 17: Multi-spacecraft observations of plasma phenomena in the near-Earth space and space weather

5. INSTEAD OF CONCLUSION

Today, in 2017, the international political situation is very far from being calm or even simply stable. It is even more tense than it was sixty years ago when there was a "cold war", which at any time could become hot. Perhaps the most important achievement of Sputnik is that it became a sort of "lightning rod" for tension between countries, and transformed irreconcilable hostility into a relatively peaceful rivalry between the socialist and capitalist systems, and then globalized the problem itself, and transferred it from the solely political plane to the field of science and technology, gradually turning it into a mutually beneficial competition. This remains the case even today, despite the fact that international cooperation plays an increasing role.

The American historian Walter McDougall later wrote that Sputnik 1 launch completely changed the essence of the Cold War. M. V. Keldysh is quoted as saying: *It is not yet known what mattered more for the defense of the country: an intercontinental combat missile or the first satellite.*

Space was and remains the sphere where cooperation continues even during times of “cold” relations. In 1975, we witnessed a wonderful experiment — docking of the Soviet and American spaceships *Soyuz* and *Apollo*, with the historic handshake of cosmonaut Alexey Leonov and astronaut Donald Slayton. Space was a bridge between the then quite hostile countries. It can be said that, from this docking, the International Space Station project, which had and still has great political and scientific significance, later developed.

It is interesting to remember that all meetings of *Soyuz-Apollo* specialists took place here at the premises of IKI, although the Institute itself was not directly involved in this project. IKI was then the ”open window” of the Soviet space industry, and all participating engineers from Korolev’s design bureau introduced themselves as IKI employees.

As was said above, in September 2017 in Adelaide (at the International Astronautical Congress) an agreement was signed on the creation near the Moon of a spaceport *Deep Space Gateway*. Negotiations were conducted between NASA and Roscosmos State Corporation, but this will be an open platform in which other countries can participate, in particular the People’s Republic of China. I think if we combine our efforts to explore the Moon by automatic and then manned spacecraft, then by 2030, the construction of an international astrophysical observatory on our satellite can become possible.

Thirty years ago, in 1987, with the support of then General Secretary of the CPSU Central Committee (Mikhail Gorbachev), IKI organized the International Forum “Cooperation in Space for Peace on Earth”. This was one of the remarkable events of *perestroika*, inspired by the hope for a new stage in the development of international cooperation in all space activities and especially space science.

The following decades were very difficult for our country and Russian science, and the year 1997 passed without a major Sputnik celebration. But in 2007, in the 50th anniversary of Sputnik, the Academy of Sciences organized and hosted a large-scale international forum “Space: Science and Problems of the 21st Century”, in which eminent scientists and engineers and heads of leading space agencies of the world took part. And in 2017, the Russian Academy of Sciences and the Roscosmos State Corporation organized the third international scientific forum “Sputnik: Sixty Years Along the Path of Discoveries”. IKI initiated the idea, which was supported by many organizations and universities related to space exploration.

The result of that Forum was a collection containing articles and presentations, given specifically for publication as a book. Thus, we pay tribute to the great event — the discovery of the space age or, as one of the authors Professor Roger-Maurice Bonnet writes, of the great October space revolution, which was launched by the small Sputnik.

Fig. 18: Sputnik 1 miniatures — designer's replication of famous Soviet souvenir specially for the Forum "Sputnik: 60 Years Along the Path of Discoveries" in 2018

ACKNOWLEDGMENTS

The Forum and the book became possible thanks to Russian Academy of Sciences, Space State Corporation ROSCOSMOS, and Federal Agency for Science Organizations.

Our special thanks is to LSR Group, who has been actively promoting Russian achievements in science and space. We greatly appreciate this support, which was especially significant for the Forum and publishing of this proceedings.

We are grateful to Russian State Archive of Scientific and Technical Documentation (RGANTD) for the special exhibition "The world's first — our, Soviet…", prepared jointly with the Scientific and Educational Building "Special Machine Building" with the participation of the Archive of the President of the Russian Federation. Two posters are presented on the following pages.

The illustrations for the paper were prepared with the use of archival images, kindly provided by RGANTD, and open image databases. Final images courtesy, unless specified otherwise, to Alexander N. Zakharov (IKI).

СОВЕТСКИЕ ИСКУССТВЕННЫЕ СПУТНИКИ ЗЕМЛИ

Создание первых в мире искусственных спутников Земли потребовало решения ряда сложнейших и принципиально новых научно-технических проблем. Это оказалось под силу благодаря высокому техническому уровню ракетостроения в СССР.

Soviet artificial Earth satellites. Author Bazykin V.V. Designer Dutov N.G. Sheet No1. Military Publishing house of MD of the USSR. Moscow, 1958. Russian State Archive for Scientific and Technical Documentation, F.31, List 15, File 89

Серия плакатов „Советские искусственные спутники Земли“ на 3-х листах.

Плакат № 2

СОВЕТСКИЕ ИСКУССТВЕННЫЕ СПУТНИКИ ЗЕМЛИ

ПЕРВЫЙ СПУТНИК

Запущен 4 октября 1957 года. Диаметр корпуса 58 см, вес 83,6 кг. Просуществовал до 4 января 1958 года.

ВТОРОЙ СПУТНИК

Запущен 3 ноября 1957 года. Общий вес научной аппаратуры, животного и источников электропитания — 508,3 кг. Просуществовал до 14 апреля 1958 года.

Международный геофизический год (МГГ)—это обширная программа одновременных исследований Земли, ее недр, водной оболочки и атмосферы, а также прилегающего к Земле космического пространства. Программа МГГ проводится учеными 66 стран с 1 июля 1957 года по 31 декабря 1958 года. Осуществление программы МГГ позволит полнее овладеть силами природы и поставить их на службу человеку, найти средства защиты от стихийных бедствий.

Советский Союз и Соединенные Штаты Америки приняли на себя обязательство в период Международного геофизического года создать искусственные спутники Земли, являющиеся наилучшим средством исследования верхних слоев атмосферы. Первым это обязательство успешно выполнил Советский Союз.

Земная атмосфера простирается до высоты около 1000 км. Она задерживает вредные для жизни на Земле коротковолновые ультрафиолетовые и рентгеновские лучи Солнца. Космические лучи в земной атмосфере сильно изменяются. В верхних ее слоях отражаются и преломляются радиоволны. Изменения в верхних слоях оказывают воздействие на явления, происходящие у поверхности Земли и связанные с погодой. Поэтому изучение верхних слоев атмосферы имеет большое научное и практическое значение. До последнего времени это удавалось лишь путем наблюдений таких явлений, как полярные сияния, метеоры и др. Недавно для изучения верхних слоев атмосферы начали применять ракеты. Но их полет кратковременен, а изучаемый район ограничивается местом запуска. Только искусственные спутники Земли позволяют вести длительные непрерывные наблюдения над всей поверхностью Земли.

С целью проведения ряда медико-биологических исследований в условиях космического полета в герметической кабине второго спутника было помещено подопытное животное—собака Лайка. С помощью различных приборов ученые систематически получали по радио сведения о дыхании, температуре, кровяном давлении и сердечной деятельности животного.

В течение всего опыта состояние собаки было удовлетворительным. Это подтверждает возможность полета живого организма в космическое пространство.

Из глубин мирового пространства на Землю приходят космические лучи—потоки электрически заряженных частиц с различной массой и энергией. Их исследования способствуют развитию атомной физики, изучению магнитного поля Земли, пониманию процессов, протекающих на поверхности звезд и в межпланетной среде.

Второй спутник был снабжен счетчиками, которые регистрировали электрически заряженные частицы космических лучей. Было обнаружено, что от высоты 225 до 700 км интенсивность лучей возрастает на 40%. Уточнено распределение различных частиц магнитным полем Земли.

Солнце оказывает воздействие на многие земные явления: на изменения в верхних слоях атмосферы, на погоду, на распространение радиоволн. Вся жизнь на Земле зависит от Солнца. Поэтому важно знать, как и почему меняется излучение Солнца.

На втором искусственном спутнике Земли были установлены приборы для исследования величины коротковолнового излучения Солнца. Солнечные лучи проходили сквозь различные фильтры и падали на фотоумножители, где преобразовывались в электрические сигналы, которые и передавались на Землю.

Спутники тормозятся в атмосфере, постепенно снижаются, плавятся и частично испаряются. Их остатки могут упасть на Землю. Скорость изменения орбиты спутника зависит от плотности атмосферы. Наблюдения за советскими искусственными спутниками Земли показали, что на высотах 225—228 км скорость изменения орбиты в 5—10 раз больше, чем предполагалось. За пределами атмосферы спутник мог бы существовать более длительное время.

Даже самые совершенные приборы не могут производить самостоятельные исследования в космосе. Для изучения далеких небесных тел и постановки некоторых опытов, необходимых для развития науки, в космический полет отправится человек. Однако, чтобы обезопасить нахождение человека в космическом пространстве, предстоит провести еще целый ряд научно-технических экспериментов. Успешно осуществив запуск искусственных спутников Земли, советские ученые со временем создадут и ракеты для полета на Луну.

В будущем искусственные спутники Земли позволят с высокой точностью определить форму и размеры нашей планеты, уточнить географические карты, ретранслировать телевизионные передачи на всю Землю, наблюдать движение облаков и делать прогнозы погоды. Они станут межпланетными станциями, где космические корабли смогут пополнять запасы горючего, израсходованные при отрыве от Земли.

1958 г.

Российский государственный архив научно-технической документации

Soviet artificial Earth satellites. Author Bazykin V.V. Designer Dutov N.G. Sheet No2. Military Publishing house of MD of the USSR. Moscow, 1958. Russian State Archive for Scientific and Technical Documentation, F.31, List 15, File 90

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SPACE REVOLUTION IN SOLAR PHYSICS

This paper describes how solar physics has been revolutionized in the last 60 years, thanks to observations made from space by the successors of Sputnik 1. It identifies the most productive of these and shows the crucial role of the SOHO mission, whose original set of highly performing instruments has opened an impressive series of other successive space missions leading to major progress in our understanding of the Sun, from the central core where nuclear energy is produced, through the radiation and convective zones, the chromosphere, the corona, and the heliosphere.

These progresses are the fruits of the development of helioseismology from SOHO, of polar observations from the out-of-ecliptic *Ulysses* mission and the exploration *in situ* of the Solar system and the heliosphere. The long-lasting enigmas of the corona and of the acceleration of the solar wind witnessed an impressive jump in the understanding of the interaction of the solar magnetic field with the corona and heliospheric plasmas through the mechanism of magnetic reconnection. Continuous observations of the Sun over several decades are now possible, allowing helioseismology to discover the surprisingly high difference between the rotation of the central core and the radiative zone as well as 3D observations of the solar magnetic field of sunspots and active regions before they appear on the visible face of the solar disk.

All these progresses are due to the successors of Sputnik 1, which have led to the definition of now commonly called space weather, a genuine succession of the Sputnik heritage in both science and applications, embracing the observation and the effects of solar activity on the space Earth environment, the whole Solar system and the heliosphere.

1. WHY THE SUN?

In 1919, a thirty-years old American journalist (and socialist!) John Reed published a famous book *Ten Days That Shook the World*, where he described his enthusiasm and analyzed his first-hand experience of the 1917 October Revolution in Russia. On the 4th of October 1957 at precisely 22 h 28 min (Moscow time), forty years later, the Soviets launched Sputnik 1. From Paris, where I lived, I could hear on the radio the familiar *beep-beep*, a lively testimony for the doubters that indeed it originated from an artificial space object orbiting the Earth at some 30,000 km per hour. This signal triggered my irreversible desire to become a space scientist and to take part in the second historical revolution of the 20th century that also shook the world and dramatically changed our civilization in the many facets that artificial satellites do present. I did not give up that ambition, and had the good luck of successively meeting three senior astrophysicists (Evry Schatzman, Jean-Claude Pecker, Jacques-Emile Blamont), who eleven years later — together with Alfred

Kastler, 1986 Physics Nobel Prize winner — would set-up my PhD dissertation jury and judge my achievements in observing the ultraviolet spectrum of the Sun with sounding rockets and stratospheric balloons.

So, why the Sun? First, it is the only star we can observe in great detail: a model laboratory for understanding the ten billion of billions of billions other stars in the Universe*. Say it differently: if we do not understand the Sun, we have no hope of understanding the Universe. Second, the Sun is also our own star: the ultimate source of energy for the more than 7.5 billion human inhabitants of Earth, and the origin of electromagnetic perturbations, which affect our normal life: the composition of the upper atmosphere, and its ability to transmit electromagnetic signals influencing telecommunications, long-distance transport, navigation, inducing electric currents in large metallic structures, in power systems, submarine cables and pipelines among several others. All these effects, which today make up what is called the "space weather" and demand special preventive attention and forecasting, find their origin in the Sun's magnetic field and require the most accurate possible understanding of the mechanisms, which govern its origin and its variability.

Observing the Sun from above the Earth atmosphere and inside the heliosphere, that part of space which is dominated by the Sun's magnetic influence, and far beyond, offers unique opportunities. It allows to observe the entirety of its electromagnetic spectrum, in particular the ultraviolet, which is absorbed by the atmosphere, create and influence the ionosphere, permitting, but also perturbing radio-telecommunications. It also permits to follow the physical phenomena that are at the origin of the eleven-years activity cycle, to estimate their destructive power and possibly forecast their occurrence and their associated space weather effects. Paradoxically, it allows to observe deep in the interior of the Sun, down to the nuclear core where solar energy is produced, and at the same time it addresses fundamental physics issues.

Solar physics is an old science, which was first revolutionized by the discovery of sunspots by Galileo Galilei in 1610. Here we will focus on the Sun's phenomena which have been discovered thanks to a few visionary scientists, whose observations and research opened the way to seminal discoveries and new theories, shaping the development of solar physics following the launch of Sputnik 1. We select six fundamental domains related to the Sun and to space, and identify eight scientists (in bold font below) whose activities have pioneered space solar physics:

- the internal structure of the Sun and the development of helioseismology;
- the structure and the high temperature of the solar corona;
- the existence, the characteristics, and the acceleration mechanisms of the solar wind;

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* Astronomers from ESA's *Herschel* Observatory estimate there are about 100 thousand million stars in the Milky Way alone, and millions upon millions in all the other galaxies of the Universe!

- The Sun's magnetic field: its origin and variability, and the 11-years activity cycle, i.e. sunspots, flares, eruptions, and active regions;
- The global character of the magnetic field and its extension into the heliosphere;
- The concept of space weather.

The ten years preceding the Second World war were marked by major inventions and discoveries. First, the invention of the solar coronagraph by **Bernard Lyot** in 1931, an instrument, which allowed to observe the corona outside of eclipses, and is presently exploited in different modern incarnations on several satellites presently in orbit as described in the following section. The second refers also to the corona and the discovery of unknown spectral lines, which were attributed to a hypothetical element logically baptized "Coronium", whose ephemeral existence lasted until 1940, when **Bengt Edlen**, a Swedish professor of physics and an astronomer who specialized in spectroscopy, showed that these lines correspond to forbidden transitions of multiply ionized iron (Fe XIV), requiring a temperature of millions of degrees. The origin of the high temperature of the corona is still being discussed today by astronomers and physicists, and analyzed thanks to several solar satellites, constantly improving our understanding of the phenomenon. **Hannes Alfven**, also Swedish scientist and 1970 Physics Nobel Prize laureate, initiated in 1942 a long-lasting effort to propose an interpretation of the corona's temperature through magnetohydrodynamic phenomena, among which the so-called Alfven waves, where the restoring force is provided by the solar magnetic field.

Following a century-long research on the existence of particles escaping the Sun's gravity field by famous astronomers such as R. Carrington, G. Fitzgerald, A. Eddington, K. Bierkland, F. Lindemann, L. Biermann and several others, in 1958, the American physicist **Eugene Parker** proposed that the high temperatures ions of the corona can escape the Sun's gravity thanks to their high energy, thereby shaping the magnetic structure of the Solar system, and defining the border between it and the Milky Way. One year later, in January 1959, using the *Luna 1* soviet satellite the existence of the solar wind was directly observed by **Konstantin Gringauz** (member of the IKI, who passed away in 1993). That discovery was verified by the Soviet *Luna 2* and *Luna 3* and then by the *Venera 1* Soviet mission to Venus in 1961, and in 1962 by the American *Mariner 2*, another space probe to Venus. The details of the mechanisms, which can accelerate the solar wind are still investigated today, and justify the enormous amount of theoretical and observational efforts developed in the post-Sputnik 1 era.

At the end of the Second World War, **Herbert Friedman** of the US Naval Research Laboratory was the first to use German V2 rocket's capabilities and to observe the Sun in the ultraviolet and X-ray spectral ranges as early as 1949, making the first observations of the hot layers of the chromosphere and the corona.

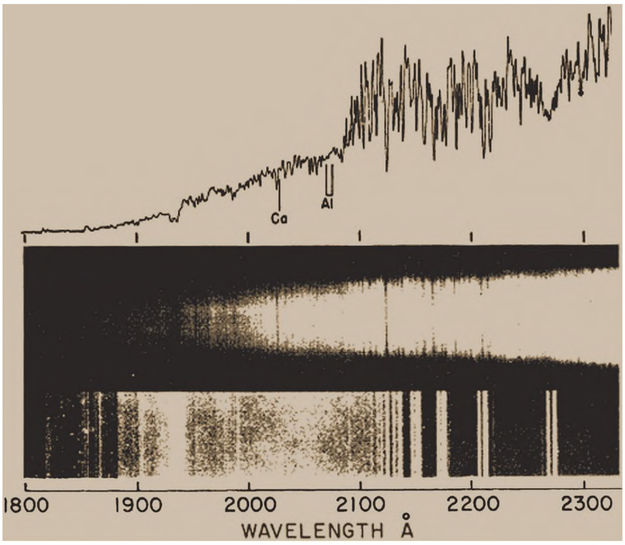
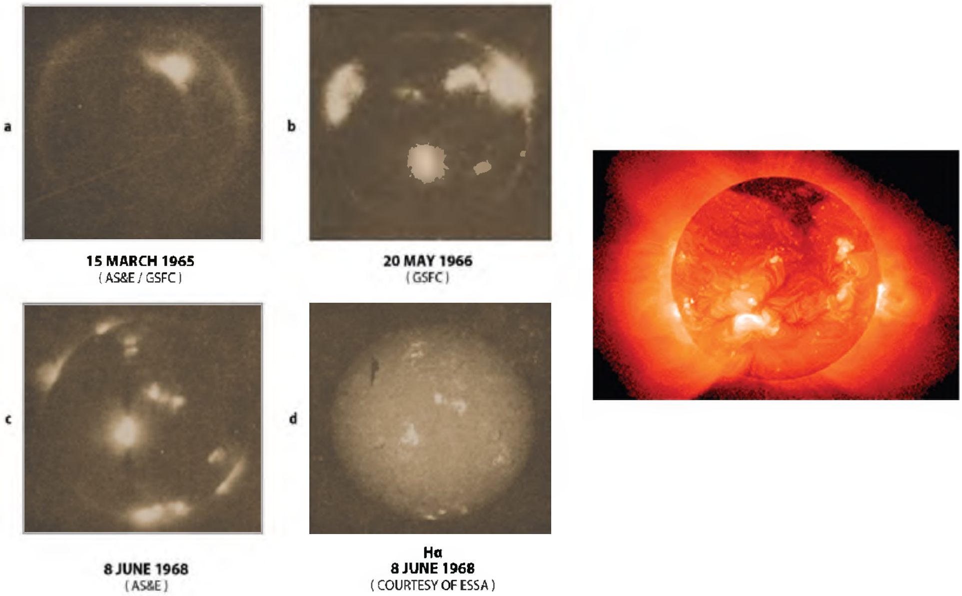


Fig. 1: Early observations of the Sun's UV spectrum. Credit: Johnson et al. (1958)



15 MARCH 1965
(AS&E / GSFC)

20 MAY 1966
(GSFC)

8 JUNE 1968
(AS&E)

Hα
8 JUNE 1968
(COURTESY OF ESSA)

Fig. 2: Left: Three X-ray photographs obtained in 1968 by R. Giacconi, G. S. Vaiana, and others from *American Science and Engineering* in Cambridge, USA (Vaiana et al., 1968), showing the evolution with time of X-ray telescopes' performances. The picture in the right lower quadrant shows the correspondence between X-ray and an H alpha images taken simultaneously. Right: For the sake of comparison, the image, from the soft X-ray telescope on board the Japanese *Yohkoh* mission of ISAS, shows the emission of the solar corona obtained some 24 years later on May 8, 1992. The effective wavelength is about 10 Å, or 1 keV, and the resolution about 10 arcs. The presence of an important coronal hole at the north pole (see also Fig. 3) is very striking!

The purpose there was to study the formation of the ionosphere, extending from about 60 km to 1,000 km altitude, and its influence on the propagation of radio waves to distant places on Earth. That research of great interest for military communications opened the way to the study of the solar spectrum at wavelengths shorter than 300 Å, which are absorbed by the Earth's atmosphere. Friedman was also the first to observe X-ray spectra of the hot corona in 1957 and his coworkers at NRL, R. Tousey and G. Bruekner, colleagues at John's Hopkins and at the University of Colorado were pioneers in the study of the UV solar spectrum (Fig. 1) (Tousey, 1963).

Friedman's X-ray spectra not only did confirm the high temperature of the corona, but offered a new means for its observations outside eclipses, because coronal X-ray radiation is several orders of magnitude more intense than visible light emitted by the colder Sun's disk. That powerful capability was extensively exploited after Sputnik 1 by **Ricardo Giacconi,** 2002 Physics Nobel Prize laureate, and his colleague G. Vaiana who in 1965–1968 were able to obtain the first X-ray images of the corona using high-altitude US rockets. Despite their relatively low spatial resolution these images were nevertheless capable of revealing the magnetic structures and the vertical extension of active regions and of the corona outside of eclipses (Fig. 2). Last but not least, **Robert Leighton** in 1960 revealed the existence of 5-minute oscillations of the solar disk's surface, randomly excited by the turbulent convective zone, corresponding to acoustic waves propagating throughout the solar interior. He opened the field of helioseismology (Leighton et al., 1962).

2. GREAT SOLAR MISSIONS OF THE POST-SPUTNIK 1 ERA

Table 1 lists all solar missions so-far launched or ready to be launched, whose objectives were the study of the Sun and the heliosphere (Section 4.4.2), including IBEX and *Voyager 1* and *2*. By comparison, X-ray and satellites total about 45.

ORIGIN	PAST	OPERATING	FUTURE	TOTAL
USA	6	11	4	21
JAPAN	1	1	1	3
EUROPE	3	2	1	6
RUSSIA	1	1	1	3
TOTAL	11	15	7	33

The post-Sputnik 1 era involves primarily the United States, Japan, and Europe. The first epoch saw a series of pioneering satellites, which generated a rich harvest of new results. Among them were the long series of NASA's *Orbiting Solar Observatories* (OSO) which totaled 8 missions, the *Solar Maximum Mission* (SMM), post-*Apollo* and *Skylab* missions, involving a substantial number of non-US Principal Investigators and Co-Investigators, mostly from European institutes. These missions were often complemented by rocket and balloon-borne instruments, and by ground-based observations in the visible and radio domains.

2.1. YOHKOH

The situation changed dramatically in 1991 when the Japanese space science organization ISAS (Institute of Space and Astronautical Science) launched the *Yohkoh* 390-kg satellite aiming primarily at the study of solar flares (Section 4.3) through spectroscopic observations in the high energy domain, offering spectacular images of the corona outside of eclipses over more than a solar cycle with a resolution of 3 arcs, never achieved before in soft X-rays (see Fig. 2).

2.2. SOHO REVOLUTION

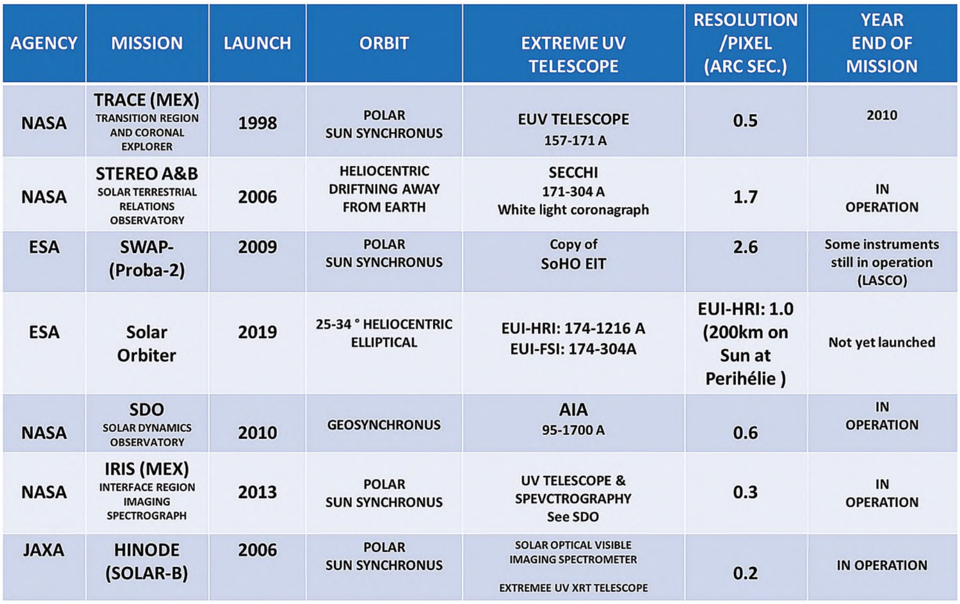
Following *Yohkoh*, a genuine revolution was triggered by the 1850-kg ESA-NASA Solar Heliospheric *Observatory* (SOHO), the longest-lived solar and heliospheric mission still operating. Launched on 2 December 1995 and placed in halo orbit at Lagrange point L_1, it allowed continuous solar observations over more than two complete solar cycles. SOHO provided the first ever images of structures and flows below the Sun's surface and of solar activity on the far side of the Sun. It eliminated uncertainties in the internal structure of our star and confirmed the existence of a new type of neutrino, which could explain the large discrepancy between their high flux as predicted from the Sun's luminosity, and the much lower flux that was observed from the ground. The ultraviolet imagers and spectrometers on SOHO have revealed an extremely dynamic solar atmosphere where plasma flows play an essential role. It measured the acceleration profiles and identified the source regions of both the slow and fast solar wind.

Table 2 gives the list of the SOHO scientific instruments. Most of them are still operational, at the time of writing this article. Of course, more modern and more powerful payloads, providing better performance, in particular in spatial resolution of EXUV images, have been flown on successive solar missions (Table 3). The SOHO LASCO coronagraph has proven to be particularly important because of its unique large field of view of 3.7–30 solar radii, offering essential observations of the corona over large distances from the Sun, which prove to be crucial for Space weather studies.

Table 2: SOHO scientific payload

1. CDS (Coronal Diagnostic Spectrometer) from Rutherford Appleton Laboratory
2. CELIAS (Charge, Element, and Isotope Analysis System) from the University of Bern
3. COSTEP (Comprehensive Suprathermal and Energetic Particle Analyser) from the University of Kiel
4. EIT (Extreme ultraviolet Imaging Telescope) from the Institut d'Astrophysique Spatiale
5. ERNE (Energetic and Relativistic Nuclei and Electron experiment) from the University of Turku
6. GOLF (Global Oscillations at Low Frequencies) from the Institut d'Astrophysique Spatiale
7. LASCO (Large Angle and Spectrometric Coronagraph) from the Naval Research Laboratory
8. MDI (Michelson Doppler Imager) from Stanford University
9. SUMER (Solar Ultraviolet Measurements of Emitted Radiation) from the Max-Planck-Institut für Aeronomie
10. SWAN (Solar Wind Anisotropies) from Service d'Aeronomie
11. UVCS (Ultraviolet Coronagraph Spectrometer) from Harvard-Smithsonian Center for Astrophysics
11. VIRGO (Variability of Solar Irradiance and Gravity Oscillations) from PMO/WRC Davos

Table 3



AGENCY	MISSION	LAUNCH	ORBIT	EXTREME UV TELESCOPE	RESOLUTION /PIXEL (ARC SEC.)	YEAR END OF MISSION
NASA	TRACE (MEX) TRANSITION REGION AND CORONAL EXPLORER	1998	POLAR SUN SYNCHRONUS	EUV TELESCOPE 157-171 A	0.5	2010
NASA	STEREO A&B SOLAR TERRESTRIAL RELATIONS OBSERVATORY	2006	HELIOCENTRIC DRIFTNING AWAY FROM EARTH	SECCHI 171-304 A White light coronagraph	1.7	IN OPERATION
ESA	SWAP-(Proba-2)	2009	POLAR SUN SYNCHRONUS	Copy of SoHO EIT	2.6	Some instruments still in operation (LASCO)
ESA	Solar Orbiter	2019	25-34 ° HELIOCENTRIC ELLIPTICAL	EUI-HRI: 174-1216 A EUI-FSI: 174-304A	EUI-HRI: 1.0 (200km on Sun at Perihélie)	Not yet launched
NASA	SDO SOLAR DYNAMICS OBSERVATORY	2010	GEOSYNCHRONUS	AIA 95-1700 A	0.6	IN OPERATION
NASA	IRIS (MEX) INTERFACE REGION IMAGING SPECTROGRAPH	2013	POLAR SUN SYNCHRONUS	UV TELESCOPE & SPEVCTROGRAPHY See SDO	0.3	IN OPERATION
JAXA	HINODE (SOLAR-B)	2006	POLAR SUN SYNCHRONUS	SOLAR OPTICAL VISIBLE IMAGING SPECTROMETER EXTREMEE UV XRT TELESCOPE	0.2	IN OPERATION

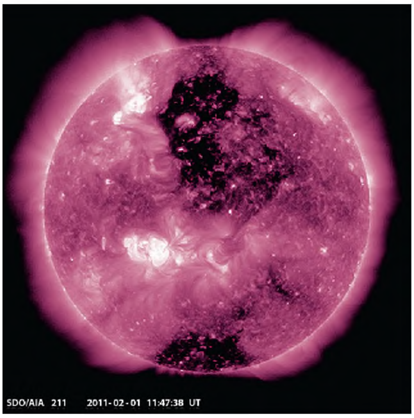


Fig. 3: A 211 Å image taken by the SDO/IAA telescope in February 2011 showing a coronal hole stretching across the top half of the Sun. Coronal holes are magnetically open regions on the Sun that stream high-speed solar wind into space. Credit: NASA/SDO

The EIT far-UV telescope provides images of the Sun in four wavelengths: 171 Å (Fe IX), 195 Å (Fe XII), 284 Å (Fe XV), and 304 Å (He II) with a spatial resolution of 6.2 arcsec per pixel.

Table 3 compares the performance of subsequent solar missions from NASA, ESA, and JAXA. The very rich new information produced by the SOHO EIT UV telescope, which served as a model for all consecutive similar instruments on board the missions listed in this Table, is the reason why the "Payload" column is showing only the UV imagers common to the majority of them. Fig. 3 obtained by the Atmospheric Imaging Array on SDO illustrates the high quality of present-day imaging capabilities of EUV solar space telescopes.

2.3. ULYSSES

Ulysses, formerly named *International Solar Polar Mission* (ISPM), started in the late 1970s as a cooperative venture between NASA and ESA. It was conceived as a two-satellites mission orbiting the Sun at an inclination of 80° above the ecliptic plane. ESA was in charge of *in situ* studies of the solar wind properties, and NASA of complementary remote sensing instruments, in particular imaging telescopes. In 1991, NASA however decided to abandon its satellite and the mission was renamed *Out-of-Ecliptic* mission, and then *Ulysses* by ESA. *Ulysses* was launched in 1990 by the Space Shuttle, first to Jupiter, whose gravity assistance placed it on its 70° inclination orbit above the ecliptic plane allowing a complete coverage of the Sun above its poles, a region of the interplanetary medium never explored before.

Ulysses completed its mission in 2009, after covering two entire solar cycles (Fig. 4). The Solar Wind Ion Composition Spectrometer (SWICS) a time-of-flight mass spectrometer, was able to provide unprecedented information on the solar wind properties (Fig. 5). Together with the NASA *Voyager 1*, *2* interplanetary probes launched in 1977, *Ulysses* results generated a series of missions, which have contributed important results for our understanding of the acceleration and propagation of the solar wind and of the coronal mass ejections (CMEs) into the interplanetary medium and the heliosphere, two phenomena which are essential to study — and possibly forecast — space weather events (see Section 3.5).

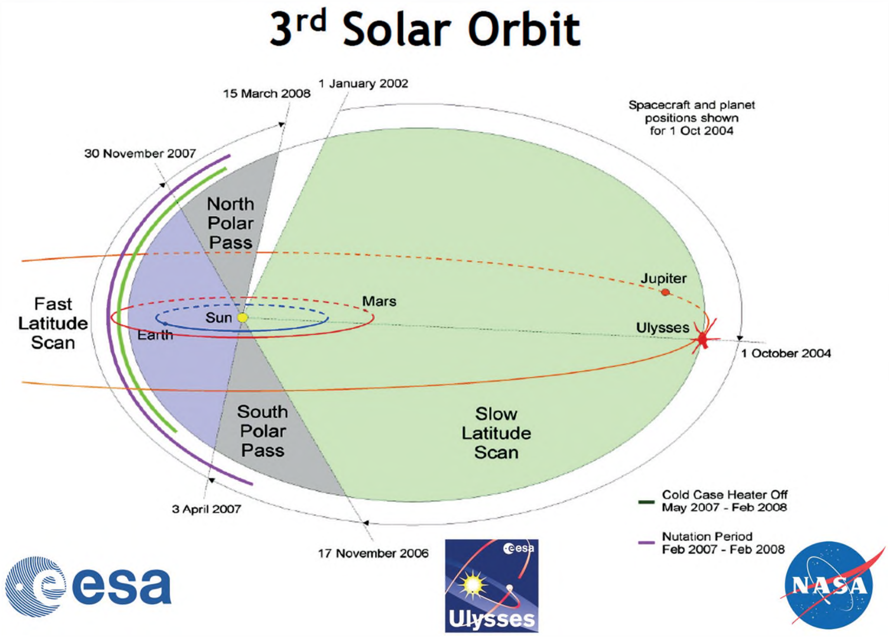


Fig. 4: *Ulysses* third polar orbit. Credit: ESA-NASA

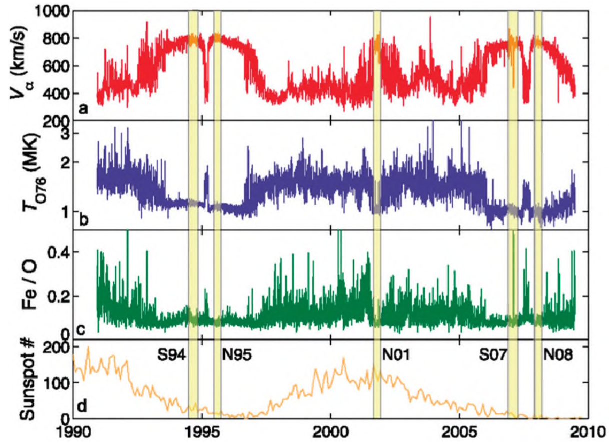


Fig. 5: Overview of solar wind properties during the entire *Ulysses* mission (a) solar wind speed, (b) freezing-in temperature derived from the O7+/O6+ charge state ratio, (c) Fe/O abundance ratio, and (d) mean monthly sunspot number. The high heliolatitude passes at 70° are indicated by shaded bands, except for the south polar pass in 2000, which was not dominated by a fast solar wind stream due to the solar maximum conditions during that time period. There are compelling observations of a clear anticorrelation between solar wind flow speed and coronal electron temperature, as determined from solar wind ionic charge states (Fisk, 2003). The slow wind nearly matches the composition of the corona, and is twice as dense and more variable in nature than the fast wind, which matches that of the photosphere. Credit: von Steiger, Zurbuchen (2011)

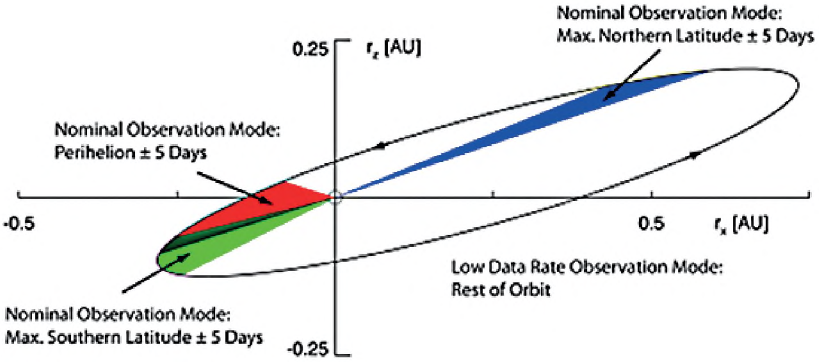


Fig. 6: ESA *Solar Orbiter* mission. Credit: ESA

Launched in 1977 to an orbit around L_1, NASA's *Advanced Composition Explorer* (ACE), still in operation at the time of writing this paper, carries six high-resolution sensors including an improved version of SWICS, and three monitoring instruments to sample low-energy particles of solar origin, as well as high-energy galactic particles, with a collecting power 10 to 1000 times larger than past or planned experiments, completing the high-latitudes *Ulysses* measurements with in-ecliptic data. Similarly, high latitude measurements were completed by NASA's WIND spacecraft, launched in 1994, which provided baseline ecliptic plane observations.

Ulysses will remain unique until it might be replaced by a successor offering better capacities and higher orbital inclination. The ESA *Solar Orbiter* mission to launch in 2020 will reach a maximum latitude of 34° (Fig. 6). It will carry a suite of remote sensing and *in situ* instruments, including the Polarimetric and Helioseismic Imager (PHI), which will deliver high-cadence images of the Sun in intensity and velocity near the polar regions, which were impossible to get after the withdrawal of NASA from the original ISPM mission. The Extreme UV Imager (EUI) will provide an indispensable link between the solar surface and the outer corona and also provide the first-ever UV images of the Sun from an out-of-ecliptic viewpoint, which are not possible so far, neither from SOHO nor from any of its in-ecliptic successors (see Table 3).

3. MAJOR ADVANCES IN SOLAR SPACE RESEARCH IN THE POST-SPUTNIK 1 ERA

The increasing capabilities of the great missions listed above have led to enormous progress in our understanding of the Sun, while at the same time raising new questions, opening new problems and new fields of research. We have selected below five domains of importance, which have witnessed major advances not only in astrophysics, but also in some of the applications of space fundamental research to problems facing our modern civilization.

3.1. HELIOSEIMOLOGY PROBING THE INTERNAL STRUCTURE OF THE SUN DOWN TO THE NUCLEAR FUSION CORE

The 5-minute oscillations of the solar disk's surface randomly excited by the internal Sun's turbulent convection, revealed by R. Leighton in 1960 (Clavery et al., 1979) correspond to the frequencies and characteristics of acoustic waves, for which the restoring force is the pressure, hence their appellation as p-modes as opposed to the lower frequencies g-modes, for which the restoring force is the Sun's gravity and which become evanescent when they reach the surface. Because they propagate through the solar interior where the sound speed varies, p-modes allow the determination of the temperature, the chemical composition, and the dynamics of the Sun's internal layers (Fig. 7), while g-modes are mostly trapped inside the solar core. Helioseismology is the process of inferring the internal structure and kinematics of the Sun from the propagation of these waves, their velocities, periods, and angular degrees.

This diagnostic tool came to the front line of solar physics when in 1976 A. Severny, V. Kotov, and others (Severny et al., 1976) reported to have discovered a new 160-minute-period global oscillation. That phenomenon, however, did not correspond to any possible solar phenomenon and was not substantiated by contemporary solar observations. It was soon interpreted as resulting from a combination of the diurnal cycle (160 min = 1/9th of a day) and atmospheric extinction. Nevertheless, the important interest of the community in their attempt to find an explanation to these controversial oscillations, triggered an intense observational effort in what would rapidly become known as helioseismology. Particularly active in that research was a group in Nice, France, involving F. Roddier, P. Delache, and co-workers. Uninterrupted continuous observations are essential for eliminating harmonics of non-solar origin from the oscillations spectra.

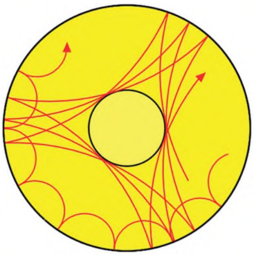


Fig. 7: Different oscillation modes have different sensitivities to the structure of a star. Their frequency depends upon the temperature and the chemical composition of the different layers they cross through. By observing multiple modes, and using inversion algorithms, one can infer a star's internal structure. The figure illustrates essentially the acoustic modes. They pass very quickly through the deeper layers and are therefore not sensitives to the star's core rotation. Only low frequency gravity waves are capable of studying the deep interior of a star. Retrieved from Wikipedia

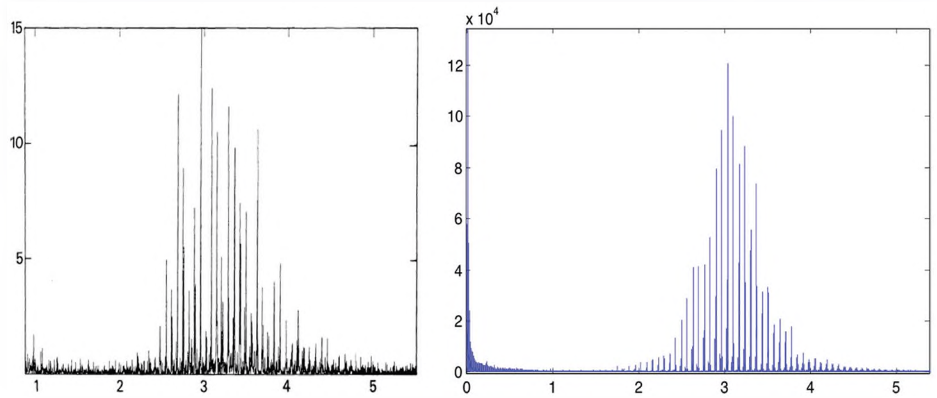


Fig. 8: Left: Historical global oscillations power spectrum obtained after 5 consecutive days of full disk velocity observations from the South pole on 1979–80 (Grec et al., 1980). Right: Power spectrum of global oscillations obtained after 16.5 years of full disk velocity from the GOLF instrument on SOHO (Fossat et al., 2017). For both, the vertical unit is $m^2 \cdot s^{-2} \cdot Hz^{-1}$ and the horizontal scale is the frequency in mHz. These two spectra illustrate the improvement in the noise level between short-time ground-based and long-time space based observations

The Nice group augmented by Eric Fossat, Martin Pomerantz, Gérard Grec, and Lyman Page took advantage of the long observing time allowed from Antarctica in the 1979–80 local summer and obtain the first high resolution frequency spectra of the Sun's global oscillations (Fig. 8).

Following this success, it was realized that both ground-based networks around the Earth and observations from space would offer ideal opportunities for even more high-quality helioseismology observations (Fossat et al., 2017).

In December 1982, Andre Balogh, Roger-M. Bonnet, Philippe Delache, Claus Fröhlich, and Chris C. Harvey sent a proposal to ESA for a cheap satellite positioned at L_1: the *Dual Irradiance and Solar Constant Observatory*, or DISCO (ESA Sci 82). Eventually, DISCO was not selected but its objectives were recovered a few years later when SOHO was accepted by ESA as a Cornerstone of its *Horizon 2000* long-term plan. Both its Michelson Doppler Imager (MDI) and the Global Oscillations at Low Frequency instrument (GOLF) fulfilled the objectives envisioned for DISCO with much higher spatial resolution. SOHO contributed a first scientific revolution in revealing the whole structure and the dynamics of the solar interior, including 3D detailed observations of sunspots* and other active regions (Kosovitchev, 2002). It also contributed to solving the so-called missing solar neutrino problem** (Bahcall et al., 1992, 2002, Turck-Chieze et al., 1993).

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* Sunspots both absorb and deflect helioseismic waves, causing a seismic deficit where next they encounter the photosphere (Lindsey and Braun, 1990).

** The neutrino flux at Earth is several ten billion per square centimeter per second, emitted mostly from the radioactive fusion process in the Sun's core where solar energy is produced. Neutrinos are

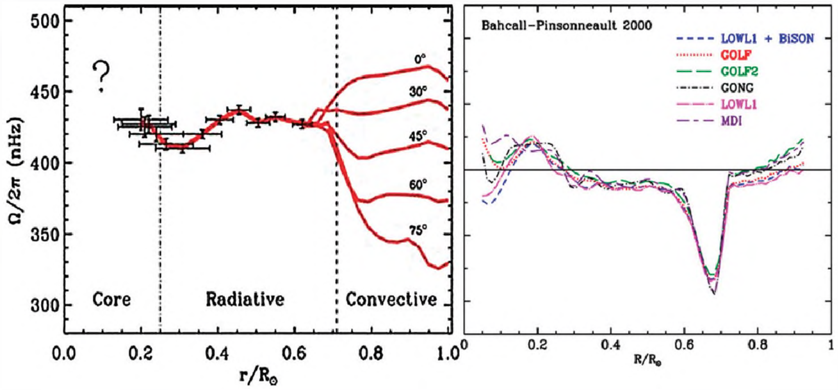

Fig. 9: Left: Sun's internal rotation as deduced from helioseismology measurements. P-waves pass very quickly through deeper layers and are not sensitive enough to measure the rotation of the core. Right: With a precision of 0.001, the agreement between helioseismology and the models are nearly perfect. The large anomaly at 0.6 solar radii is due to the tachocline, the name given to the transition between the convective zone, where solar rotation is differential in latitude, and the radiation zone, where rotation is uniform. Credit: Turck-Chieze et al. (1997), NSO-NSF, and Bahcall, Pinsonneault (2000)

SOHO/GOLF data, complemented by observations from ground-based networks, allowed to establish a model of the Sun's internal rotation down to 0.15 solar radii (Fig. 9, left). Within a precision of one per thousands, the helioseismology-deduced rotation is nearly identical to the standard model (Fig. 9, right), leaving opened the question of the nature of the solar neutrinos, which was independently resolved in 2002 when the Sudbury Neutrino Observatory in Canada showed that neutrinos from the Sun change species on their way to the Earth (Bahcall, 2002). Unfortunately, p-mode helioseismology is unable to get close enough to the Sun's core.

That goal was achieved in 2017 by GOLF's 16.5 years of continuous observations. Applying various analytical and statistical techniques, by means of a regular imprint of the g-modes on the p-modes, GOLF eventually accessed the center of the Sun for the first time and revealed that the core is rotating with a period of one week, nearly four times faster than the observed surface and intermediate layers, which vary from 26 days at the equator to 35 days at the poles (Fig. 9, left). These surprising results raise new questions about the functioning of the Sun's core nuclear fusion processes and require an interpretation of the observed shear between the core and the layers above. Future studies may give access to the chemical composition of the core and re-open the dis-

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hard to detect, because they interact very weakly with matter. The solar neutrino problem concerned a large discrepancy of about one half and two thirds between the flux of neutrinos as predicted from models of the solar internal structure and the Sun's luminosity, and ground-based measurements from underground detectors. The discrepancy was first observed in the mid-1960s. Two possibilities were proposed: either the validity of the solar model is incorrect or the physics of neutrinos would have to be reviewed.

cussions about the production of solar neutrinos. They mark a milestone in the development of helioseismology and prove its power for the study of the whole interior of the Sun and most likely of other stars.

3.2. STRUCTURE OF THE CORONA, THE ENIGMA OF ITS HIGH TEMPERATURE, AND THE ACCELERATION OF THE SOLAR WIND

Since Bengt Edlen offered an explanation to the presence of unknown spectrum lines of the corona, nearly 80 years have passed. However, the source of energy which causes the rise of temperature from the 6000° photosphere to the several million degrees corona, despite the impressively high number of theoretical and observational activities, has not yet been convincingly identified. Several possible explanations have been proposed then abandoned: a situation, which illustrates the complexity of the problem. However, the post-Sputnik 1 period, in recent years, has identified more probable explanations to this long-lasting enigma.

3.2.1. Sound waves

In 1949, E. Schatzman did propose that the dissipation of acoustic waves from the convection zone could dissipate enough energy in the corona in the form of heat (Schatzman, 1949). Unfortunately, observations of these waves in the low corona from the OSO-8 satellite (Bruner, 1981) showed that, *on the average, about as much energy is carried upward as downward so that the net acoustic flux density is statistically consistent with zero!* The statistical uncertainty in this null result is three orders of magnitude lower than the flux level needed to heat the corona.

3.2.2. Alfven waves

Another source of energy, and most likely the only alternative to acoustic waves, is to be found in the solar magnetic field. Magnetic energy is continuously built up by motions in the convective zone and at the surface and then released in the corona through magnetic reconnection (Priest, 1999).

As early as 1942, Hannes Alfven was the first to propose the existence of electromagnetic-hydrodynamic waves, which are transverse motions of ions and of associated magnetic field perturbations (Alfven, 1942). In 1949, in order to interpret the far-UV solar spectrum corresponding to million degrees temperatures, Friedman also suggested the existence of magnetohydrodynamic waves (Osterbrock, 1961).

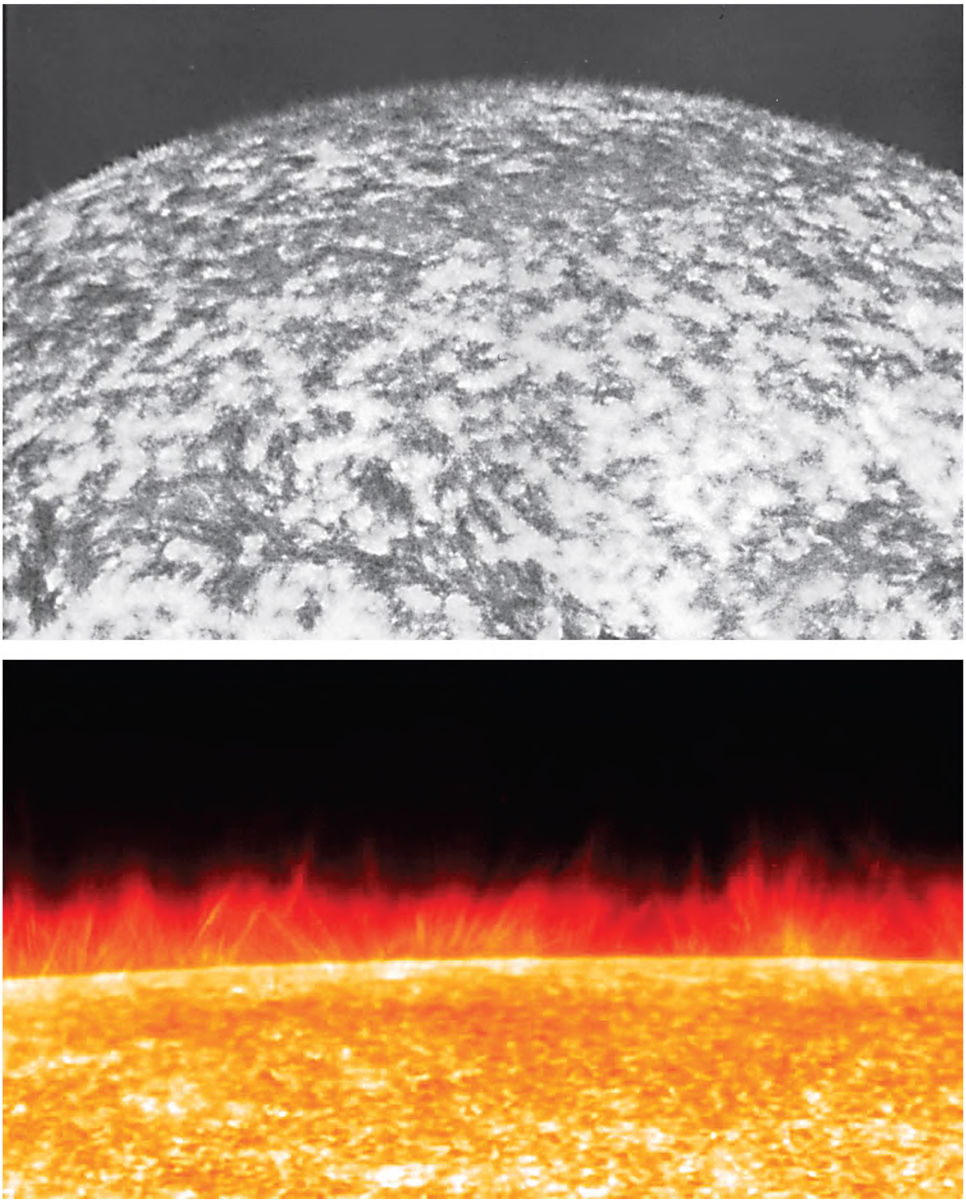

Fig. 10: Top: Spicules, as observed in 1980 from the rocket-born Transition Region Camera in Lyman-alpha (Bonnet et al., 1982). Down: Spicules observed by the Solar Optical Telescope on the ISAS *Hinode* mission. Spicules are dynamic chromospheric jets of about 500 km diameter and supposed to be generated by the 5-min p-modes oscillations of the Sun's surface. They move upwards at about 20 km/s from the photosphere and are usually associated with regions and tubes of high magnetic flux. These tubes do focus and guide the rising material up into the solar atmosphere to form a spicule*

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* There is still some controversy about the issue in the solar physics community.

These waves are able to reach the corona but not to transfer enough energy to the surrounding plasma, and therefore not the solution to coronal heating. Later, Parker (1972) proposed that nanoflares, which are triggered by magnetic activity, might also explain the high coronal temperature*, but it was found that their frequency is insufficient by a factor of 5 to produce the required heating rates and the million degrees coronal temperatures.

More recently, however, the Alfven wave hypothesis was revisited taking advantage of the capabilities offered by *Hinode*, SOHO, and SDO (see Table 2). *Hinode*'s high spatial resolution images revealed the presence of 20 km/s Alfven waves in spicules (Fig. 10), forty times higher than the 0.5 km/s velocity they reach in the corona, while multispectral EUV observations made by the SDO/AIA UV imager (at 171 Å and 304 Å), and their ability to explore the chromosphere and the corona allowed following these waves along their propagation from spicules to coronal altitudes of 20 000 km and temperatures of 1 000 000 K (Fig. 11).

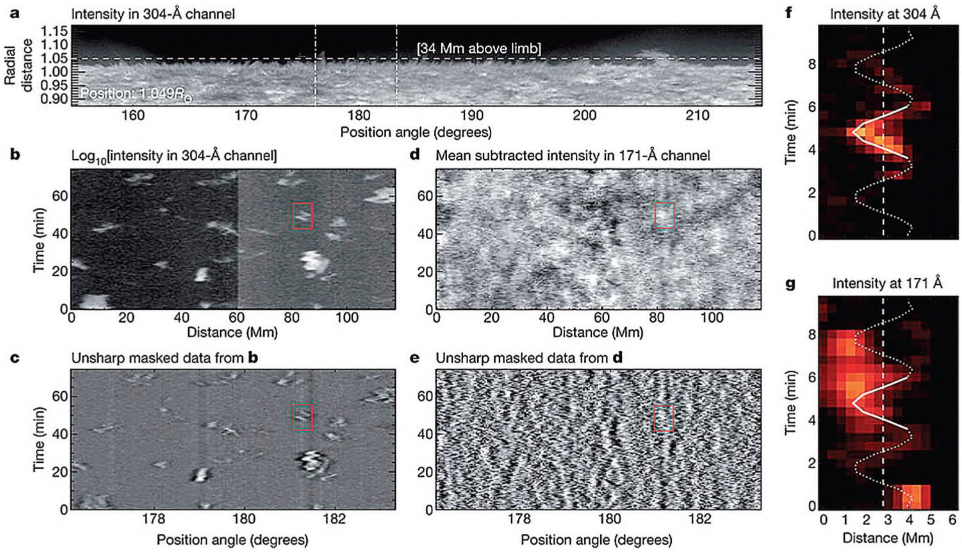

Fig. 11: Space–time plots of SDO/AIA data, demonstrating the visibility of the ubiquitous transverse waves above the solar limb in a coronal hole. The color image at the right shows one transverse oscillation as an example; it is compatible with propagation along the spicule (**f**, 304 Å channel), and with propagating coronal disturbance (**g**, 171-Å channel). A sine wave with a period of 180s and an amplitude of 24 km·s^{-1} is drawn on **f** and **g.** Credit: McIntosh et al. (2011)

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* Nanoflares are orders of magnitude weaker than the faintest flares, which release sudden flashes of increased Sun's brightness, usually observed near its surface. Flares are often, but not always, accompanied by a coronal mass ejection (Section 3.3).

3.2.3. Acceleration of the solar wind

Since Parker's theoretical work and Gringauz' *Luna 1* first observations, the study of the solar wind has been a subject of intense scientific interest. By the 1960s it was clear that thermal acceleration alone could not account for the high speed of the wind. Satellite observations together with an intensive modelling activity have been essential to understanding its properties, in particular its origin and the mechanisms of its acceleration from the solar surface through to the corona and the heliosphere (see Section 3.4). Two satellites among several others have played a pioneering role in solar wind research: *Ulysses* and SOHO, which showed that the solar wind velocity is extremely variable and exists in two fundamental states. The slow wind of about 400 km/s is confined to the equatorial regions. However, the exact coronal structures involved in the formation of this slow wind and the physical processes by which the material is released are still under debate. The fast wind reaches velocities about 800 km/s, prevalent at high solar latitudes and in the areas corresponding to coronal holes, funnel-like regions of open field lines particularly prevalent around the Sun's magnetic poles (see Fig. 5). This two-speed regime is associated with the structure of the magnetic field, with high velocities corresponding to open field lines, and low velocities to closed lines.

The acceleration of the solar wind to these high velocities is still not understood and cannot be fully explained by Parker's theory. The SOHO Ultraviolet Coronal Spectrometer (UVCS) found that the fast wind accelerates to supersonic velocities much faster than can be accounted for by thermodynamic expansion alone.

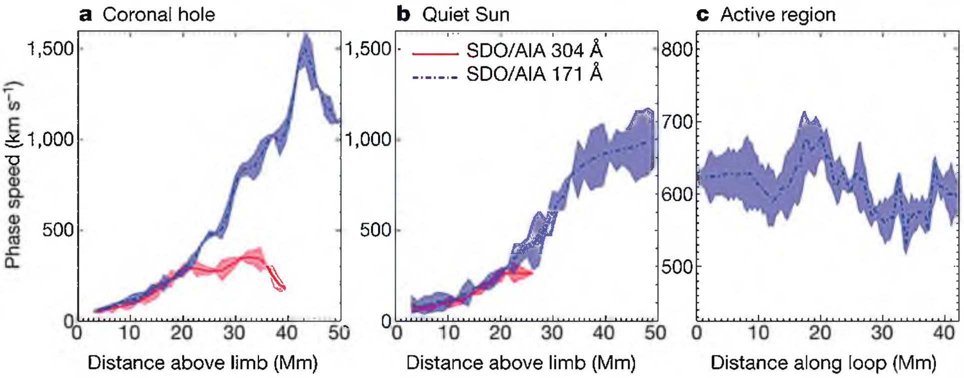

Fig. 12: Phase speed of the observed disturbances are shown for three cases for two wavelengths (304 Å and 171 Å). We see that the coronal hole and quiet regions observations of the phase speedup to 20 000 km are consistent with chromosphere measurements. The continued increase to 1000 km/s at 40 000 km is consistent with previous coronal speeds determinations. Credit: McIntosh et al. (2011)

While Parker predicted that the wind should become supersonic at an altitude of about 4 solar radii above the photosphere, the transition observed by UVCS seems to be lower, about only 1 solar radius, suggesting that additional mechanisms, probably related to the magnetic field lines created by the convective motions, might accelerate the wind. These fields should confine the plasma and transport it into the narrow necks of coronal funnels through magnetic reconnection at only 20,000 km above the photosphere (Fisk, 2003). McIntosh et al. (2011) were able to follow the propagation of Alfven waves in different coronal structures and show that they carry sufficient power to accelerate the solar wind to nearly 1000 km/s (Fig. 12). However, the question of how and where the waves are generated and how they deliver their energy to the coronal plasma, is not yet answered.

At this stage, the progress made in the search of answers to the two great questions about the temperature of the corona and the acceleration processes of the solar wind is spectacular, but does not lead yet to detailed and clear answers. The powerful diagnostic tool offered by multispectral observations as achieved by the SDO/AIA instrument should be exploited in the future with higher spatial resolution capabilities. Important progress is also expected from the *in situ* analysis of the corona and the solar wind that NASA's *Parker Solar Probe* (under discussion and object of numerous studies since 1958, i.e. one year after Sputnik 1) aims at achieving.

3.3. SOLAR ACTIVITY

Following the first observations in 1610 of sunspots with images recorded by Galileo Galilei's "cannocchiale", the study of these intriguing features was surprisingly hampered during 70 years covering the period 1645–1715, due to their low number*. By the 19th century, long before the space age was triggered by Sputnik 1, series of sufficient records allowed to infer the existence of a periodic 11-year solar cycle in the number of sunspots appearing on the solar disk.

Fig. 13 presents a recent time-evolution of this cycle since 1950, which incidentally shows that Sputnik 1 launch date corresponds to the highest solar maximum** observed over the past 60 years, and in fact the highest ever since 1700!

Whether the Sun's disk luminosity is modulated as function of the solar cycle has been, long before Sputnik 1, an important question. In fact, the study of the solar constant (the rate at which the Sun's total radiative energy reaches the Earth's surface of about 1,388 W/m^2) has started as early as 1838, when Claude

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[*] What is now recognized as an extended period of low solar activity, known as the Maunder Minimum.

[**] We should remember that the International Geophysical Year in 1957–58 was established in order to correspond to cycle number 12 (1954-1965) at the occasion of the 1957 solar maximum.

Pouillet (Dufresne, 2008) made the first estimate. It is however only after Sputnik 1 that space observations provided the first and longest time record of the solar constant measured from above the Earth atmosphere (Fig. 14). These delicate observations clearly reveal a direct relationship with the sunspot cycle, and a peak-to-peak amplitude of about 0.1 % between maximum and minimum (Frölich, 2012). These observations have allowed to assess the influence of solar activity on Earth and to disregard any direct correlation between solar activity and the global Earth climate.

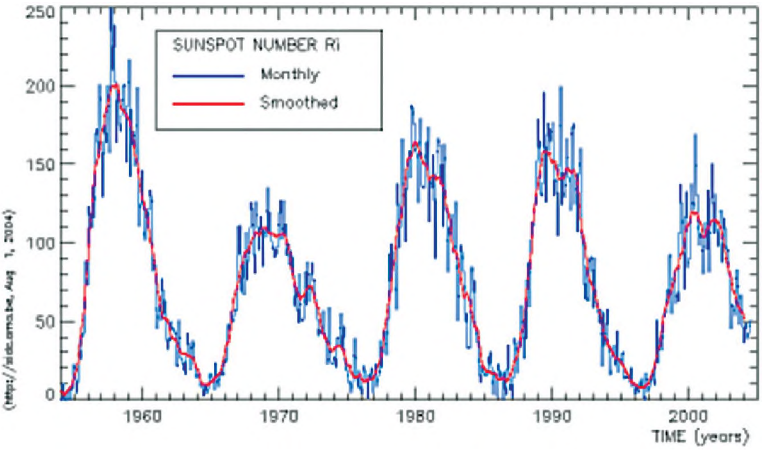

Fig. 13: Periodic variability of the solar cycle over the post-Sputnik 1 period which shows that the Sun's activity in October 1957 was the highest recorded over the past 60 years. Retrieved from Wikipedia

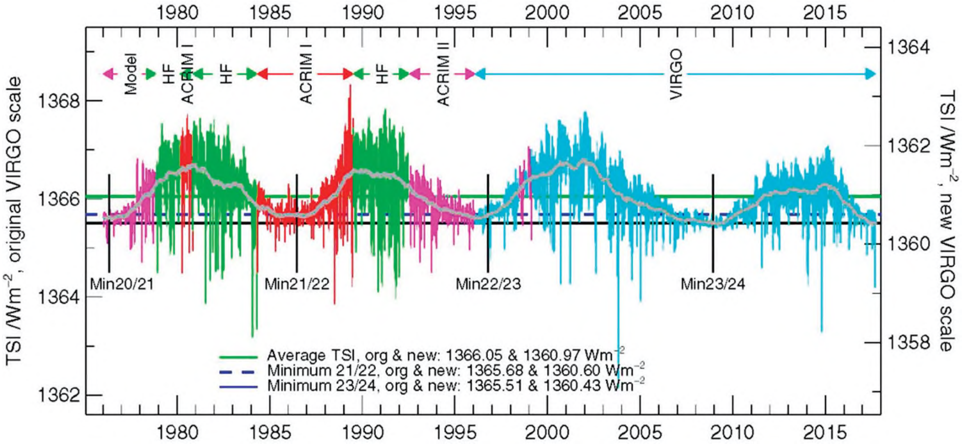

Fig. 14: Composite daily values of the Sun's Total Solar Irradiance (TSI) obtained with radiometers on different space platforms since November 1978: HF on Nimbus 7, ACRIM 1 on SMM, ERBE on ERBS, ACRIM II on UARS, VIRGO on SOHO, and ACRIM III on ACRIM Sat. The /VIRGO data represent the longest set of observations made with the same detector. Credit: PMOD-WRC

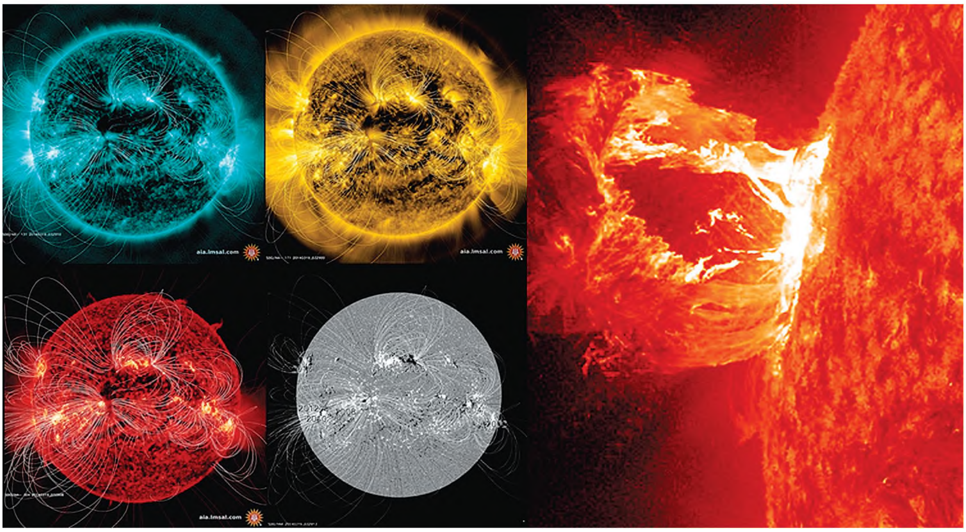

Fig. 15: Left: Collage of four simultaneous extreme ultraviolet (artificially-colored) images obtained on 2014/03/19 by the Atmospheric Imaging Assembly (AIA) instrument on NASA/SDO (Table 2) corresponding to 131, 171, and 304 Å, together with one magnetogram image (lower right). They indicate how magnetic field lines emerge, reach high above the Sun, and connect the two magnetic poles of active regions (which appear brighter in the extreme UV images and black and white in the magnetogram image) and with other active regions as well. The larger image on the right shows a prominence eruption observed by IAA on 2012/04/16. Credit: NASA and SDO/AIA team

In 1908, about 50 years before Sputnik 1, George Ellery Hale first linked magnetic fields with sunspots and observed that the solar cycle period is 22 years, covering two periods of increased and decreased sunspot numbers, accompanied by polar reversals of the solar magnetic dipole field. Sunspots were soon identified as the source of solar flares and several other manifestations of solar activity like prominences observed during eclipses, and outside of eclipses thanks to Lyot's invention of the coronagraph. The space age following Sputnik 1 rapidly proved without ambiguity the tight correlation between all manifestations of solar activity and the Sun's magnetic field (Fig. 15). The solar satellites launched in the past 22 years (see Table 2) have truly revolutionized the study of the cycle through all its manifestations.

Over short periods of time, solar activity manifests itself through the occurrence of flares, prominences, and CMEs. Flares correspond to sudden flashes of increased brightness. They affect all layers of the solar atmosphere heating them to tens of millions of degrees. They are powered by the sudden release of magnetic energy stored in the corona, most likely through the reconnection of the magnetic field. They radiate across the whole electromagnetic spectrum although most of their energy is spread over frequencies outside the visual range and can only be observed with radio telescopes and from space, in particular in the high energy frequencies (Fig. 16). All satellites of Table 2 as well as the WIND, RHESSI, and ACE NASA missions have strongly contributed to the study of these powerful phenomena of major importance for space weather research (Section 3.5 below).

Prominences are dense clouds of incandescent ionized gas anchored in the photosphere, and extending outwards, sometimes hundreds of thousands of km above the chromosphere into the corona (see Fig. 15). However, they are much cooler and hundred times more lit and denser than the coronal plasma. They form over about a day and may persist for several weeks or months. Their causes are most likely linked to the magnetic field. They are currently the object of active research because, as do flares, they are often followed by a CME (Vial, Engvold, 2015).

CMEs are significant releases of coronal plasma and magnetic field. Most often, they originate from active regions on the Sun's surface, such as groupings of sunspots and associated with frequent flares (although the relation between CMEs and flares is still not well established). They may also result from the braking apart of prominences. The plasma is released into the solar wind, and can be easily and regularly observed from space coronagraph imagery, far away from the Sun surface (see Fig. 16). Near solar maxima, the Sun produces about three CMEs every day, whereas near solar minima there is about one CME every five days (Fig. 17), (Robbrecht et al., 2008).

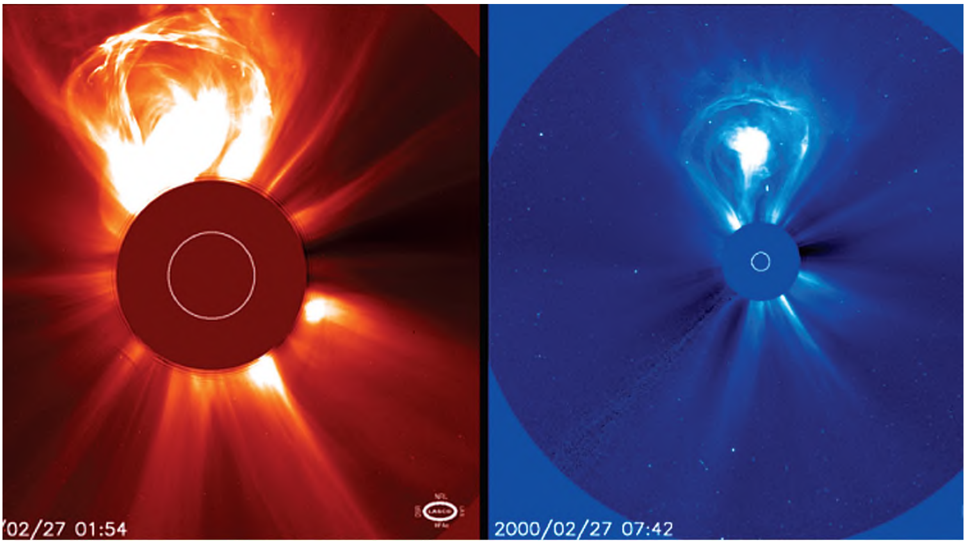

Fig. 16: A CME as recorded by the SOHO satellite on 27 February 2000 showing a billion tons of plasma launched two million kilometers off the Sun! The dark area in the middle of the images is the occulting disk of the coronagraphs: LASCO-2 (left) has a field of view 1.5–6 solar radii, and LASCO-3 (right), a field of view of 3–32 solar radii. The white circle in the middle of each picture outlines the Sun's surface. Credit: SOHO (NASA/ESA)

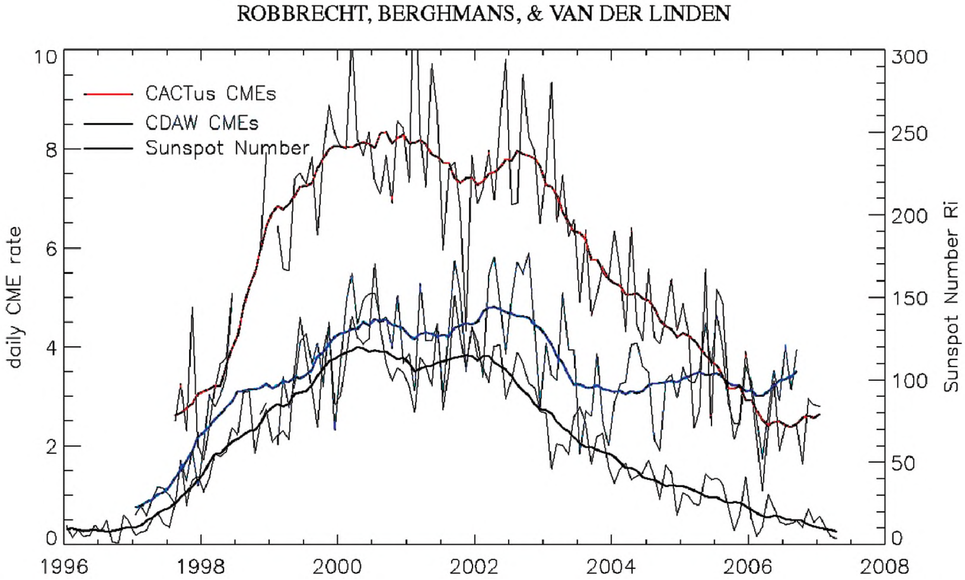

Fig. 17: Daily SOHO/LASCO CME rates for activity cycle 23 between 1997 to 2006 (thin curves: smoothed per month, thick curves: smoothed over 13 months). The daily and monthly smoothed sunspot number is also plotted for reference. Credit: Robbrecht et al. (2008)

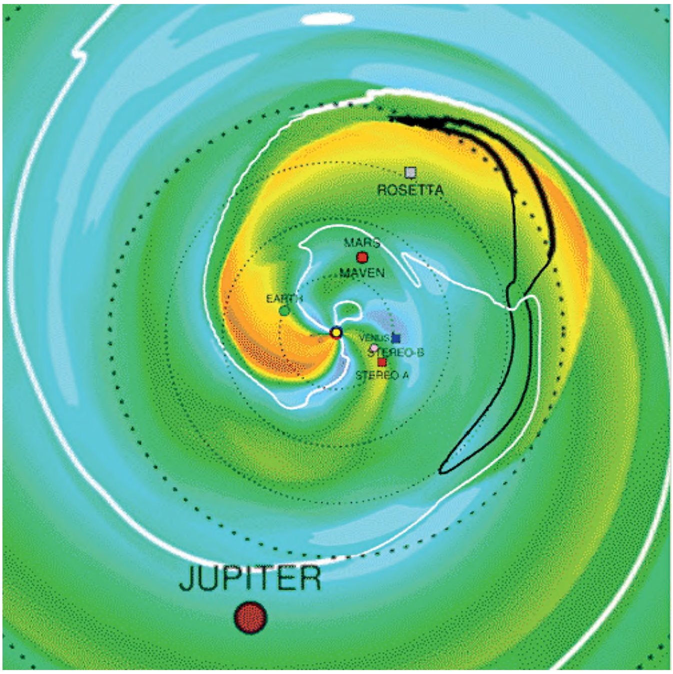

Fig. 18: Artist representation of the first observations of a CME on its way through the entire Solar system. Credit: NASA /Goddard Space Flight Center

On October 14, 2014, a CME left the Sun (Fig. 18) and was first observed at 18:48 GMT by the SOHO/LASCO 2 coronagraph. The SDO/AIA, Proba 2/SWAP telescopes, and STEREO/SECCHI extreme UV imager, also observed the event as it was leaving the Sun. The CME was then observed and successfully traced through the interplanetary medium, first by ESA's *Venus Express*, then by NASA's *Curiosity* on Mars, and further away near comet 67P/Churyumov-Gerasimenko, with ESA's *Rosetta* mission, and out to Saturn. NASA's Goddard Space Flight Center have combined these observations to provide the most comprehensive look to date at how the speed of a CME evolves over time. Several additional NASA spacecraft had probable detections of the CME as well — a few months and then over a year after it burst from the Sun. NASA's *New Horizons* spacecraft on its way to Pluto very likely observed this same CME in January 2015, and *Voyager 2* on the edge of the heliosphere may have observed it in March 2016 (from: *NASA and ESA Spacecraft Track a Solar Storm Through Space* press release on GSFC web site August 15, 2017, https://nasaviz.gsfc.nasa.gov/12687).

3.4. SUN'S GLOBAL MAGNETISM AND ITS EXTENSION IN THE HELIOSPHERE

3.4.1. Global magnetic field

SOHO and ground-based helioseismology networks have confirmed that the Sun's magnetic field is produced in the convection zone by a solar dynamo located between the tachocline and the solar surface (see Fig. 9). The field is variable as evidenced through the appearance of many phenomena related to the 11-year activity cycle. The close time and space simultaneity in the appearance of these phenomena has led solar observers, long before Sputnik 1, to baptize them "sympathetic" events. The combination of SOHO and SDO Heliospheric Magnetic Imager (HMI), and of the two STEREO spacecraft's unique coverage of the Sun's surface, of the chromosphere and the corona, allowed viewing much of these possibly-connected magnetic field events simultaneously and continuously over long-distance synchronous interactions.

Figure 19 shows coronal observations of a series of flares, filament eruptions and CMEs on 1–2 August 2010 extending over a full hemisphere of the Sun. The help of global field modeling allowed Schrijver and Title (2011) to establish many magnetic connections between series of events occurring at different locations. They found that events of substantial coronal activity, cause changes in the magnetic field: "*that lead to a destabilization elsewhere in the corona at nearly the same time or short time later*". In other words, the events are not "a *chain in which one induces another, but rather a signature of a larger change around them*". This is a major result of the post-Sputnik 1 era and a precious tool for space weather forecasting, as discussed in the following Section 3.5.

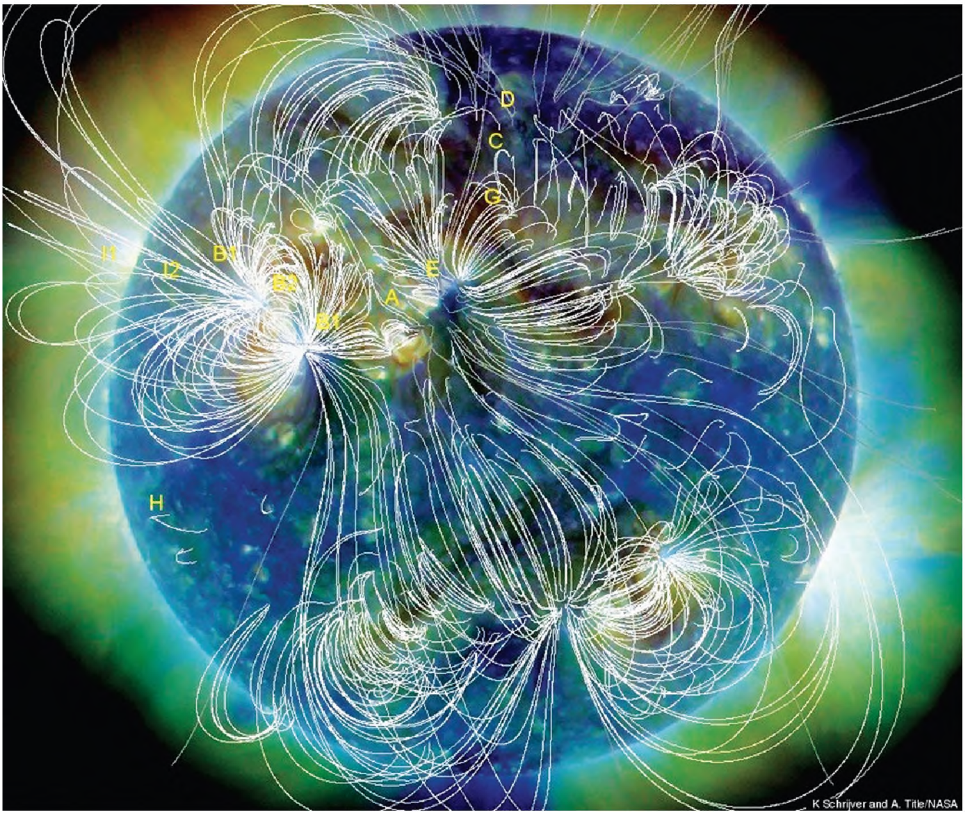

Fig. 19: Three-color composite EUV image taken by SDO/AIA on 1 August 2010 in the 211 Å (Fe XIV; ~2 MK), 193 Å (Fe XII, ~1.5 MK), and 171 Å (Fe IX and X, ~1 MK) channels. Selected field lines are shown here on the basis of a potential field source surface (PFSS) extrapolation for the full-sphere magnetic field. White field lines denote closed field, and grey field lines are open to the heliosphere beyond the model's source surface. Credit: Schrijver, Title (2011)

3.4.2. The heliosphere

The heliosphere is the bubble-like region of our galaxy which is dominated by the Sun's magnetic field. The solar wind frames and maintains the heliosphere against the outside pressure of the hydrogen and helium gas that permeates the interstellar medium (Fig. 20). Without space probes and satellites, the heliosphere would most likely still be considered today as a theoretical concept. Only space missions are able to explore that bubble of space. From the early post-Sputnik 1 era, the heliosphere was mostly explored *in situ* by NASA, which fully exploited the unique advantage, not accessible by other space agencies, of the availability of the Radioisotope Thermoelectric Generator (RTG), the only system capable of providing electric power beyond the orbit of Jupiter, far away from the Sun. Developing the RTG and at the same time the Deep Space Network (DSN) was a strategic visionary development, which gave the United States a quasi-monopole of *in situ* exploration of the heliosphere.

The most famous missions, which have contributed so far to the *in situ* exploration of the heliosphere at large distances are listed below:*

- *Pioneer 10*, NASA, 1972–2003,
- *Pioneer 11*, NASA, 1972, 1995,
- *Voyager 1, 2*, NASA, 1977, still operating (see Fig. 20),
- *Ulysses*, ESA/NASA, 1990–2009,
- *Cassini-Huygens*, NASA/ESA, 1997–2017,
- *New Horizons*, NASA, 2006, still operating.

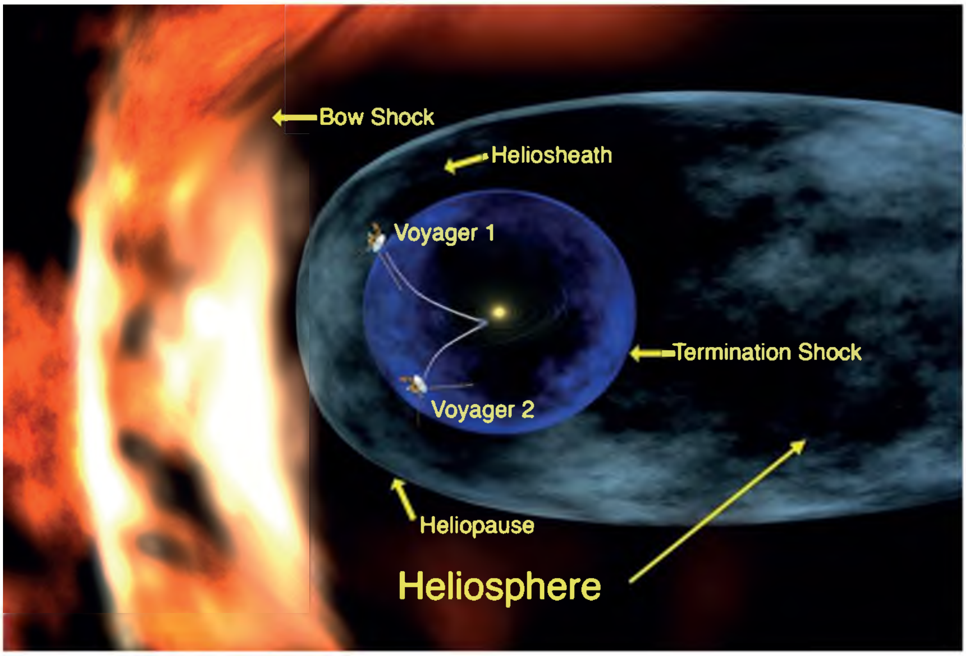

Fig. 20: Structure of the heliosphere. The termination shock is the point where the solar wind becomes slower than the speed of sound. The heliopause, is the boundary where the interstellar medium and the solar wind pressures balance. Retrieved from Wikipedia

Fig. 21 offers an up-to-date picture of all the international missions, which are observing or will observe in the near future the Sun and heliosphere covering the period 2009–21. Not mentioned in these two diagrams are the Chinese SPORT and ASOS missions still under study at this time.

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* The author's personal selection.

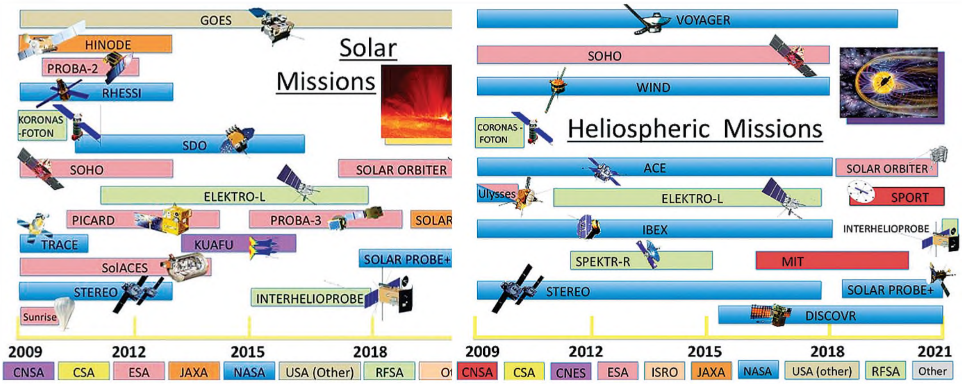

Fig. 21: Credit: ILWS*

Among all of them, the most impressive are the two NASA *Voyagers*. Although their original mission was to study only the planetary systems of Jupiter and Saturn (*Voyager 2* continued on to Uranus and Neptune), they are Humanity's first incursion in the Milky Way and the farthest and longest-lived spacecraft, achieving 40 years of operation and exploration. Despite their vast distance to Earth, they continue to communicate with NASA's DSN daily.

The heliopause (see Fig. 20) has never been reached by any spacecraft so far. On 15 June 2012, NASA reported that *Voyager 1* was very close to entering interstellar space, as was inferred by a sharp rise in the number of high-energy particles from outside the Solar system. In September 2013, NASA announced that *Voyager 1* had crossed the heliopause one year before on August 25, 2012, making it the first spacecraft to enter interstellar space, escaping the Solar system at the speed of 3.6 AU per year (about 3.3 AU per year for *Voyager 2*). Both spacecraft will eventually go on to the stars. However, because of the RTG's declining power, they might be able to return science only through 2020. Sometime around 2025, there will no longer generate sufficient power to operate any science instrument.

The IBEX mission is worth some attention. It is a small mission, part of NASA's Small Explorer program, launched at low-cost with a *Pegasus-XL* rocket on October 19, 2008, to reach a Sun-oriented spin-stabilized orbit around the Earth (perigee of 59,190 km and apogee of 312,199 km). Its science objectives are to discover the nature of the interactions between the solar wind and the interstellar medium at the edge of our Solar system. IBEX is collecting Energetic Neutral Atoms (ENA) emissions that are created on the boundary of our Solar system by the interactions between solar wind and interstellar medium particles travelling through the Solar system toward the Earth that cannot be measured by conventional telescopes (Gruntman, 1997). IBEX results

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* International Living With a Star (ILWS) is the name given to NASA' Living With a Star program (LWS), which includes mostly NASA missions, after it was enlarged to incorporate all international missions from world space organizations dealing with Space weather.

are remarkable, not matching with any of the previous theoretical models and showing that the interstellar environment has far more influence on structuring the heliosphere than anyone previously believed.

3.5. SPACE WEATHER

Long before Sputnik 1, the effects of "space weather" were noticed, but not fully understood! Examples of these manifestations, are displays of aurorae light observed at high latitudes, the occurrence of Earth magnetic storms, unusual extreme noise occurring on radio communication, radar jamming during large solar events. The very first results from the International Geophysical Year (IGY) research programs rapidly lead the a more precise understanding of the space weather concept, which got more visibility and fame after Sputnik 1. In 1958, *Explorer 1* discovered the Van Allen belts and in 1959 *Luna 1* the solar wind, and measured its strength. In 1969, INJUN 5 (*Explorer 40*) made the first direct observation of the electric field impressed on the ionosphere, and that permanent electric currents would flow between the auroral oval and the magnetosphere. Later, solar physics missions, offered continuous and synoptic data of essential importance for understanding the dangers of space weather. SOHO in particular, revolutionized our understanding of solar-terrestrial relations and dramatically boosted space weather forecasting by providing, in a near-continuous stream, a comprehensive suite of images covering the Sun's dynamic atmosphere and the extended corona, measuring and characterizing several ten-thousands of CMEs.

3.5.1. What is Space weather?

Very few examples exist of transfers into the space applications domain of scientific knowledge acquired with missions originally planned for the study of the Sun, the Earth's magnetosphere, the ionosphere, the thermosphere and the whole set of objects, planets, comets, and all components of the Solar system. Space weather offers a very clear such example. The name refers to the varying physical conditions of the Sun: flares, CMEs, solar energetic particles (SEP), and more generally, the solar wind and its magnetic field, which may affect one way or another the performances and reliability of terrestrial sensitive infrastructures as well as scientific, commercial, and military satellites (Riley et al., 2018, Lanzerotti et al., 2018). Fig. 22 illustrates the many components of our post-Sputnik 1 civilization, which might be affected by space weather phenomena, their amplitude and intensity*. These can interfere with radio signals, impeding communications, and modifying the orbits of the Global Positioning System (GPS) satellites.

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* A report of the US Academy dated 2008 estimated to 10 billion US$ the economic consequences of the perturbations due to the Sun's vagaries.

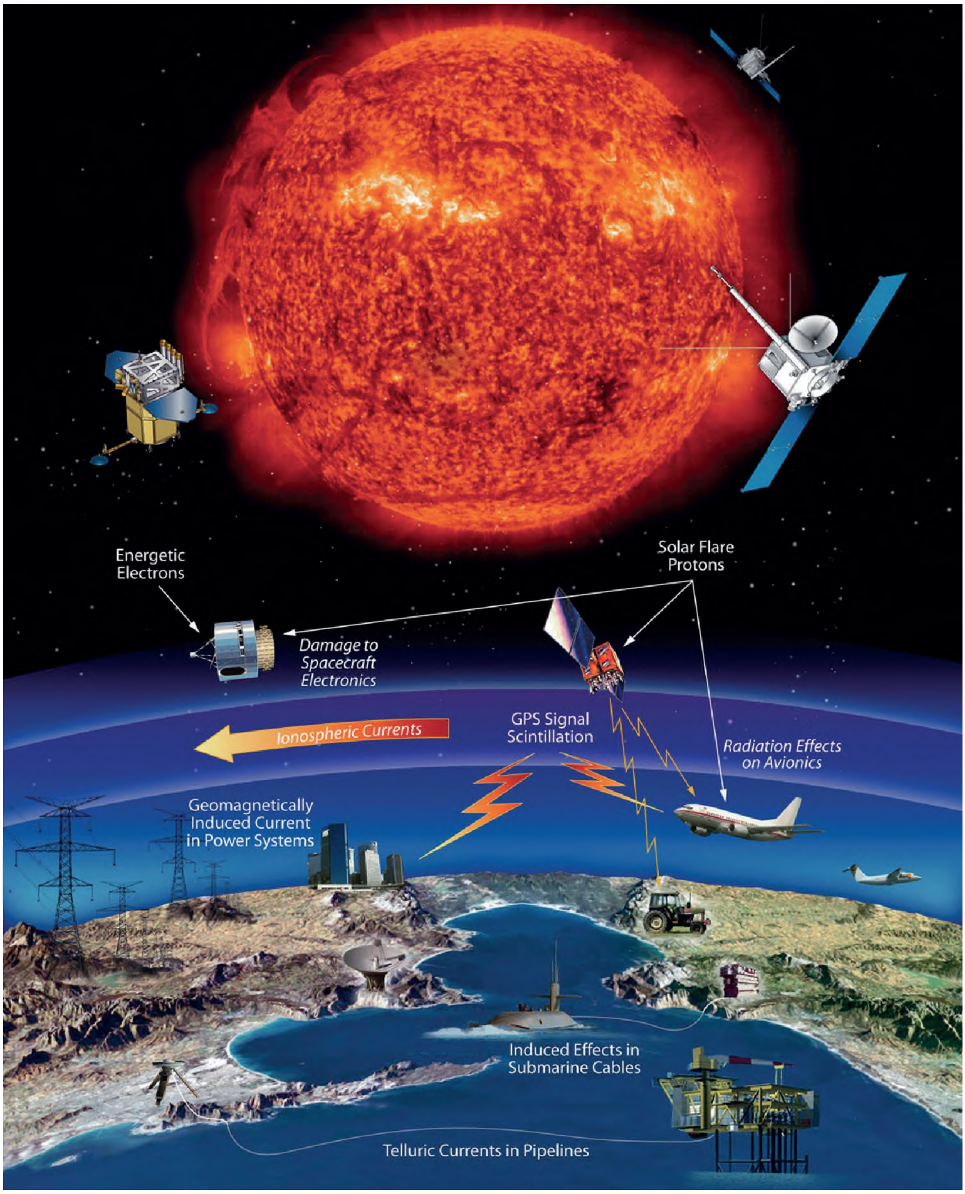

Fig. 22: Artist representation of the way the space weather influences the Earth. Retrieved from Wikipedia

They can cause damaging surges in long metallic structures such as long-distance communication networks, pipelines, railway tracks, electricity cables, driving uncontrolled electric currents that interfere with grid operation, damage transformers, sometimes causing blackouts*. They expose to radiations

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* Such as the complete collapse of the Hydro-Quebec electric-power grid in Canada in 1999.

the passengers and the crew of aircraft travelling above 8 km altitude. Manned space systems such as the International Space Station require special equipment to protect their astronauts against the effects of an SEP burst, when the radiation flux might increase by orders of magnitude and reach the human's body lethal domain. The economic and technical importance of all manifestations of space weather calls for the development of a comprehensive set of means, both ground-based* and space-based, as well as extensive modelling efforts.

3.5.2. Monitoring and forecasting space weather from space

In the post-Sputnik 1 era, the science of space weather has witnessed a lot of substantial progress while facing today serious challenges in view of the increasing necessity to develop protective measures against the effects of phenomena originating in the Sun (Koskinen et al., 2017).

Space weather forecasting requires continuous monitoring of the Sun and an adequate analysis for a timely evaluation of their potential danger. The monitoring of the magnetic field on the hemisphere invisible from Earth's perspective, is essential to assess the evolution, and possibly even detect flares and eruptions before they can be observed by spacecraft and by ground-based instruments (Schrijver, Title, 2011). Space missions do offer unique means in that respect. Since 1995 SOHO, SDO, and STEREO (see Table 2) have compiled information about the state of the solar surface and its atmosphere in three dimensions. The STEREO satellites are the only ones to monitor the Sun's far side and possibly provide an early warning of forthcoming CMEs, and improve the perspective of forecasting potentially dangerous events. Very soon, NASA's *Parker Solar Probe* (Fig. 23) will be able to study the corona *in situ*. Its primary science goals are to trace how energy released by flares and CMEs move upward into the corona and in the birthplace of the highest-energy solar particles.

Helioseismology can also be used to image and to provide seismic images of the central portion of the entire far side of the Sun (Braun, Lindsey, 2001), (see Section 3.1). Helioseismology may also offer another possibility for forecasting the magnetic activity over months and years thanks to observations of the solar dynamo along the polar axis. Such observations have never been made before (Fig. 24). They require observing the low degree modes at high latitude above the poles. In other words, they require another incarnation of the — unfortunately never built — US satellite of the joint NASA-ESA Out-of-Ecliptic mission (see Section 2.3).

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* Space weather is monitored at ground level by observing changes in the Earth's magnetic field over periods of seconds to days, by observing the sunspot number in visible light, and the radio noise created in the corona. However, space-borne instruments offer a more powerful set of tools.

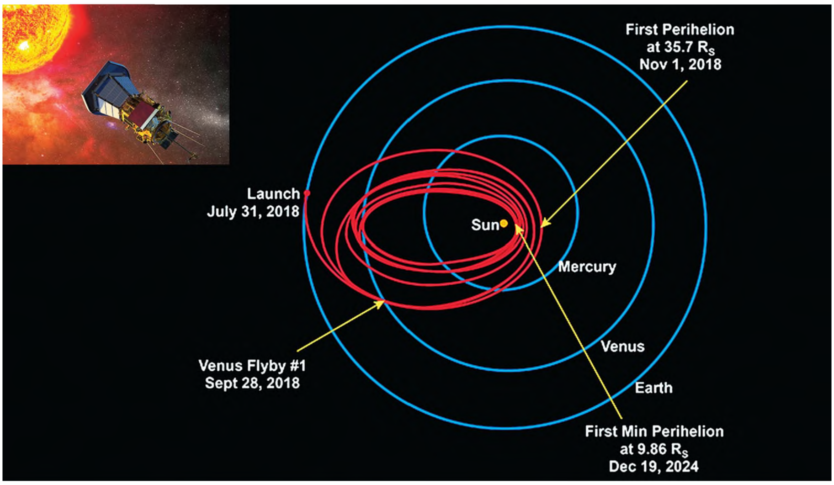

Fig. 23: NASA's *Parker Solar Probe* will use seven Venus flybys over nearly seven years to gradually shrink its orbit around the Sun, coming as close as 5.9 million kilometers to the Sun, well within the orbit of Mercury and about eight times closer than any spacecraft has come before. Credit: NASA and JU-APL

However, the prospects are not high that such a mission might be approved soon. Only the Chinese National Space Science Center (NSSC) in Beijing is presently studying the concept of a Solar Polar Orbiting Radio Telescope (SPORT) which could be placed on a high inclination orbit would have to be equipped with a dedicated helioseismology instrument, though not foreseen at this time (Fig. 25).

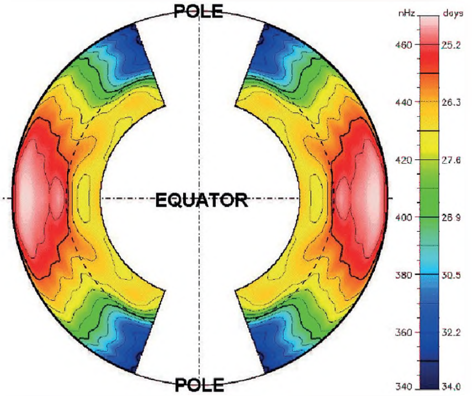

Fig. 24: This image shows the internal rotation rate of the Sun with red for fast and blue for slow. The polar axis has never been observed from any of the in-ecliptic solar satellites. Credit: Thompson (1996), Schou et al. (1998)

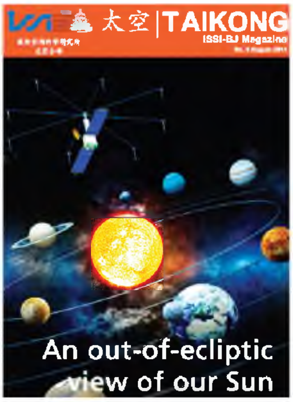

Fig. 25: Cover of the 2014 ISSI-BJ report from the TAIKONG ISSI-BJ Magazine N 4. Credit: ISSI-BJ

3.4.3. Spacecraft for space weather applications

Several of the early space-borne instruments were developed for scientific research, and then re-purposed for space weather applications, such as IMP 8 (Interplanetary Monitoring Platform), which orbited the Earth at 35 Earth radii and observed the solar wind for two-thirds of its 12-day orbits from 1973 to 2006. It was followed by ISEE 3, from 1978 to 1982, by WIND from 1994 to 1998, and by the Advanced Composition Explorer (ACE), from 1997 to present. Fig. 21 shows the high number of satellites that will be able to follow the propagation of space weather events toward the Earth, from their source through the extreme limits of the heliosphere.

Figures 21, 26, and 27 display all existing and nearly-planned space missions whose capabilities can provide series of sequential observations to be exploited for space weather research.* They include the Geostationary Operational Environmental Satellite (GOES) series of NOAA and NASA spacecraft, the POES series, the DMSP series, and the *Meteosat* series. The GOES spacecraft have carried an X-ray sensor (XRS) inspired by the Solar X-ray Imager developed for the *Yohkoh* Mission (Section 2.1), and a magnetometer for measuring space weather-induced distortions of the Earth's magnetic field, and particle sensors (EPS/HEPAD) measuring ions and electrons in the energy range of 50 keV to 500 MeV. The most recent GOES spacecraft carry a solar EUV image similar to the SOHO/MDI particle sensors extending the energy range down to 30 eV. The NOAA Deep Space Climate Observatory (DSCOVR) launched in 2015, on a L_1 orbit can be used for early advance warning of Earth-oriented CMEs.

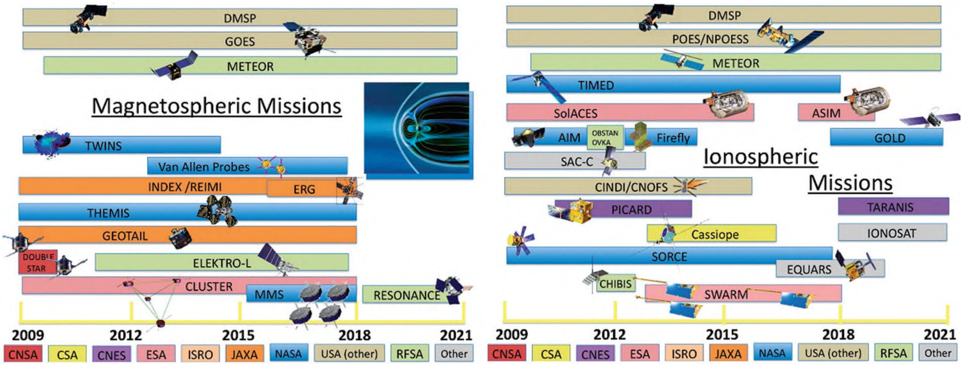

Fig. 26: Up-to-date picture of all international magnetospheric and ionospheric missions so far still in operation or planned in the future, covering the period 2009-2021. Credit: ILWS

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* NASA's *Van Allen Probes*, launched in 2012 into a highly elliptical Earth-orbit, unfortunately not mentioned therein, are recording detailed data about the radiation belts and geomagnetic storms.

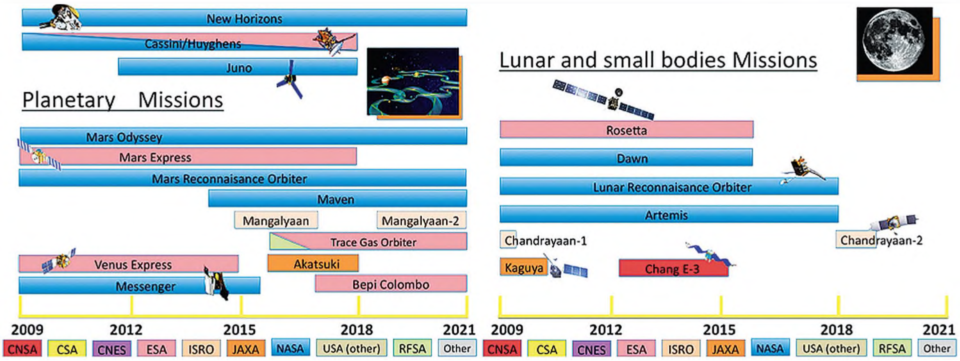

Fig. 27: Up-to-date picture of all planetary, lunar and small bodies missions so far still in operation or planned in the future, covering the period 2009-2021. Credit: ILWS

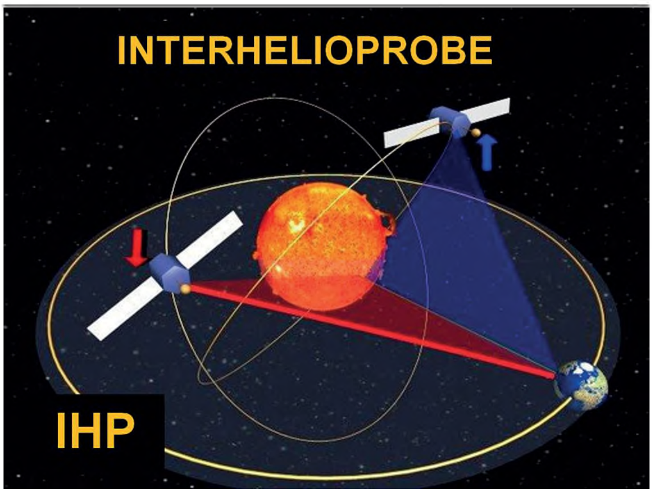

Fig. 28: The Russian *Interhelioprobe* mission for solar and heliospheric studies is one genuine of the latest most advanced successor of Sputnik 1. Credit: Roscosmos, IKI

Solar physics and space weather research both appear today as a genuinely, truly international and multidisciplinary activity, which serves the needs and interests of a large variety of people, including scientists, the civilian organizations, and the military. It appears as one of the most remarkable examples of the heritage of Sputnik 1 (Fig. 28).

CONCLUSION

Solar observations from space have contributed enormously to uncover new faces and aspects of our star. They confirmed the solar model and contributed to solve the enigma of the missing neutrinos, while offering surprising views on the Sun's magnetism and the understanding of the causes and mechanisms, which make the corona so hot and the solar wind so fast in open field lines. Observing solar activity from space over long periods of time has proved to be crucial for the study and forecasting of space weather events. The future of solar space observations in the perspective of space weather research will rely on:

- the need for more continuous and long-term high spatial resolution observations;
- out-of-the ecliptic helioseismology;
- a high number of specific space weather missions.

Sixty years after the launch of Sputnik 1, space machines have continuously explored our star thanks to more and more sophisticated and highly ingenious technologies for new telescopes, new detectors, and the choice of a large variety of orbits. Such a peaceful scientific research activities lent itself naturally to a broad international endeavor involving most of the space-faring organizations. The future of this pioneering space science research is guaranteed because it is peaceful and at the same time essential for ensuring that all the means necessary to protect our planet against the effects of solar activity will be developed. It is also ensured because new actors are entering the scene and can provide new means for both solar research and what can be called now the applications of space research. Thanks to Sputnik 1!

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SPACE WEATHER: HISTORY AND CURRENT STATUS

The solar-terrestrial space is of the considerable significance for human activities. Since the first artificial-satellite Sputnik 1 launched in 1957, more knowledge about the dynamic conditions of the space environment has been acquired. As evidenced in both ancient legend and the historical records, human activities and technologies have suffered from the extreme space weather. With a growing dependence on modern technology — both in space and on the ground, the vulnerability of the modern society and its infrastructure to space weather has increased dramatically. To better understand, forecast, and reduce the adverse effects of space weather, a series of space weather programs and strategies have been proposed or implemented by the worldwide scientists and institutions. In the future, more and more innovative and international collaboration programs will be implemented and improve the space weather service.

1. BEGINNING OF SPACE AGE AND DANGEROUS ENVIRONMENT

The solar-terrestrial space is the main domain for human space activity, which is the fourth environment for human being after land, ocean, and atmosphere. In 1957, the launch of the first artificial satellite, Sputnik 1, ushered in a new era for modern space science. The attendant space race began a period of explosive growth in our knowledge of the geospace and its interaction with the solar wind.

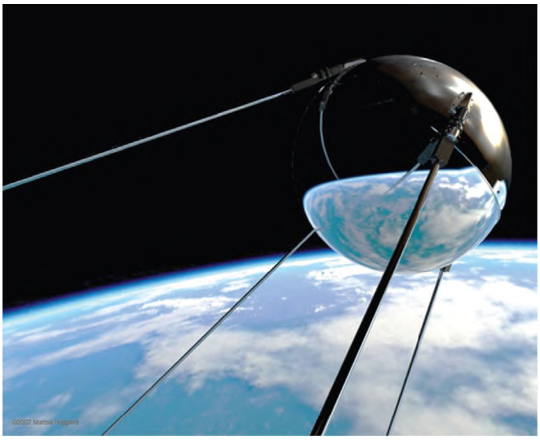

Fig. 1: On October 4 1957, first artificial satellite, Sputnik 1 was launched, ushering in the Space Age

In 1958, *Explorer 1* was launched. It's the first satellite of the United States with scientific object to explore the radiation environment of geospace. The *Explorer 1* enabled Van Allen to discover the trapped radiation belt. Before that, Sputnik 2 launched on 3 November 1957 had detected the Earth's outer radiation belt in the far northern latitudes, but researchers ignored the significance of the elevated radiation. The main reason was the fact that the region where Sputnik 2 passed through the Van Allen belt was not covered by the Soviet tracking stations.

That was the beginning of the space exploration. At that time, what we knew was that there is an electrically charged layer, called the ionosphere, in the upper atmosphere. Little knowledge did we have about the higher altitude region, which we called the exosphere. The instrumented spacecraft with longer life expectancies were later launched into this area with more rarefied air to reduce atmospheric drag. It also provided the opportunity to start the exploration of the magnetosphere and the solar wind. In 1961, *Explorer 10* was launched and it detected the magnetopause, the boundary between the flowing solar wind and the Earth's magnetic field for the first time. The magnetopause existence was evident from the data provided by the spacecraft that were launched into the solar wind [1]. So far, our satellites running space expand more wide and we did realize more about what happened above the atmosphere.

Since the space age began, we rely ever more and more on the space infrastructure for industrial and daily life applications, such as communication, navigation and global positioning, Earth observation systems, etc. To date, there are more than 1000 satellites in operation. Even more satellites will join in, with the fast space development in the future. If count the number of satellites, which have suffered any failures during operation, one may note that almost 50 % of such failures result from space radiation and other kinds of space environment influences. Statistics from the United States dated 1996 show that space environment caused more than 40 % of the satellite failures during 1958–1986, and 36 % in 1986–1996 [2]. It shows that the space environment is not peaceful. According to the statistics of the National Geophysical Data Center from the United States, space radiation environment was the cause of about 2300 satellite failures of all the 5000 failure events during the period of 1966–1994. Thus, one may see that space radiation environment is one of the main causes of satellite failure, particularly in the beginning of the space age.

Until now, even though the industry has developed the space-qualified components, still about 30 % failures are attributed to environmental hazards. Besides the particle radiation, atmospheric drag also leads to satellite failure by altering the location of spacecraft or threatening their functionality by collisions with debris. In 1979, the *Skylab* space station succumbed to the long-term effects of atmospheric drag and plunged back to Earth. It suggested that the space environment is so dangerous that we need to pay more attention to it.

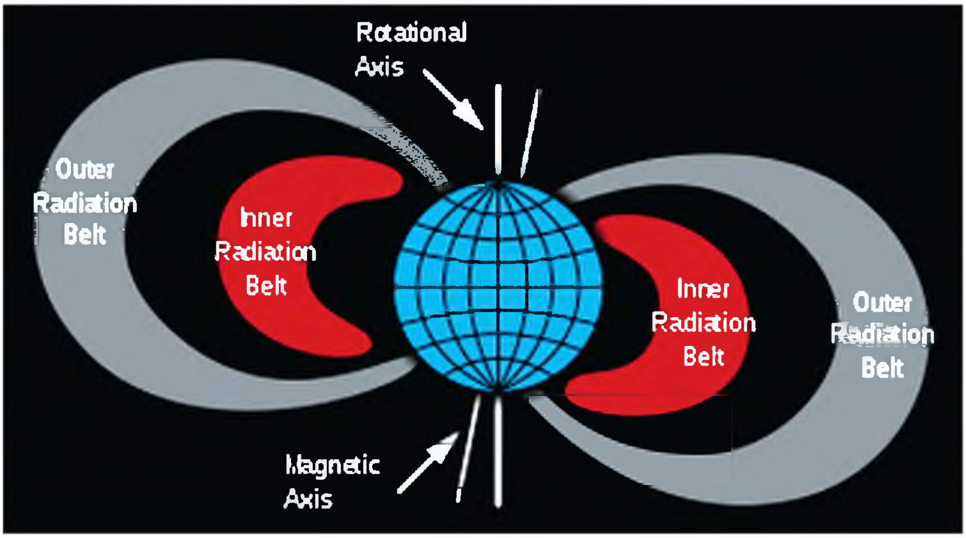

Fig. 2: The *Explorer 1* enabled Van Allen to discover the trapped radiation belt. Earth's Van Allen belts have two distinct regions of trapped radiation surrounding the Earth

Fig. 3: In 1979, the *Skylab* space station succumbed to the long-term effects of atmosphere drag and plunged back to Earth

Solar storms also cause changes in space environment and make it dangerous, for example, as in cases of Coronal Mass Ejections (CMEs) or electromagnetic wave emission from flares, leading to physical impacts on geospace. All of them impose variations in the amount of energy the Sun releases into space, such as the intensity of electromagnetic radiation, the number and energies of solar plasma particles, or most often in both of them, which can be sudden and large [3]. The hazard degree of the solar storms depends on the energy the Sun releases, which is often related to the solar activity. "Solar activity" is a general term used to describe the nature and extent of solar magnetic fields. The most common index by which it is described is the number of sunspots visible on the disk of the Sun. The sunspot number exhibits an approximately 11-year period. Many solar activity phenomena, such as solar flares, solar proton events, CMEs, solar total radiation, and solar wind, also appear to have 11-year period variations on average, known as the solar activity cycle.

Around the end of the 20th century, developed societies became vulnerable to the extreme events driven by the solar activity. Examples of the impacts of the solar storms on the Earth are numerous, such as disturbances from the telegraph networks disruptions. Severe solar storms can cause a disaster, resulting in satellites destroyed and technical stations disturbed. The most famous event perhaps was the collapse within 90 seconds of northeastern Canadian Hydro-Québec power grid during the great geomagnetic storm on 13 March 1989. It occurred during 22nd solar cycle and caused a 9-hour outage of Hydro-Québec's electricity transmission system. This storm resulted in the breakdown of the *Galaxy 4* satellite, halted news transmissions and electronic pagers across North America for several days. The aurora related to the storm was very huge and could be observed in the low latitudes, such as New York City region [4].

Fig. 4: Photograph of the aurora related to the magnetic storm on 13 March 1989, taken from New York City

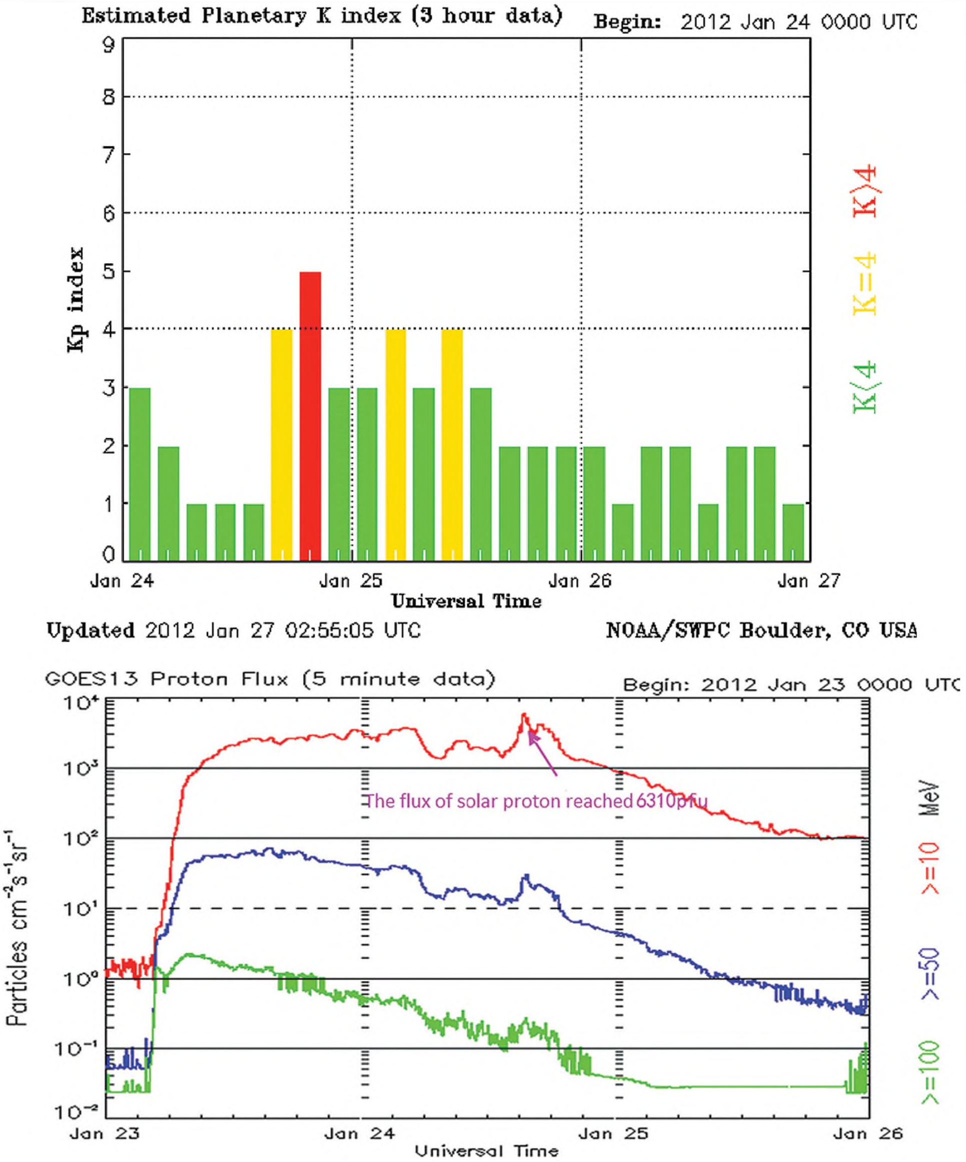

Fig. 5: On 23 January 2012, a M8.7 flare with solar proton event was burst on AR1402. The maximum flux of solar proton event reached 6310 pfu, high-speed CME reached the Earth in 1.5 days later and caused geomagnetic disturbances

Another solar storm event recorded on 23 January 2012 called "China Dragon Event" also caused an alarm, in which a M8.7 flare with solar proton events was burst in the active area of 1402 on the solar disk. In this event, the flux of solar protons reached 6310 pfu (particle flux unit) and the driven CMEs reached the Earth and caused the geomagnetic disturbance for several days. To avoid failures, many satellites in orbit were shut down.

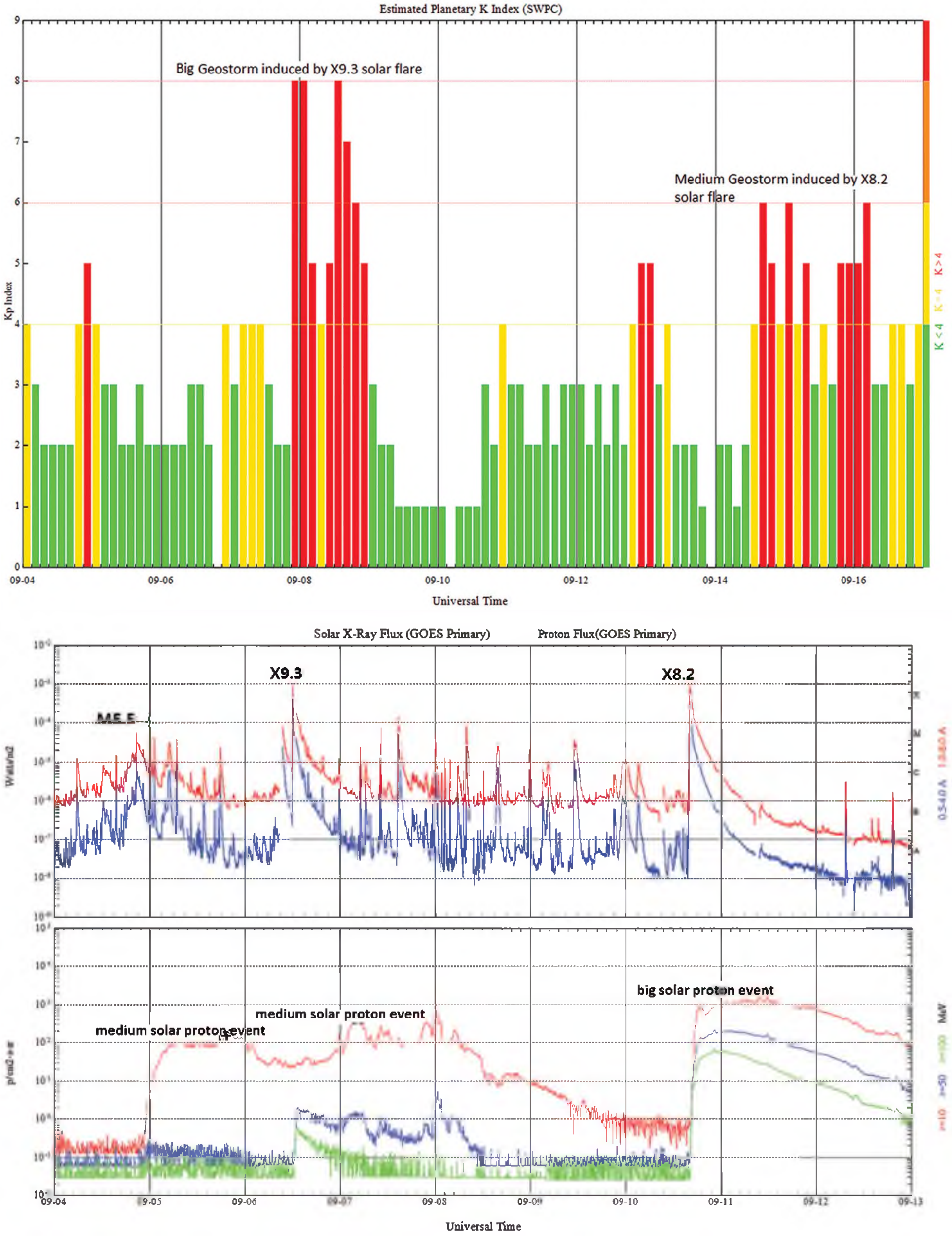

Fig. 6: The pictures show the overview of the "Hungry Ghost Festival Event". On 6 September 2017, a large flare (X9.3) triggered solar proton events and CME. It was the strongest event of solar activity since 2005

"Hungry Ghost Festival Event" is also a strong solar storm happened recently. At 7:53 in the evening of 6 Sep. 2017 a large flare up to X9.3 triggered solar proton events and CMEs. It was the strongest manifestation of solar activity since 2005, and it fired the first shot of a new solar storm. The second day of this event coincided with the Chinese traditional festival — "Hungry Ghost Festival", so it was named as "Hungry Ghost Festival Event". In 2017 we have well passed solar activity peak, so the event, which occurred at solar minimum, shows that the solar storm is unpredictable.

Since the beginning of the first solar activity cycle from 1756 to 1766 recorded and numbered by the human beings, only 24 solar activity cycles have we experienced. At the same time, the history of space exploration counts last 60 years only. There are limited great solar storm events on record. Even though some big storms occurred during space exploration age, they might have not reached the Earth and be left outside in the outer space.

However, the Sun was there for several billions years already. We do not know how a severe space weather event far more intense than any experienced during the space age may affect our modern technological systems. In particular, even though we have already been in space for only 60 years, what we have experienced so far is definitely not what we will experience in the future.

Fig. 7: Low-latitude red auroras, such as those widely reported to have been observed during the Carrington Event, are a characteristic feature of major geomagnetic storms. The aurora shown here was photographed over Napa Valley, California, during the magnetic storm of 5 November 2001 [5]

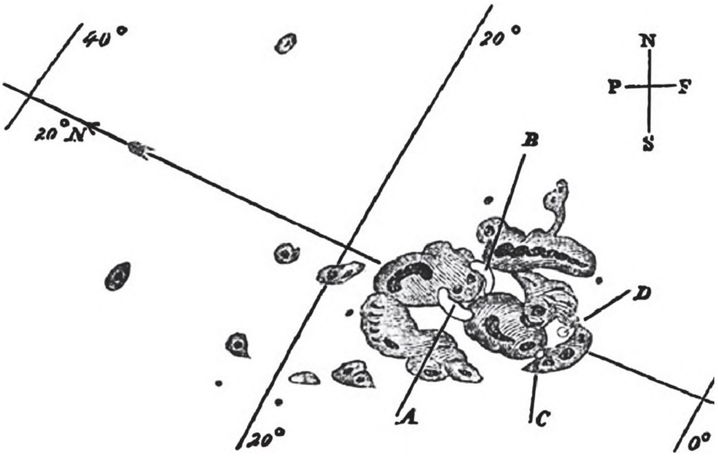

Fig. 8: Sunspots of 1 September 1859 near the center of the Sun's disk, as sketched by Richard Carrington [6]

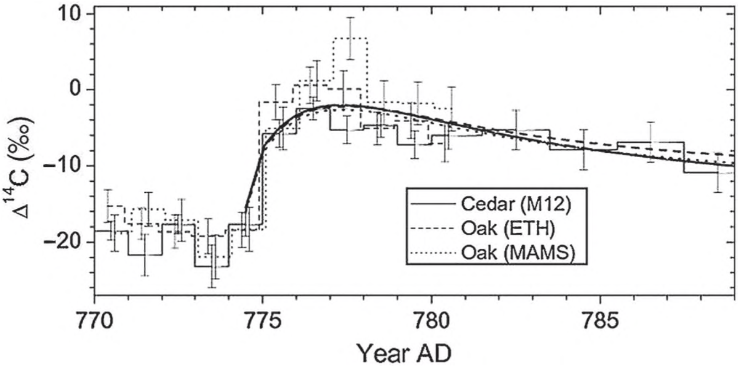

Fig. 9: ^{14}C variation in tree rings around 775 AD. Data are obtained from Japanese cedar (M12) and German oak (ETH and MAMS) [9]

In history, there was several severe space weather events before space age were recognized. For example, about 100 years ago from August 28 through September 4, auroras of enormous brilliance were seen as far south as Hawaii in Northern hemisphere, and as far north as Santiago, Chile, in Southern hemisphere. Magnetic observations recorded disturbance in Earth's field so extreme that magnetometer traces were driven off scale and telegraph networks around the world experienced major disruptions and outages. The recorded auroras were the visible manifestation of two powerful magnetic storms. This two storms, which occurred in about the peak of the solar activity cycle in rapid succession, are referred to as the "Carrington Event".

On September 1, the day before the onset of the second storm, Richard Carrington observed an outburst of "two patches of intensely bright and white light" from a large and complex group of sunspots near the center of the solar disk [6]. We know today that what Carrington observed was an extraordinarily intense white-light flare associated with powerful CMEs. The CMEs and the shock wave hit the Earth's magnetosphere triggering that severe geomagnetic storm. Carrington's observation provided the first evidence that solar activity is the ultimate cause of geomagnetic storms. Recent analysis indicates that the "Carrington Event" was also accompanied by a solar energetic particle event four times more intense than the most severe solar energetic particle event of the space age. By this as well as other estimates, the Carrington Event ranks as one of the most severe space weather events — and by some deemed to be the most severe — on record [7].

Recently, researchers from National Space Science Center (NSSC) of Chinese Academy of Sciences (CAS) studied a solar storm event, which occurred on the Chinese lunar calendar day of 11 December 774 AD, using carbon-14 analysis. Rapid increase of radiocarbon ^{14}C content has been reported in cedar and oak tree rings [8] dated 774–775 AD. So far, the origin of the ^{14}C increase is still uncertain, the possibilities are either supernova or solar particle event. The most probable of them are strong solar flares and CMEs with strong particle emission. Evidence of the super auroras in 775 AD was first found in a Chinese Chronicles Old Tang Book. These auroras were observed in Xi'an City, the capital of Tang Dynasty, with geomagnetic latitude of lower twenties. Such low latitude indicates that both the auroras and the intensity of associated solar particles were strong. It supports the views that the rapid ^{14}C increase and strong auroras around 775 AD are the outcome of strong solar storms with intense particles emission. It was identified that such solar particle event around 775 AD would be the strongest one in the past 1400 years [9]. The discovery is significant for the research on the history of solar activity, space weather, as well as for forecasting the radiation effect from solar energetic particles. One can hardly imagine, what damage we may face, if such a storm happens today and reach geospace.

2. DYNAMIC SPACE ENVIRONMENT TO THE BEST OF OUR KNOWLEDGE

The solar-terrestrial system includes the solar atmosphere, interplanetary space, magnetosphere, ionosphere, thermosphere, near space, and other key regions. There is no doubt that the main domain in the solar-terrestrial system is the Sun. In addition to the heat and light, the Sun also releases a continuous flow of matter, called solar wind. It comprises plasma and magnetic field and is of considerable significance for the Earth and other planets.

When the solar wind flows into the interplanetary space, it interacts with the Earth and thus the magnetosphere is formed. Magnetosphere is a region dominated by Earth's magnetic field and plasma, which are also driven by its magnetic field.

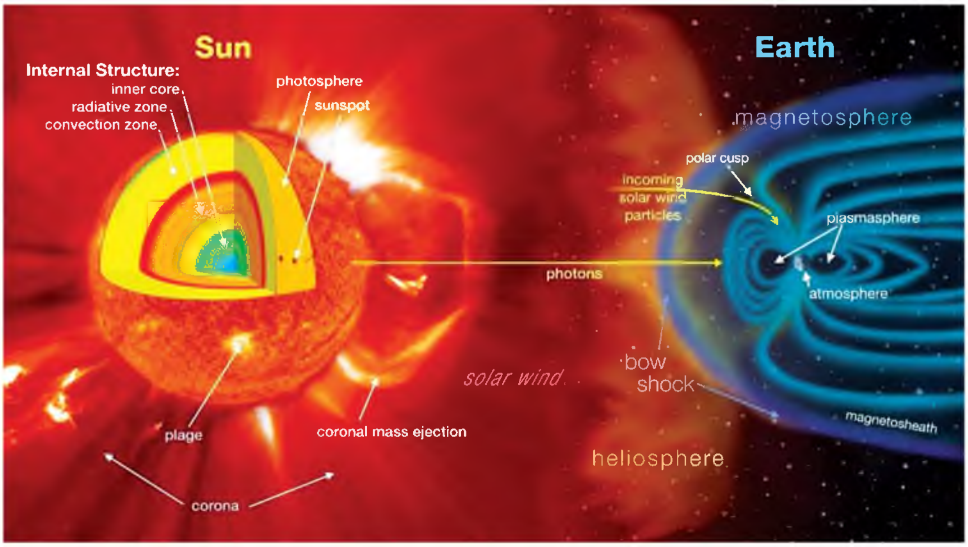

Fig. 10: A schematic view of the solar-terrestrial system

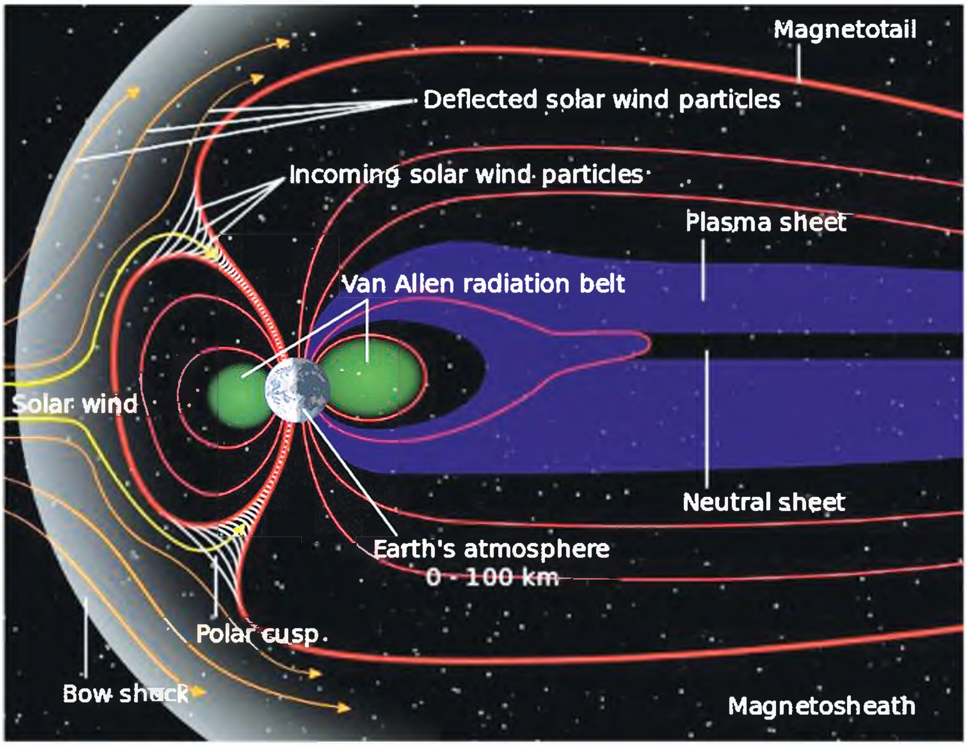

Fig. 11: Schematic view of the Earth's magnetosphere

The shape of the magnetosphere is determined by the extent of Earth's magnetic field and the solar wind. It consists of some large-scale structures including bow shock, magnetopause, radiation belts, ring current, plasma sheet, and magnetotail. Generally, solar wind originates in the solar atmosphere, and solar activity events in this region produces strong disturbances in it.

Thus, dynamic solar wind inevitably affects the magnetosphere. When the interplanetary magnetic field (IMF) is southward, it can also reconnect with the magnetic field lines of the Earth's dayside magnetopause. Energetic particles along the open magnetic field lines can penetrate into the high latitude ionosphere and form the aurora. It is a primary way, by which solar wind's energy enters the geospace. Otherwise, the magnetosphere is strongly disturbed during geomagnetic storms. All in all, it indicates the space environment is very dynamic rather than a stable and peaceful one.

Many scientific spacecraft, such as ACE, SOHO, STEREO, and SDO were launched to carry out critical measurements for alerting and forecasting the space environment over the past decades or more. However, their number is not enough to measure and monitor space environment so vast and to study the physical processes of individual domains in the solar-terrestrial subsystems, their complex interactions or coupling. Thus, many important computer simulation models of the solar-terrestrial system have been developed, such as AWSOM model from Michigan University, COIN model from SIGMA Group of NSSC, and ENLIL model from Space Weather Research Center of NASA. In recent years, many new discoveries were made thanks to simulations based on models.

For example, in response to interplanetary shocks, magnetic field may have regular variation in nightside magnetosphere, while at high latitudes on the ground it has two-phase bipolar variations. Sun et al. used global MHD simulation to investigate the links between the magnetospheric and ground magnetic field to an interplanetary shock and revealed the intrinsic physical related chain response of the former to the latter [10].

The Kelvin-Helmholtz (K-H) instability is found to occur at the low-latitude magnetopause during a period of northward interplanetary magnetic field. Guo et al. [11] used global MHD simulation to present the global picture of the nonlinear evolution of the K-H instability at the magnetopause. It shows that vortices are generated by the K-H instability at the dayside low latitude magnetopause and transport to the far distant magnetotail region along the flank of the magnetosphere. This simulation picture indicates the magnetosphere boundary layer is very active and complex, with many wave-like structures and small pores inside the magnetopause.

Significant progress has been also made in numerical simulation of CMEs event in last few years. CMEs are large-scale eruptions with magnetized plasmas ejected from the solar corona. The derived Interplanetary Coronal Mass

Ejections (ICMEs) may cause geomagnetic storms that induce severe space weather. The measurements of STEREO contribute much to this progress. The principal benefit of the STEREO is stereoscopic images of the Sun, because it includes two satellites at different points along the Earth's orbit and distant from the Earth. They can photograph parts of the Sun that are not visible from the Earth [12]. This permits scientists to monitor the far side for CMEs and provide data foundation for simulation. This progress show that the development of technology and more *in situ* observations can enhance the accuracy of the model prediction and thus can help understand space environment more deeply.

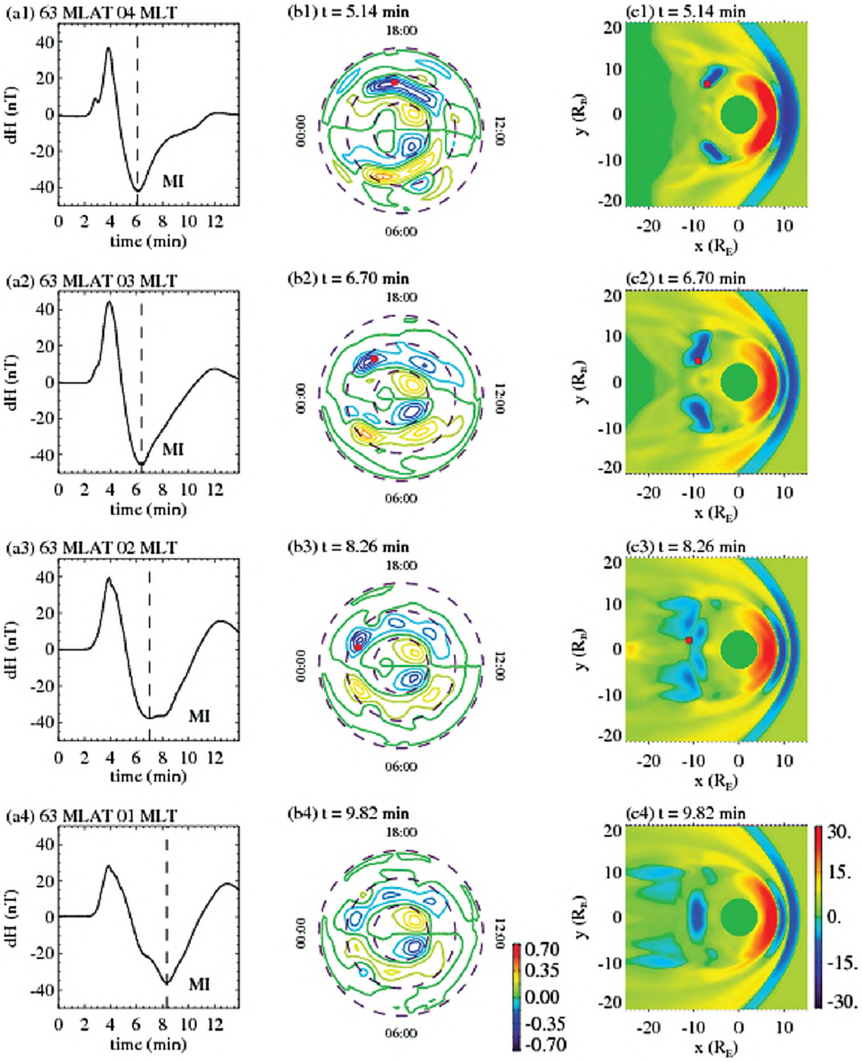

Fig. 12: Time evolution of the ground and magnetospheric magnetic field, as well as the MI-FAC variations [10]

In geospace, a comprehensive database of measurements can be acquired easier from many kinds of *in situ* observation satellites. It is useful to understand the magnetosphere structure. In 2013, NASA's *Van Allen Probes* mission discovered a previously unknown third radiation belt around the Earth, revealing the existence of unexpected structures and processes within these hazardous regions of space [13]. Previous observations of Earth's Van Allen belts revealed two distinct regions of trapped radiation surrounding the Earth. Recent discovery shows the dynamic and variable nature of the radiation belts and improves our understanding of how they respond to solar activity.

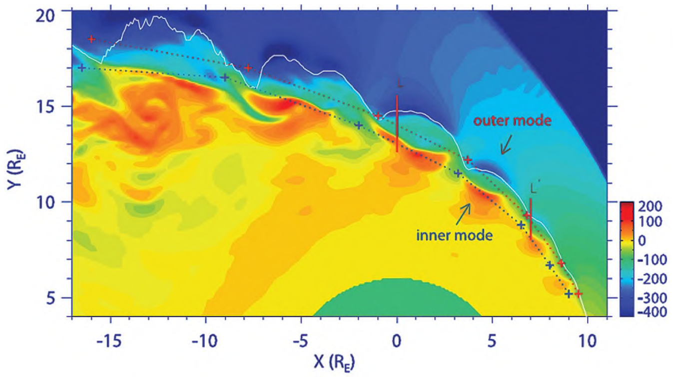

Fig. 13: Inner and outer modes of surface waves on the color contours of x component velocity in the equatorial plane, the continuous white line illustrates the magnetopause boundary [11]

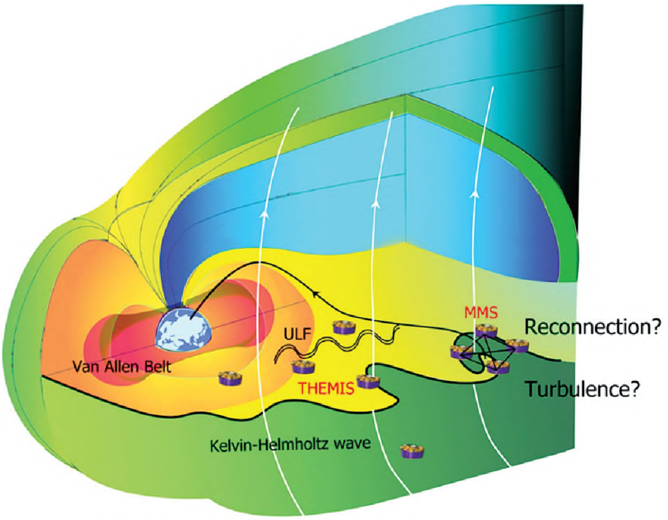

Figure: Schematic drawing of Kelvin-Helmholtz wave and its related reconnection, turbulence and ULF (ultra-low-frequency) wave in Earth's magnetosphere.

Fig. 14: The scientific satellites constellation orbiting in the low latitude magnetopause boundary layer deepen the understanding of the magnetopause instability

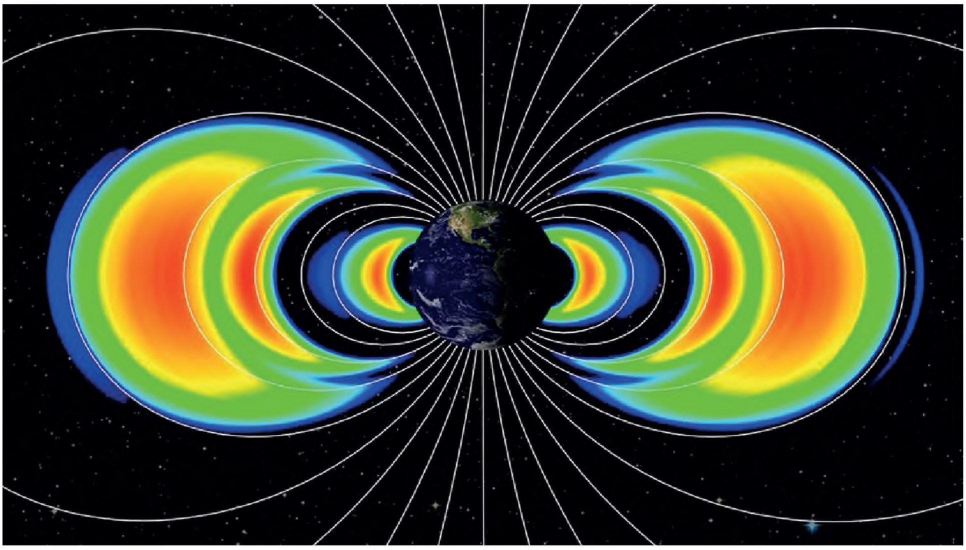

Fig. 15: In 2013, a new radiation belt around the Earth was discovered by *Van Allen Probes*. Image courtesy NASA

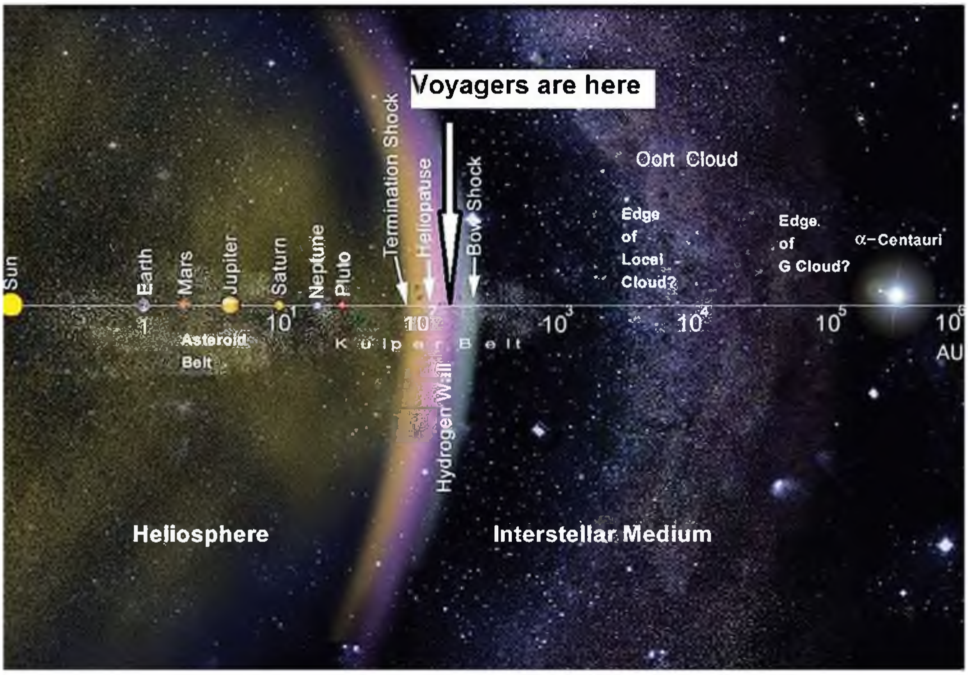

Fig. 16: The twin *Voyager 1* and 2 spacecraft are still exploring the border of the Solar system

When spacecraft leaves the outer boundary of magnetosphere, they travel to a much harsher environment called heliosphere. Heliosphere is the vast region, which solar wind controls. The interactions of the solar wind with the local interstellar medium result in the heliospheric boundaries, which include the termination shock and heliopause. The interface between the interstellar plasmas and the solar wind plasma is called the heliopause, which is estimated at about 120 AU. This boundary is dynamic and changes with variations of the solar wind dynamic pressure. In 1993, D. Gurnett reported the first evidence of the heliopause based on the kHz radio emissions coming from the heliopause, which was later detected by the *Voyager 1* and *2* spacecraft [14].

3. SPACE WEATHER CONCEPT AND CURRENT PROGRAMS

3.1. THE CONCEPT OF SPACE WEATHER

The term of "space weather" was first used in 1950s and was widely spread in the United States. In 1990s the National Space Weather Plan was first proposed, which also gave the definition of "space weather". Space weather is the dynamic conditions on the solar-terrestrial environment (including the Sun and in the solar wind, the mesosphere, thermosphere, ionosphere, and magnetosphere, etc.) that can influence the performance and reliability of space load and ground based technological systems and can endanger human life or health [15]. This is the formal definition currently be accepted by the community. Gradually, space weather studies developed into interdisciplinary field of research, which integrates observations, theory, modeling, application, and services. Now, it' is of the common interests for scientists from different countries, regions, and international organizations, and many cooperative activities expanded worldwide.

As evidenced in the historical record, human activities and technologies always suffered from the extremities of terrestrial weather, such as droughts and floods, hurricanes and tornadoes. If we compare space weather to terrestrial weather, the former also have phenomena such as solar flares and auroras. However, unlike the latter, space weather is a global issue and it can affect simultaneously the whole of North America or reach even wider geographic regions of the planet [16]. To measure and monitor the weather, the instruments such as thermometer and energetic particles sensors, are still used, primarily in the weather and space weather measurement.

Since we entered the 21st century, with the growth of electric power industry, the development of telephone and radio communications, and growing dependence on space-based communications and navigation systems, the vulnerability of modern society to space weather has increased dramatically [16]. Space weather forecast becomes important to alleviate or dodge space weather disasters. Weather forecast can enhance preparedness by providing timely, accurate, and relevant forecasting products. Terrestrial weather forecast has already reached maturity. In contrast to it, space weather forecast systems are in the preliminary stage and cannot predict solar storms. However, those of them, which are installed aboard the satellites, can use the warnings from the ground stations in case of a solar storm breakout and make arrangements to diminish the risk of failure.

3.2. DEVELOPMENT OF SPACE WEATHER MONITORING AND FORECAST

To forecast the adverse effects of space weather better, series of the programs and strategies were proposed by the scientists worldwide. These have promoted the establishment and development of the space weather studies largely.

The first space weather movement or sorts of program was put forward from the United States in 1995 with publication of abovementioned Strategic Plan, called National Space Weather Program (NSWP), which united the resources of different departments in the United States within the joint national program. There, Dr. George Siscoe made great contribution to it. He was one of the editors of the book *Space Weather* and published series of influential papers on space weather. He also was the first editor-in-chief of the scientific journal *Space Weather*, and initiated Geospace Environment Model Plan (GEM). It was this plan that lead to the National Space Weather Plan established by several department of United States.

Mentioned should be also another US scientist, Dr. Madhulika Guhathakurta. She is a key person to push the International Living With a Star (ILWS) program, which focuses on the Sun-Earth relations system and the effects upon life and society (for more information on the ILWS program see below). Then, Dr. Joseph Davila, scientist from Goddard Space Flight Center, proposed the International Heliophysical Year program, which is a UN-sponsored science-driven international program of scientific collaboration to understand external drivers of planetary environments and universal processes in solar-terrestrial-planetary-heliospheric physics (see the next section for the details).

On the other side of the Atlantic, European Space Agency (ESA) held a round table discussion on space weather in 1996 and the first workshop on the topic in 1998. From 1999 to 2001, ESA implemented the feasibility study on a Space Weather Programme and set up the Space Weather Working Team. In 2003, ESA Space Weather pilot-project formally started. European Space Weather Program focused on monitoring conditions at the Sun and in the Earth's magnetosphere, ionosphere, and thermosphere that can affect space-borne and ground-based infrastructure or endanger human life or health. Above all, ESA actively promoted the development of the space weather studies.

In Russia we may name Prof. Geliy Zherebtsov. He made a significant progress on space weather promotion in Russia, especially focusing on the ground observation instruments, such as the incoherent scatter radar for earth observation and solar observation to study the ionosphere and global climate change. He is one of the key person to contribute to Russian space weather program.

In China, we name two key scientists. One of them is Wei Fengsi, who made great contribution to promote the space weather program in China. He introduced the concept of "space weather" to China and contributed to the establishment of the State Key Laboratory of Space Weather. At the same time, he dedicated in promoting Chinese Meridian Project and proposed the International Space Weather Conference, which enhanced global cooperation in space weather. The other one is Du Heng, who had established the first space environment forecast center in China as early as in 1996.

3.3. CURRENT SPACE WEATHER PROGRAMS

3.3.1. Living With a Star (LWS)

Living With a Star (LWS) is NASA scientific program to study those aspects of the connected Sun-Earth system that affect life and society directly. The program is managed by the Heliophysics Division of NASA's Science Mission Directorate.

LWS is composed of three major components: scientific investigations on spaceflight platforms to study different regions of the Sun, interplanetary space, and geospace; an applied science Space Environment Testbeds program, where protocols and components are tested; and a Targeted Research and Technology Program.

The first two science missions were launched: *Solar Dynamics Observatory* (SDO), launched on February 11, 2010, and *Van Allen Probes*, launched on August 30, 2012. Balloon Array for Radiation-belt Relativistic Electron Losses (BARREL) and Space Environment Testbeds (SET) are currently in development. *Solar Orbiter* will be launched in 2020 and *Parker Solar Probe* was launched in August, 2018.

3.3.2. International cooperation

International cooperation has long been a vital element in the scientific investigation of solar variability and its impact on Earth and its space environment [18].

(1) International Solar Terrestrial Physics (ISTP) Program

The International Solar Terrestrial Physics (ISTP) Program is a large, multinational program involving three space agencies and up to eight spacecraft. NASA, together with the Institute of Space and Astronautical Science (ISAS) of Japan and the ESA, has agreed in principle to coordinate their efforts in investigating the Sun and the Earth from the 1990s till now [19].

ISTP program combines resources and scientific communities on an international scale using a complement of several missions, *Geotail* provided by ISAS, Solar Heliospheric Observatory (SOHO), and CLUSTER (four spacecraft) contributed by ESA, and *Wind* and *Polar* by NASA. This flotilla is complemented by ground facilities and theoretical efforts, to obtain coordinated, simultaneous investigations of the Sun–Earth space environment over an extended period of time.

The primary science objectives of the ISTP Science Initiative are as follows:

(1) Determining structure and dynamics in the solar interior and their role in driving solar activity;
(2) Identifying processes responsible for heating the solar corona and its acceleration outward as the solar wind;
(3) Determining the flow of mass, momentum and energy through geospace;
(4) Gaining a better understanding of the turbulent plasma phenomena that mediate the flow of energy through geospace; and
(5) Implementing a systematic approach to the development of the first global solar-terrestrial model, which will lead to a better understanding of the chain of cause-effect relationships that begins with solar activity and ends with the deposition of energy in the upper atmosphere.

The ISTP Science Initiative uses simultaneous and closely coordinated measurements from several spacecraft. These measurements of the key regions of geospace will be supplemented by data from equatorial missions and ground-based investigations. It will provide a measurement network to determine the local state of several key magnetospheric regions. The integration of theory and modeling with satellite and ground-based observations completes the ISTP Science Initiative.

(2) International Living With a Star

The International Living With a Star (ILWS) initiative is a broad international effort to develop the scientific understanding necessary to address effectively those aspects of the connected Sun–Earth system that directly affect life and society [18].

The first step in establishing ILWS was taken in the year 2000 when the NASA Living With a Star (LWS) program was established. This program, along with other complementary NASA Earth and Space Science programs, many of which involve international partnerships, provide a set of ongoing and planned missions that serve as a foundation for the ILWS program. The proposal to establish an International Living With a Star program originated at the September 2000 meeting of the Inter-Agency Consultative Group (IACG) for Space Science. The IACG formed a task group to study the possibility of establishing a new international cooperative program in solar-terrestrial physics, ILWS. The ILWS task group, which includes 14 representatives from ESA, ISAS, NASA, and so on recommended to the IACG that an ILWS program be established after a joint meeting on May 15–17, 2001. The IACG accepted this recommendation at its January 2002 meeting and asked NASA to serve as the lead agency in setting up a working group to coordinate the ILWS program. In 2003, NASA's Sun-Earth Connection Division led the ILWS consisting of more than 25 of the world's most technologically advanced space agencies to contribute towards the scientific goal for understanding space weather through observations made in space [20].

The mission of the ILWS program is to *stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun–Earth System as an integrated entity*. The objectives are to stimulate and facilitate:

(1) Study of the Sun-Earth connected system and the effects which influence life and society;
(2) Collaboration among potential partners in solar-terrestrial space missions;
(3) Synergistic coordination on international research in solar-terrestrial studies, including all relevant data sources as well as theory and modeling;
(4) Effective and user-driven access to all data, results and value-added products.

(3) International Heliophysical Year

In 1957 a program of international research was organized as the International Geophysical Year (IGY) to study global phenomena of the Earth and geospace. Fifty years after IGY, the world's science community again came together for an international program of scientific collaboration: the International Heliophysical Year (IHY) 2007. IHY provided a successful model for the deployment of arrays of small scientific instruments in new and scientifically interesting geographic locations, and outreach, involving more than 70 countries during a two-year period from February 2007 to February 2009 [21, 22].

IHY had three primary objectives:

(1) Advancing the understanding of the fundamental heliophysical processes that govern the Sun, Earth and heliosphere;
(2) Continuing the tradition of international research and advancing the legacy of IGY on its 50th anniversary;

(3) Demonstrating the beauty, relevance, and significance of space and Earth science to the world.

IHY is an integrated program consisting of many diverse activities that are coordinated on an international level to achieve all of the above goals.

(4) International Space Weather Initiative (ISWI)

Building on the concept realized during the IHY, in February 2009 the International Space Weather Initiative (ISWI) was proposed to the Science and Technology Subcommittee (STSC) of the United Nations focusing exclusively on space weather. ISWI is designed to continue the study of universal processes in the Solar system that affect the interplanetary and terrestrial environments, and to continue to coordinate the deployment and operation of new and existing instrument arrays aimed at understanding the impacts of space weather on Earth and the near-Earth environment. In addition to the United Nations, ISWI is supported by NASA, ESA, the Japan Aerospace Exploration Agency (JAXA), and the International Committee on Global Navigation Satellite Systems (ICG) [20, 24].

The ISWI was initiated to help develop the scientific insight necessary to understand the physical relationships inherent in space weather, to reconstruct and forecast near-Earth space weather, and to communicate this knowledge to scientists and to the general public. This is accomplished by (1) continuing to deploy new instrumentation, (2) developing data analysis processes, (3) developing predictive models using data from the instrument arrays, and (4) continuing to promote knowledge of heliophysics through education and public outreach.

The ISWI continues a portion of the IHY program, providing a forum for the formation of scientific collaborations between instrument providers and instrument hosts. Initially data will be used primarily for understanding the physical processes important for space weather phenomena. Later, ISWI will move toward near real-time data availability as internet connectivity improves, allowing data ingest predictive modeling. A robust program of outreach is envisioned, with a continuation of the space science schools, support for university space science curricula, and a public outreach program [25].

(5) World Meteorological Organization's Involvement in Space Weather

In June 2008, the World Meteorological Organization (WMO) Executive Council (EC-LX) noted the considerable impact of space weather on meteorological infrastructure and important human activities. It acknowledged the potential synergy between meteorological and space weather services to operational users. The Council agreed that WMO should support international coordination of space weather activities and urged WMO Members to provide corresponding resources through secondments and Trust Fund donations.

In May 2010, WMO established the Interprogram Coordination Team for Space Weather (ICTSW) with a mandate to support space weather observation, data exchange, product and services delivery, and operational applications [26]. As of May 2016, ICTSW involves experts from 26 different countries and 7 international organizations.

The overarching goal of the ICTSW is to facilitate, in partnership with International Space Environment Service (ISES) and other organizations, the international coordination of space weather observations, data, products, and services, building on the respective assets of the ISES and of WMO.

On June 21, 2016 the Executive Council approved the four-year plan for WMO activities related to space weather in 2016–2019 [27].

(6) COSPAR Space Weather Roadmap

An international approach is paramount to advance our scientific understanding of space weather successfully. This realization prompted the Committee on Space Research (COSPAR) of the International Council for Science (ICSU) and the International Living With a Star (ILWS) Steering Committee to commission a strategic assessment of how to advance the science of space weather with the explicit aim of better meeting the user needs around the globe. COSPAR PSW-ILWS Roadmap is the outcome of that activity. It expresses a focus on the terrestrial environment.

They expect that "the roadmap" would cover as minimum:

(1) Current available data and upcoming gaps;
(2) Agency plans for space-based space weather data (national and international): treating both scientific and monitoring aspects of these missions;
(3) Space and ground based data access: where current data is either proprietary or where the geographic location of the measurement makes data access difficult;
(4) Current capability gaps, which would provide a marked improvement in space weather service capability.

In the spring of 2013, the leadership of COSPAR and ILWS appointed a team of experts charged to create this roadmap. The roadmap identifies high-priority challenges in key areas of research that are expected to lead to a better understanding of the space environment and an improvement in the provision of timely, reliable information pertinent to effects on space-based and ground-based systems. The roadmap prioritizes those advances that can be made on short, intermediate, and decadal time scales, identifying gaps and opportunities from a predominantly geocentric perspective. This roadmap does not formulate requirements for operational forecast or real-time environmental specification systems, nor does it address in detail the effort required to utilize scientific advances in the improvement of operational services. However, it recognizes that forecasts (whether in near-real time or retrospectively) can help uncover gaps in scientific understanding or in modeling capabilities.

4. THE FUTURE SPACE WEATHER PROGRAMS

The programs mentioned in the previous sections greatly contribute to space weather studies. They promote further integration of science innovations and social needs, advocate the establishment of the global space weather forecast framework for even greater scientific and social benefits. However, the list is not finished; we need more missions to understand the puzzles of space weather. The missions under development today will focus mainly on the Sun and solar activity phenomena, such as flares and CMEs. Below, we describe some of them.

4.1. SOLAR AND HELIOSPHERIC MISSIONS

(1) Parker Solar Probe

NASA's *Parker Solar Probe* [28] (previously *Solar Probe Plus* or *Solar Probe* +) will be the first spacecraft to fly into the low solar corona to determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what processes accelerate energetic particles. On May 31, 2017 the probe was renamed after solar astrophysicist Eugene Parker. This was the first time a NASA spacecraft was named after a living person [29].

The mission design and the technology and engineering developments enable *Parker Solar Probe* to meet its science objectives to [30]:

(1) Trace the flow of energy that heats and accelerates the solar corona and solar wind: How is energy from the lower solar atmosphere transferred to, and dissipated in, the corona and solar wind? What processes shape the non-equilibrium velocity distributions observed throughout the heliosphere? How do the processes in the corona affect the properties of the solar wind in the heliosphere?
(2) Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind: How does the magnetic field in the solar

wind source regions connect to the photosphere and the heliosphere? Are the sources of the solar wind steady or intermittent? How do the observed structures in the corona evolve into the solar wind?

(3) Explore mechanisms that accelerate and transport energetic particles: What are the roles of shocks, reconnection, waves, and turbulence in the acceleration of energetic particles? What are the source populations and physical conditions necessary for energetic particle acceleration? How are energetic particles transported in the corona and heliosphere?

The *Parker Solar Probe* mission was confirmed in March 2014 and is under development as a part of NASA's LWS Program [31]. *Parker Solar Probe* was launched in August, 2018, and will perform 24 orbits over a 7-year nominal mission duration. Seven Venus gravity assists gradually reduce the perihelion of its orbit from $35R_S$ for the first orbit to $<10R_S$ for the final three orbits.

The *Parker Solar Probe* instrument for science investigations, selected by NASA in September 2010, are: the Electromagnetic Fields Investigation (FIELDS); the Integrated Science Investigation of the Sun, Energetic Particle Instruments (ISIS); the Solar Wind Electrons Alphas and Protons Investigation (SWEAP); and the Wide Field Imager for Solar Probe Plus (WISPR). In addition to the four instrument investigations, there is also a theory and modeling investigation — Heliospheric Origins with *Solar Probe Plus* (HeliOSPP).

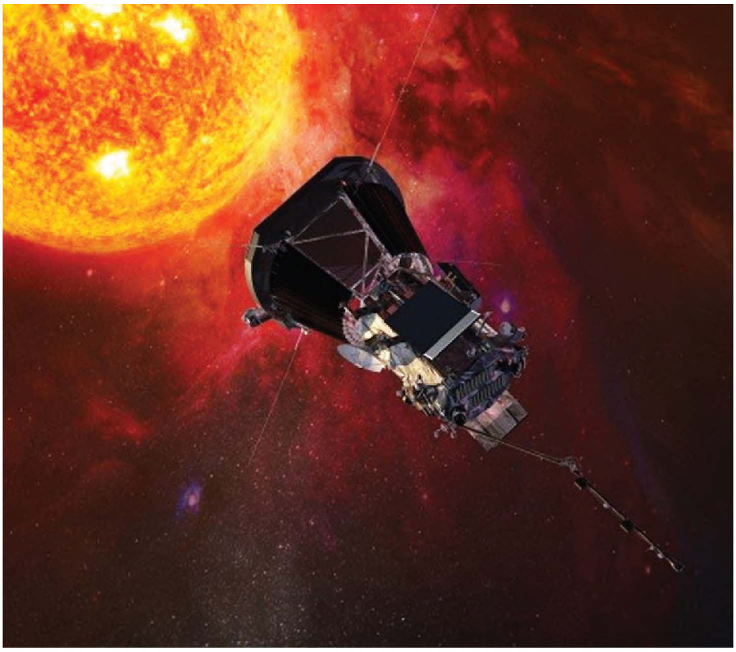

Fig. 17: Artist's impression of NASA's *Parker Solar Probe* spacecraft on approach to the sun [33]. Image courtesy NASA

The FIELDS investigation comprises two fluxgate magnetometers, a search coil magnetometer and five electric antennas measuring electric and magnetic fields and waves, spacecraft floating potential, density fluctuations, and radio emissions. The SWEAP investigation has two electrostatic analyzers and a Faraday cup. This investigation will count the most abundant particles in the solar wind — electrons, protons, and helium ions — and measure their properties such as velocity, density, and temperature. The ISIS energetic particle instrument suite is composed of two independent instruments (EPI-Hi and EPI-Lo) covering different (and overlapping) energy ranges. This suite will make observations of energetic electrons, protons, and heavy ions that are accelerated to high energies (10 s of keV to 100 MeV) in the Sun's atmosphere and inner heliosphere. The WISPR white light telescope will take images of the solar corona and inner heliosphere. The experiment will also provide images of the solar wind, shocks, and other structures as they approach and pass the spacecraft. This investigation complements the other instruments on the spacecraft providing direct measurements by imaging the plasma the other instruments sample.

(2) Solar Orbiter

Solar Orbiter, the first medium-class mission of ESA's Cosmic Vision 2015–2025 program, is dedicated to solar and heliospheric physics research [33]. The mission was selected in 2011 with a launch year of 2020 [34, 35]. The spacecraft will approach the Sun as close as 0.28 AU and reach heliographic latitudes of up to 34°, which will allow *Solar Orbiter* to observe the solar poles directly at a much lower angle than possible from Earth.

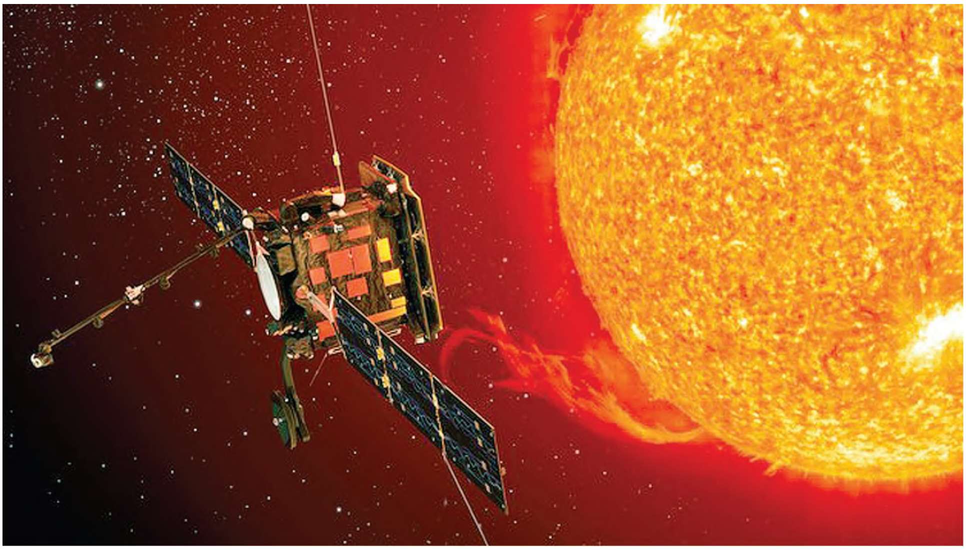

Fig. 18: Artist's impression of ESA's *Solar Orbiter*. Image courtesy ESA

With a combination of *in situ* and remote-sensing instruments and its inner-heliospheric mission design, *Solar Orbiter* will address the central question of heliophysics: How does the Sun create and control the heliosphere? This primary, overarching scientific objective can be expanded into four interrelated top-level scientific questions that will be addressed by *Solar Orbiter*:

1. What drives the solar wind and where does the coronal magnetic field originate from?
2. How do solar transients drive heliospheric variability?
3. How do solar eruptions produce energetic particle radiation that fills the heliosphere?
4. How does the solar dynamo work and drive connections between the Sun and the heliosphere?

The scientific payload elements of *Solar Orbiter* will be provided by ESA member states, NASA, and ESA and have been selected and funded through a competitive selection process. They can be grouped in three major packages, each consisting of several instruments [36, 37]:

1. Field Package: Radio and Plasma Waves Instrument (RPW) and Magnetometer (MAG);
2. Particle Package: Energetic Particle Detector (EPD) and Solar Wind Plasma Analyzer (SWA);
3. Solar remote sensing instrumentation: Polarimetric and Helioseismic Imager (PHI), Extreme Ultraviolet Imager (EUI), Multi Element Telescope for Imaging and Spectroscopy (METIS), Solar Orbiter Heliospheric Imager (SoloHI), Spectral Imaging of the Coronal Environment (SPICE) and Spectrometer/Telescope for Imaging X-Rays (STIX).

(3) Advanced Space-based Solar Observatory (ASO-S)

Advanced Space-based Solar Observatory (ASO-S) is a mission proposed for the 25th solar maximum by the Chinese solar community. The conception study of ASO-S was carried out from September 2011 to March 2013 (Phase-0/A) and its background study was started in January 2014, and completed by the end of 2017 (Phase A/B).

The ASO-S mission is exclusively proposed to understand the relationships among the solar magnetic field, solar flares, and CMEs. Its major scientific objectives could be abbreviated as '1M2B': one Magnetism plus two Bursts (flares and CMEs), to study their physical formation and mutual interactions. More explicitly, four major goals are described as follows:

1. To observe simultaneously non-thermal images of flares in hard X-rays, and the formation of CMEs, to understand the relationships between flares and CMEs;

(2) To observe simultaneously full-disc vector magnetic field, energy build-up and release of solar flares, and the initiation of CMEs, to understand the causality among them;
(3) To observe the response of solar atmosphere to eruptions, to understand the mechanisms of energy release and transport; and
(4) To observe solar eruptions and the evolution of magnetic field to provide clues for forecasting space weather.

To fulfill the scientific objectives, three payloads are proposed: a Full-disc vector MagnetoGraph (FMG), a Lyman-alpha Solar Telescope (LST), and a Hard X-ray Imager (HXI). FMG measures the magnetic fields of the photosphere over the entire solar disk. To observe CMEs continuously from solar disk to a few solar radii, another payload LST will be aboard. HXI aims to image the full solar disk in the high-energy range from 30 keV to 300 keV, with good energy resolution and high time cadence [38].

The launch date of ASO-S is planned for 2022.

(4) Solar Polar ORbit Telescope (SPORT)

The *Solar Polar ORbit Telescope* (SPORT) project for space weather mission has been under intensive scientific and engineering background studies since it was incorporated into the Chinese Space Science Strategic Pioneer Project in 2011. The development of the SPORT mission continues with the goal of a launching around 2020 [39, 40].

The SPORT mission is specifically designed to target the unsolved mysteries of solar and heliospheric physics and potential application to space weather. The SPORT mission addresses the following four top-level scientific questions:

(1) Characterize CME propagation through, and interaction with, the inner heliosphere, in particular a global view of the longitudinal dimension that is so far integrated by all observations;
(2) Discover solar high-latitude magnetism associated with eruptions and solar cycle variation;
(3) Investigate the origin and properties of the fast solar wind; and
(4) Understand the acceleration, transport, and distribution of energetic particles in the corona and heliosphere.

A suite of SPORT payloads is expected to detect the radiation, particles, waves, and fields in the inner heliosphere include Synthetic Aperture Radio Imager (SARI), White-light HI, Solar EUV Imager, Solar Vector Magnetograph, etc.

Furthermore, coordinated observations between SPORT and other spaceborne and ground-based facilities within the ILWS framework can significantly enhance scientific output.

SPORT has been selected for Phase A study during 2011–2016 and now is still remaining in the study phase.

(5) Interhelioprobe

The *Interhelioprobe* mission, funded by Russian State Corporation "Roscosmos", aims to investigate the inner heliosphere and the Sun from close distances (up to 0.3 AU) and from out of the ecliptic plane (up to 30°). *Interhelioprobe* is scheduled for launch after 2025 [41, 42].

The major concept of the *Interhelioprobe* mission is to perform:

(1) Detailed multi-wavelength solar observations with high spatial resolution at small distances from the Sun (up to 0.3 AU);
(2) Out-of-ecliptic solar observations (up to 30°) and observations of the Sun's opposite side, which is not visible from the Earth at a given time;
(3) *In situ* measurements of electric and magnetic fields, and particles in the inner heliosphere and out of the ecliptic plane onboard the same spacecraft.

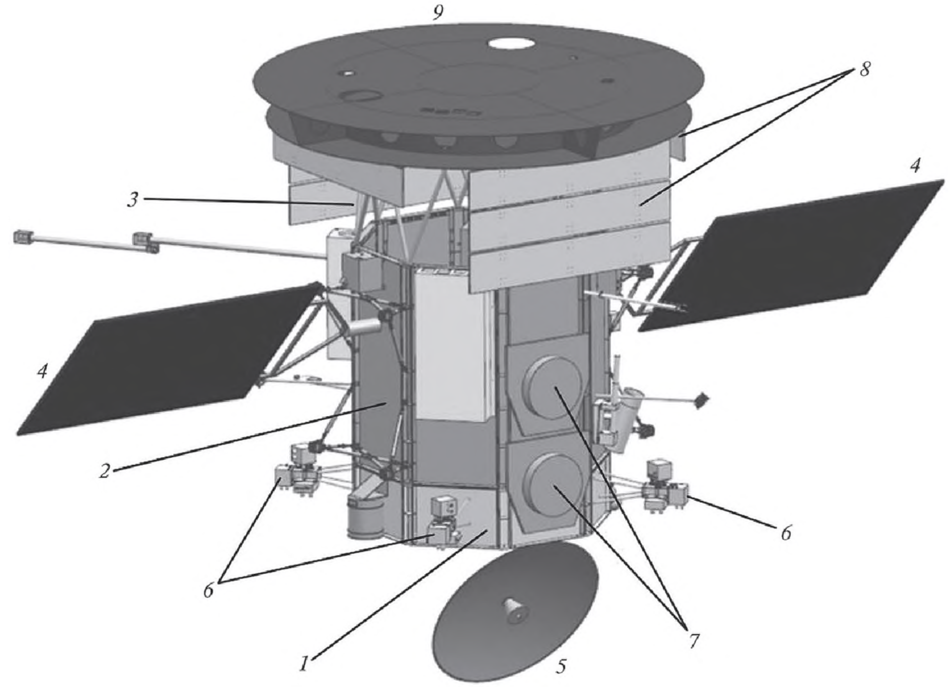

Fig. 19: Scheme of the *Interhelioprobe* spacecraft: (1) engine module; (2) payload module; (3) framework; (4) solar panels with drives; (5) high-gain parabolic antenna; (6) engine units of the orientation and stabilization system; (7) engine units of the electric propulsion system; (8) radiators; (9) protective thermal shield with windows

The goals of the *Interhelioprobe* mission include:

(1) To contribute to understanding of the solar dynamo mechanisms and solar cycle;
(2) To imagine fine structure and dynamics of the solar atmosphere better;
(3) To achieve progress in finding mechanisms of solar corona heating and acceleration of the solar wind;
(4) To understand further the nature and global dynamics of the most powerful manifestations of the solar activity — solar flares and CMEs — and their influence on the heliosphere and space weather; and
(5) To recognize better processes of generation and transport of energetic particles (solar cosmic rays) at the Sun and in the heliosphere.

Scientific payload of the *Interhelioprobe* mission consists of 19 instruments to measure specific physical quantities and 4 supplementary (service) systems, with 10 instruments for remote observations of the Sun and 9 for local (*in situ*) measurements in the interplanetary space.

Interhelioprobe is now still in is study phase with key technology breakthroughs by engineering tests.

(6) Solar-C

Solar-C is the next space mission to be proposed by the Japanese and international solar community to the JAXA. *Solar-C* aims at exploring the physics of the Sun, and confronts new challenges revealed by the currently operating *Hinode* (*Solar-B*) and other missions such as SDO, SOHO, and the Solar-Terrestrial Relation Observatory (STEREO) [43].

The mission science goals can be summarized as:

(1) How are elementary atmospheric structures created and how do they evolve in each temperature domain of the atmosphere;
(2) How is energy transported through small elementary structures into the large scale corona and how does it drive the solar wind;
(3) How is magnetic energy dissipated in astrophysical plasmas;
(4) How do small-scale physical processes initiate large-scale dynamic phenomena creating space weather?

These science goals will be achieved by a suite of three instruments. First is a Solar Ultraviolet, Visible, and Infrared Telescope (SUVIT) for spectropolarimetry of the photosphere and chromosphere of the Sun. With a diameter of 1.5 m, it will be the largest solar telescope to fly in space by a factor of 9 in collecting area. The second is an X-ray or extreme-ultraviolet imaging telescope (XIT) that will observe the corona at unprecedented spatial resolution. Finally, the LEMUR Extreme UltraViolet Spectroscopic Telescope (EUVST) has resolution and effective area an order of magnitude higher than currently available for solar studies. This set of instruments will allow studying the solar atmosphere as an integrated system by establishing the dynamical coupling between its various temperature regions (e. g., by following the flow of mass and energy from the photosphere to the corona).

Solar-C is still in the study phase.

4.2. MAGNETOSPHERIC AND IONOSPHERIC MISSIONS

(1) Solar wind Magnetosphere Ionosphere Link Explorer (SMILE)

Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) is a planned joint venture mission between the European Space Agency and the Chinese Academy of Sciences to study the interaction between Earth's magnetosphere and the solar wind, while simultaneously monitoring the magnetosphere's plasma environment [44, 45]. Launch is expected at the end of 2021 [46].

SMILE will investigate the dynamic response of the Earth's magnetosphere to the impact of the solar wind in a unique manner, never attempted before: it will combine soft X-ray imaging of the Earth's magnetopause and magnetospheric cusps with simultaneous UV imaging of the Northern aurora. For the first time SMILE will be able to trace and link the processes of solar wind injection in the magnetosphere with those acting on the charged particles precipitating into the cusps and eventually the aurora. SMILE will also carry *in situ* instrumentation to monitor the solar wind and magnetosheath plasma conditions, so that the simultaneous X-ray and UV-images can be compared and contrasted directly, and self-sufficiently, with the upstream and local driving conditions.

The key science questions for SMILE are:

(1) What are the fundamental models of the dayside solar wind/magnetosphere interaction;
(2) What defines the substorm cycle; and
(3) How do CME-driven storms arise and what is their relationship to substorms?

SMILE's payload will consist of four instruments. First is Soft X-ray Imager (SXI), a telescope with a wide field of view microchannel plate optic and CCD detector at the focal plane. The second is UV Imager (UVI), a wide field of view optic sensitive to the Lyman-Birge-Hopffman band of ultraviolet radiation. The third is Light Ion Analyser (LIA), a wide field of view proton and alpha particle analyser. And finally a Magnetometer (MAG), a dual-redundant digital fluxgate magnetometer, with two tri-axial fluxgate sensors connected by a boom to a spacecraft-mounted electronics box.

The launch date of SMILE is planned for 2022.

(2) Magnetosphere, Ionosphere and Thermosphere Coupling (MIT)

Targeting at the coupling of magnetosphere-ionosphere-thermosphere system, a future Chinese mission, Magnetosphere-Ionosphere-Thermosphere Coupling Small Satellite Constellation (MIT) is a proposed Chinese spacecraft mission and will be composed of two magnetosphere small satellites and ionosphere/thermosphere small satellites, mainly focusing on the material exchange between magnetosphere, ionosphere, and thermosphere [47]. The launch is scheduled for 2021.

MIT's major scientific objectives are:

(1) To investigate the origin of the outflow ions and their acceleration mechanisms;
(2) To understand the impact of the outflow ions on magnetic storm development;
(3) To characterize the ionosphere and thermosphere storm caused by magnetic storm;
(4) To explore the key mechanisms for the magnetosphere, ionosphere, and thermosphere coupling.

The instrumentation proposed for MIT has state-of-the-art capability to measure the electric and magnetic fields, the cold plasma and neutral wind, 3D ion and electron distribution functions, low-energy neutral particles and UV from the aurora, utilizing identical instruments onboard the two high altitude (MA/MB) and low altitude (ITA/ITB) spacecraft, respectively.

The launch date of MIT is planned for 2021.

(3) Resonance

Resonance mission within Russian Federal Space Program is a four-spacecraft microsatellite constellation designed to measure plasma parameters of the Earth's inner magnetosphere. While following the pattern of multi-spacecraft observations, *Resonance* is unique as well thanks to its orbit, which allows four spacecraft to stay in the same region of the magnetosphere for a long time. Moreover, as the distance between the spacecraft is changeable, multi-scale observations are also possible [48].

Main scientific goals of the mission will be studies of the evolution of the magnetic field, the ring currents, magnetospheric storms, and plasma dynamics. A special objective will be the study of magnetospheric cyclotron resonance masers, which might play a significant role in the shape of the radiation belts.

The mission is currently under development. International collaboration on the project includes Russia, Ukraine, Austria, Bulgaria, Greece, Poland, Czech, Slovakia, the USA, Finland, and France. The launch will be performed by pairs [49]. Nominal mission lifetime is 5 years [50].

The launch date of Resonance is planned after 2022.

4.3. GROUND-BASED OBSERVATION MISSIONS

(1) *International Space Weather Meridian Circle Program*

The International Meridian Circle Program (IMCP), a key international program initiated by Chinese space community in the early 21st century. The program team members come from National Space Science Center (NSSC), the Institute of Geology and Geophysics, the Institute of Atmospheric Physics, University of Science and Technology, China, National Astronomical Observatories, and so on.

The IMCP is proposed by NSSC, CAS, and based upon the Meridian Space Weather Monitoring Project (Meridian Project), a grand Chinese scientific and technical basement facility project that is under construction. The Meridian Project will be extended north to Russian, and south to Southeast Asia countries such as Australia, and so on. Furthermore, it will be extended to the countries located in the west hemisphere near 60° meridian line. The first and only ground-based global space weather monitoring circle will be formed [51].

The first step of the IMCP will be to investigate further the ground-based monitoring network along 120° E and 60° W regions, and to study in detail the recent and future advances in space weather monitoring. Then, the goal is to set up, taking into account all possible suggestions from the scientist in this Circle and relevant international organizations, the scientific goals of the IMCP, and form the feasible implementation plan of the ISWMCP [52]. Chinese scientists have started discussing this proposal with the scientists from Russia and Australia and other countries or regions running through the East Longitude 120° E as well as in related countries whose territories are traversed by the West Longitude 60° W, and got very positive feedback.

(2) Chinese Meridian Project II

Furthermore, on the basis of Meridian Project I, the China Meridian Space Weather Monitoring Project II will increase the monitoring facilities which can cover most of the territorial in China and even the North and South Pole regions. In December 2016, the Meridian Project II was selected as one of the 10 priority construction projects listed in the 13th Five-year Plan for Major National S&T Infrastructure Construction Plan. On September 5, 2017, the China International Engineering Consulting Corporation was commissioned by the National Development and Reform Commission to evaluate the project proposal. The Meridian Project II is planned to start construction in 2018 and completed in 2022.

(3) Mid-latitude Observation Chain

Mid-latitude Observation Chain intend to connect all the ground stations from Japan to Spain to form an observation chain and provide space weather service. Once established, it will become the longest mid-latitude observation chain on the Earth and provide opportunity to observe the space environment from the Sun to the atmosphere crossing different time zone at mid-latitude. The Mid-latitude Observation Chain program is proposed by NSSC and is now in the study phase.

SUMMARY

The human beings have entered the space for 60 years and had great advancements in understanding of space environment, which turned out to be dynamic and dangerous, rather than empty and quiet. It affects the performance and reliability of technological systems and endangers human life and health. Space weather forecast, and in particular the forecast of its source, the solar storms, still is a very difficult scientific frontier.

We have already experienced many severe space weather events in the space age. But this encompasses less than 6 solar cycles. Compared with this, the Sun have been there for 4.6 billion years. It may burst more severe solar storms and cause enormous adverse impacts on the Earth than what we can imagine. Therefore, to study it and to try to forecast, give warning, and protect our society is a very important job and duty for the space community. Unlike the terrestrial weather, space weather is a global issue. Countries around the world must work together to foster international collaborations and prepare for the extreme space weather in the future.

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60 YEARS OF SPACE RESEARCH — 70 YEARS OF MAGNETIC RECONNECTION

In October 2017 the Space Research Institute (IKI) of the Russian Academy of Sciences organized in Moscow an international conference devoted to the 60th anniversary of the launch of the first artificial satellite of the Earth — the Sputnik.

I thank the organizers for the opportunity to talk on this occasion about magnetic reconnection, i.e. an astrophysical phenomenon whose proof and *in situ* investigation became possible in the space era, opened by the Sputnik.

1. THE SPUTNIK, POLITICS AND COMMERCE

Space exploration deeply influenced my life, although at the time of the launch of the first Sputnik I was too young to understand its significance. Looking at the publications of that time, I understand that the big excitement that time was merely its political impact during the time of the first big "cold war". The allies of the Soviet Union interpreted the Sputnik launch as a proof of the superiority of the "socialist science" as *Neues Deutschland*, the central newspaper of the United Socialist Party, ruling the (East-) German Democratic Republic of October 9th, 1957 declared (Fig. 1).

At the same time, the West was shocked about the launch of the first artificial satellite of the Earth by a Soviet intercontinental missile, but recovered soon by business as usual (Fig. 2).

The 1957 US newspaper photograph's caption was "Not to be outdone — Harriet Phydros samples a Sputnikburger which in an Atlanta café rushed onto the menu. It's garnished with Russian dressing and caviar, topped by satellite olive and cocktail hotdog". Such immediate commercial answer might have made the Soviet Sputnik challenge less scary for American citizens (e. g. Forman, https://www.theatlantic.com/technology/archive/2011/01/the-food-SPUTNIK-inspired/69733/).

The beginning space exploration deeply impressed me. I keenly followed the next steps into space: the launch of Sputnik 2 with Laika onboard, the first animal in space still in 1957. In 1959, *Lunnik-1* (later called *Luna-1*) — the first flight to the Moon and in 1961, the first man in space, Yuri Gagarin. That time Soviet engineers and technicians provided one "first" after the other. Fascinated by the furious beginning of the space era, I became fond of mathematics and physics, the sciences laying the ground for space flights. After finishing university studies and my PhD in physics, I was happy to get a chance to work on topics enabled by the space exploration.

NEUES DEUTSCHLAND
ORGAN DES ZENTRALKOMITEES DER SOZIALISTISCHEN EINHEITSPARTEI DEUTSCHLANDS

Berliner Ausgabe „Vorwärts" Berlin, Mittwoch, 9. Oktober 1957 12. (68.) Jahrgang / Nr. 239 / Einzelpreis 15 Pf

Auch am 5. Tag nach dem Start des sowjetischen Erdtrabanten:

Die Welt im Banne des Sputnik

Internationale Anerkennung der Überlegenheit der sozialistischen Wissenschaft

Warum gelang dem Sowjetvolk der große Wurf?

Bis Dienstag 2 Mill. km

Berlin (ND). Nach wie vor gilt das Interesse der Weltöffentlichkeit dem sowjetischen Erdtrabanten, der bis Dienstag nachmittag die Erde fünfzigmal umkreist und dabei eine Strecke von etwa 2 Millionen Kilometern zurückgelegt hatte. (Siehe auch S. 2)

TASS: Aufgabe erfüllt

Bonner Sternwarte: Umlaufzeit unvermindert

Auch in der DDR gesichtet

Heutiger „Fahrplan"

Mit bloßem Auge

Überall in der Welt versuchen Millionen Enthusiasten — wie hier in London — den Flug des sowjetischen Erdtrabanten zu verfolgen
Fotos: Zentralbild

Markantes Datum in der Menschheitsgeschichte

Fig. 1: Facsimile of the front page of "Neues Deutschland" as of October 9th, 1957: "International recognition of the superiority of the socialist science". Image courtesy Deutsches Historisches Museum, Bonn (https://www.hdg.de/lemo/bestand/objekt/druckgut-neues-deutschland-1957.html, downloaded 2.10.2017)

Fig. 2: A 1957 US newspaper photograph. Image courtesy *The Atlantic* (https://www.theatlantic.com/technology/archive/2011/01/the-food-SPUTNIK-inspired/69733/, downloaded 3.3.2018)

Fig. 3: Original GDR cars "Trabant" over the years (started by the P600 in 1958) which was called after the first Sputnik. Image courtesy Kira Hoffmann (https://pixabay.com/de/trabi-autos-ddr-1435369)

My other relation to the Sputnik was my first own car, the "Trabant", THE car of the (East-) German Democratic Republic (GDR) (Fig. 3). This full-plastic car, that time a world leader in design and engineering, was supposed to be sold starting 1958. A public contest looked for its name. Inspired by the Sputnik, a vast majority of voters favored "Trabant", the Slavic word for "guide" or "escort", alike the Russian "Sputnik". In different modifications, the "Trabant" was built till 1990, with waiting periods for a new car reaching 10 years. In order not to wait that long I paid for my first car, a used "Trabant", the price of a new one. Later, in 1990, the "Trabant" became famous worldwide when East Germans started to cross the border to Western Germany in large numbers in 1989 preceding the German unification — a "re-connection" of the two post-WWII Germanys in 1990.

2. MAGNETIC RECONNECTION IN THE SPACE ERA

In physics, reconnection also means some kind of unification — that of two plasmas, which this way release magnetic energy. The current understanding of reconnection is that of an universal process of efficient conversion of magnetic energy into heat and the kinetic energy of plasma flows and accelerated charged particles. In the laboratory magnetic reconnection causes disruptions of magnetically confined nuclear fusion plasmas, at the Sun — flare eruptions and coronal mass ejections (CMEs). Now we think that magnetic reconnection controls space weather phenomena in the solar system and magnetic energy release processes in the whole plasma Universe.

Thinking about magnetic reconnection started in 1946 by a conjecture of R.G. Giovanelli. He suggested as a solution of the long-lasting problem of the origin of the optical emissions during solar flares might be an excitation of atoms by magnetic discharges in the solar atmosphere, at neutral points of sunspot magnetic fields. In chapter 8 of his book *The Sun* (1953) T. G. Cowling estimated that Joule heating in the solar chromosphere during flares, however, would require very many current sheets, which all are as thin as a few meters only. In the same year J. Dungey pointed out that near magnetic neutral points plasmas could become unstable causing the compression of current sheets. There he used for the first time the word "re-connection" stating that magnetic fields might be discharged best, if they change their connections.

Based on similar topological considerations and on the assumption of oppositely directed interplanetary and Earth' magnetic fields J. Dungey suggested in 1961 that reconnection could be responsible also for geomagnetic phenomena like the aurora. After controlling the interaction of interplanetary and Earth's magnetic field at the dayside it might also control the internal dynamics of the magnetosphere at the nightside (see Fig. 4 taken from his 1961 paper). Essential is, again, the formation of current sheets and magnetic null points.

After the Sputnik launch opened the space era, the Earth's magnetosphere was in reach for direct observations. N. Ness (1965), e. g. discovered, using his magnetometer on board NASA's IMP-1 spacecraft, a finite normal magnetic field component in the direction perpendicular to the mid-plane of the geomagnetic tail — another indication that J. Dungeys topological conjectures were correct, in principle. Despite of increasing evidence for the very existence of reconnection, nevertheless, the Nobel prize winner Hannes Alfven resisted for a long time to accept that reconnection really takes place in space — in particular, because for a long time the theoretical understanding of reconnection was missing as well as any experimental proof. This has only gradually changed.

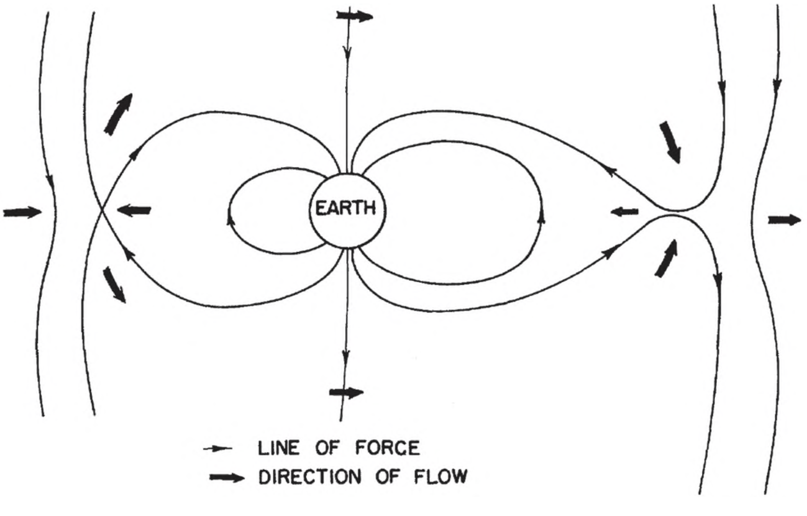

Fig. 4: Reconnection at the dayside and in the nightside of the Earth's magnetosphere in its interaction with a magnetized solar wind plasma. Image courtesy Dungey (1961)

3. SLOW RECONNECTION: SWEET AND PARKER

After topological considerations of magnetic discharges near null points, etc. were not really convincing, finally quantitative models and estimates of the efficiency of reconnection were needed. In the course of the IAU-symposium “Electromagnetic Phenomena in Cosmical Physics” in 1956 P. A. Sweet quantitatively described reconnection as the break-down of a current-sheet equilibrium between two plasmas penetrated by oppositely directed magnetic fields. His famous derivations were published in the 6th IAU proceedings (editor B. Lehnert, published by Kluwer, Dordrecht in 1958). In contrast to J. Dungey who argued mainly topologically, P. Sweet also took into account the plasma pressure away from the magnetic neutral point. He concluded that the electric field strength in a long (compared to its thickness) resistive current layer might become as large as 600 V/m. It remained unclear, whether this suffices to power flares. Eugene Parker attended the same 1956 IAU-symposium as Peter Sweet. After he listened to P. Sweet’s talk, he derived scaling relations for the rate of reconnection through long current sheets (Parker, 1957). According to the Parker-Sweet model the energy conversion, the reconnection rate, strongly depends on the electrical resistivity in a non-ideal plasma region, being indirectly proportional to the magnetic Reynolds-number. In a fluid description the electrical resistivity quantifies a dimensionless magnetic Reynolds number $Rm = Lv/\eta$, which compares the characteristic size L with resistive scale length η/v (v is a typical plasma flow velocity and η is the electrical resistivity). And the reconnection rate in the Parker-Sweet calculations appeared to be indirectly proportional to it for the velocity taken the plasma inflow velocity. Although Sweet-Parker-type magnetic reconnection provides a more efficient conversion of magnetic energy than pure magnetic diffusion, it predicts only negligibly small energy conversion rates for reconnection in the solar corona (see, e. g., Priests, Forbes, 2000). It also cannot explain the rates needed for Dungey’s model of the Earth’s magnetosphere and its interaction with the solar wind, the polar cap potential as well as other space plasma characteristics, which where meanwhile observed by the spacecraft that followed Sputnik 1. Later laboratory experiment of reconnection like of the PPPL MRX showed some agreement with a Sweet-Parker-type reconnection model, if one additionally incorporates compressibility, the downstream plasma pressure of the accelerated plasma and assumes a strong anomalously resistivity (see, e. g. Yamada et al., 2010). Nevertheless, such extended Parker-Sweet type models did not include effects of reconnection in three dimensions, viscosity and other important physical phenomena.

4. FAST RECONNECTION: PETSCHEK

A major reason of the low efficiency of Sweet-Parker reconnection is, however, the large aspect ratio of the reconnection layer in high-Reynolds-number plasmas. Hence, the plasma inflow velocity must stay small and thus the reconnection rate. In 1964 H. Petschek suggested a solution to this problem: if inflow and outflow regions of reconnection are separated by stationary slow mode shocks, the aspect ratio of a small diffusion region can become as large as of the order of unity. This emphasizes the formation of an X-point geometry rather than the double Y-point geometry of resistive Parker-Sweet reconnection (see also Syrovatskii, 1971). According to Petschek's theory, reconnection might become much more efficient than predicted by Parker and Sweet and almost independent of the actual value of the magnetic Reynolds number. Now the maximum reconnection electric field could become up to one tenth of the value of the convection electric field in the (ideal-plasma) inflow region. This is now considered to be the limit of fast reconnection, i.e. of the most efficient energy conversion by reconnection. MHD simulations with uniform resistivity showed, however, that in the case of constant resistivity immediately long, elongated current sheets develop so that the smaller Sweet-Parker reconnection rate applies, not Petschek's (Biskamp, 2000). Only in case of a sufficiently large, localized resistivity MHD allows fast Petschek-type reconnection. A strong localization of the resistivity corresponds, however, to particle mean free paths larger than the size of the non-ideal so called diffusion-layer of reconnection. Hence, direct consequences of collisionless plasmas would likely become important before Petschek reconnection becomes real. Also, unfortunately, slow mode shocks were never found, neither in space nor in the laboratory. Another caveat of Parker-Sweet- and Petschek-type reconnection models is their two-dimensionality.

5. GENERALIZED MAGNETIC RECONNECTION

In two-dimensional geometries it is possible to identify separatrices as lines, which topologically divide regions of different plasma magnetization as surfaces through magnetic null points. Magnetized plasmas flowing through such separatrices allow a merging of magnetic fluxes, a property, used by V. Vasyliunas (1975) to define reconnection (or magnetic merging) in two-dimensional geometries.

I. Axford defined reconnection in a more general way rather than V. Vasyliunas. In his opening speech of the workshop “Magnetic Reconnection in Space and Laboratory Plasmas”, held at the Los Alamos National Laboratory in October 1983, he emphasized the local breakdown of the “frozen-in-field” condition (Alfvén's theorem) of ideal, non-resistive, non-viscous plasmas as a necessary condition for magnetic reconnection. Such breakdown could result in changes of the magnetic connection. The latter means that plasma elements, once connected by magnetic field lines, become magnetically disconnected (Axford, 1984). In contrast to Vasyliunas' definition, restricted to two-dimensional topologies, Axford's applies also to the case of non-vanishing, everywhere finite magnetic fields. Schindler et al. (1988) and Hesse and Schindler (1988) showed that an essential ingredient of magnetic reconnection without the necessity of magnetic nulls is the presence of a finite electric field parallel to magnetic field in the non-ideal plasma region. In magnetic fields without nulls, e. g. in the solar corona, these regions could be, e. g. quasi-separatrix layers, which divide magnetic fields of different origin (e. g. Demoulin et al., 1996). In the limiting case of the existence of magnetic nulls, surfaces through lines connecting them, forming a topological skeleton, would be the location of reconnection in three dimensions (Maclean et al., 2009).

6. EFFICIENCY OF RECONNECTION

What is the efficiency, the rate of energy conversion by general magnetic reconnection? In what is now referred to as the "Axford conjecture" I. Axford stated that: *Magnetic reconnection cannot occur unless there is a non-zero electrical resistivity (or some other departure from ideal MHD). However, the large-scale properties of the process are governed primarily by global dynamics and boundary conditions, not by the values of the resistivity or other non-MHD effects* (Axford, 1984). This does not allow, however, a quantification of the energy conversion.

The interplay of global and local conditions for reconnection is nicely illustrated by a result of data-driven numerical simulations of coronal Bright Point (BP) magnetic fields in the solar atmosphere (see Fig. 5, from Büchner et al., 2004). The figure illustrates the change of the magnetic connection between the two photospheric endpoints of several magnetic field lines. All the field lines shown start in the photosphere, the bottom boundary of the box, on the right side from close to each other positions. At their other end the field lines are again anchored, "line-tied" in the conjugated photosphere. This is a static picture, illustrating the topology of the magnetic field. In accordance with solar observations the numerical simulation, however, moves the plasma around the closely located footpoints of the field lines. As conjectured by Axford, the boundary conditions determine the global configuration of reconnection. The dynamical change of the magnetic connectivity can take place, however, only through a region of non-ideal plasma. In the simulation the latter occurs since a finite (anomalous, see below) resistivity was switched on, assuming that plasma turbulence arises, when the current density exceeds a certain threshold. A yellow-colored iso-surface, corresponding to the plasma-physical instability threshold as derived for the solar corona by Büchner and Elkina (2006), depicts this. The efficiency of reconnection is obtained as the amount of re-connected magnetic flux per time unit (an electrical voltage). Though depending on the speed of the footpoint motion of the magnetic field lines, it depends, however, also on the resistivity in the non-ideal (some times called the diffusion-) region of reconnection. As expressed by Axford's conjecture, although non-MHD effects are essential for the occurrence of reconnection, they act locally, confined to small regions. If the location of the maximum field line divergence overlaps with region of finite resistivity (as shown in Fig. 5), the non-ideal plasma response removes constraints, which allow flow- and field re-configurations that otherwise could not occur. Of course, these newly allowed flows are again subject to the continuity and momentum balance conditions, Newton's and Maxwell's laws (cf. Vasyliunas in Gonzalez, Parker, 2016, p. 17). Further: while the large-scale properties of the flows are governed — to the first approximation — by large scale (global) phenomena, the reconnection rate is constrained by the possibility of a removal of plasma and magnetic flux in (distant) post-reconnection flows. At the same time the pre-reconnection inflow could always adjust itself to any required rate (see also Vasyliunas' discussion in Gonzalez, Parker, 2016, p. 17). But Axford's conjecture does not make any prediction about local properties of non-MHD regions, which limit the amount of magnetic flux that can be re-connected!

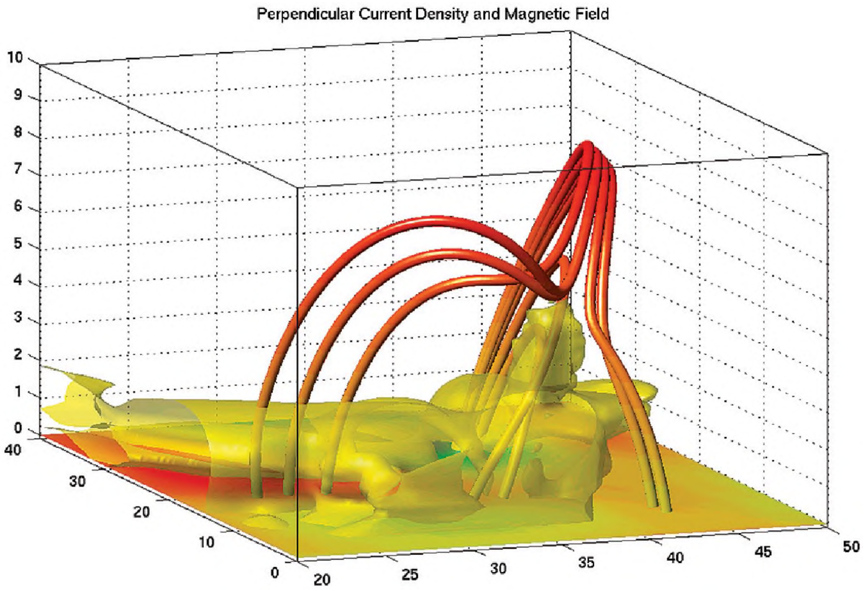

Fig. 5: Change of the magnetic connectivity between opposite photospheric footpoints of magnetic flux tubes (bottom plane) through a region of non-ideal plasma due to anomalous resistivity (yellow: iso-surface of sufficiently large current densities) below a magnetic null point in the solar corona, which coincides with an observed EUV bright point. Image courtesy Büchner et al. (2004)

Quantitatively, therefore, the reconnection rate can be determined in two ways. Locally — by integrating the electric field in the non-ideal plasma (diffusion-) region parallel to the reconnected magnetic field to obtain the voltage induced inside the non-ideal plasma region. And globally — by calculating the annihilated magnetic flux per time unit, which provides the induced voltage. In simple quasi-two-dimensional geometries both definitions reveal the same rate.

The second recipe allows obtaining a global, large-scale, macro-scale reconnection rate. For a characteristic reconnecting magnetic field B, threading a region of characteristic radius R and having and out-of-plane extent L_{ext} (each assumed uniform for simplicity) the magnetic flux processed by reconnection per time unit, via Faraday's law, is associated with an electric field E. This reconnection electric field extends over a distance L_{ext} out of the reconnection plane. The reconnection rate is usually given as a dimensionless quantity obtained by normalizing the reconnecting magnetic field B by the Alfvén speed V_A calculated for the reconnecting magnetic field B and the ambient plasma density n. The geometrical interpretation of the resulting expression is that it is a ratio with the radial distance of magnetic flux reconnected during a time unit over the distance, over which the flux tube would have been reconnected during the same time, if the inflow speed were V_A (Cassak et al., 2017).

In the local approach, the finite electric fields in the region of non-ideal plasmas determines the reconnection rate, at the very re-connection site. This approach is of particular importance for *in situ* space observations. Usually, the resulting energy conversion rate is given by the (dimensionless) reconnection-related electric field in the diffusion region. The normalization of the electric field is obtained using the macroscopic magnetic field and plasma parameters directly upstream of the dissipation region. Note that this "local" rate is not necessarily the same as the one obtained globally. Their difference depends on geometry, configurations, parameters and is not, generally, well understood, yet.

7. COLLISIONLESS RECONNECTION

In situ observations of space plasmas, as they became possible after the Sputnik, revealed that these plasmas are mostly collisionless. This means that in them direct Coulomb-scattering of electrons and ions is not very efficient.

Further, in reconnecting current sheets ions might become demagnetized at length scales shorter than the ion inertial length (c/ωci, where ωci is the ion plasma frequency). In this case the magnetic field becomes frozen into the moving electron fluid rather than into the bulk plasma flows dominated by the ions. Hence, a Hall effect of different behavior of electron and ion fluids becomes important. Its consequences is described by two-fluid descriptions, which treat electron and ion fluids separately. Since the ions can move through a wider "bottleneck" of reconnecting current sheets and because the electrons are moving much faster, two-fluid theories reveal higher reconnection rates than single-fluid treatments.

The Hall effect, though, does not provide a non-ideal plasma response. In collisionless plasmas the latter could be due to irreversible interaction of the current carrying electrons with the (micro-) turbulence, self-generated in the current sheets (see, e. g., Zelenyi, Büchner, 1988). For a derivation of the macroscopic (fluid) consequences of the resulting current breaking for reconnection it is usually considered as a macroscopic “anomalous” resistivity. Since the underlying processes are strongly non-linear, i.e. quasilinear do not apply, the anomalous resistivity has to be estimated by kinetic numerical simulation using, e. g., Vlasov-codes. This was done for the lower-hybrid drift turbulence in magnetospheric plasmas (LHD (e. g. Silin et al., 2005) and for the ion-acoustic turbulence in the solar corona (e. g., Büchner and Elkina, 2006).

Other deviations from plasma ideality collisionless reconnecting plasmas could by, e. g., a gyroviscosity (Vasyliunas, 1975), i.e. the breaking of the gyrotropy of the electron motion and the occurrence of off-diagonal elements of the electron pressure tensor (Dungey, 1989; Lyons, 1990), the pure electron inertia. The dominating process can differ in dependence on the macroscopic plasma parameters, magnetic field and plasma flow configurations. *In situ* observations in space plasmas are a most welcomed tool to address these still open questions about magnetic reconnection. But historically the investigation of reconnections started with the Sun, for which so far only remote observations were possible.

8. RECONNECTION IN THE SOLAR CORONA

The evidence for magnetic reconnection during flares, CMEs, and other phenomena in the solar atmosphere includes the determination of plasma inflows into and outflows out of reconnection regions (e. g., Innes et al., 1997), collapsing loop-like structures and eruptions (e. g., Inoue, 2018 and references therein), and other indications obtained by indirect remote optical observations. For most of the solar atmosphere large magnetic fields behind solar reconnection are either inferred by extrapolating photospheric magnetic fields or using large-Reynolds-numbers numerical simulations (see, e. g., Skala et al., 2015 and references therein). Such models revealed, e. g., structure of magnetic reconnection and connectivity change around regions of vanishing magnetic fields (cf. Fig. 5). Together with observations of, e. g., the ESA-NASA space mission SOHO the global structure and dynamics of reconnection at Sun was explored. The Japanese *Yohkoh* mission, NASA’s TRACE and RHESSI spacecraft were collecting information about many different particle-energy and electromagnetic-radiation wavelength ranges up to the hard X-rays. Direct observations of solar magnetic reconnection were gathered also starting 2012 by the High Resolution Coronal Imager of NASA’s SDO (Solar Dynamics Observatory) mission. New modes of reconnection were discovered in the very complex geometry of the solar magnetic field, both with and without three-dimensional magnetic nulls. Additional information channels for remotely investigating reconnection at the Sun are radio-observations. They revealed, e. g., cascading reconnection through elongated currents sheets trailing ejected CMEs (see, e. g., Barta et al., 2011-1, -2).

Remote observations allow estimates of the upper limits of the global, large-scale reconnection rates. The impulsive phase of a flare lasts about 100 s. Let us use solar coronal plasma parameters given by Priest and Forbes (2002). A reasonable assumption for the magnetic field strength is $B = 100$ G. The field threads flux tubes with a radius of, say, $R = 3 \cdot 10^7$ m and extend over about $L_{ext} = 10^8$ m. The corresponding absolute reconnection electric field is then, on average, $E = 3$ kV/m. Compare this to Sweets 1956/58 estimate of 0.6 kV/m (see above). With an Alfven speed of $V_A = 4 \cdot 10^6$ m/s the normalized, dimensionless reconnection rate would, finally, be $E' = 0.075$, slightly less than the magic number for the reconnection rate — 0.1 (Cassak et al., 2017).

But what are the reconnection electric fields, which accelerate plasmas and electric fields in the solar atmosphere? Despite of all past efforts this question is still open. Therefore, the investigation of solar reconnection continues, in particular, because of its relevance for the space weather in the Solar system. Methods are improved, numerical simulations and new space projects are developed. A first space mission was launched in August 2018 directly into the solar corona — NASA's *Parker Solar Probe* (PSP, formerly called *Solar Probe Plus*, SPP). The PSP will reach an unprecedented close distance to the Sun of 6 million km or 4 % of an astronomical unit (AU). ESA, on the other side, prepares the *Solar Orbiter* (SO) mission to a position 0.3 AU from the Sun, but 30° out of the ecliptic plane, to watch also the solar polar regions. The SO launch is planned for 2020 to reach its closest approaches to the Sun in the early 2020s. China decided to launch in 2022 a suite of three telescopes (ASO-S), in order to cover simultaneously the most relevant for the space weather wavelength ranges of electromagnetic radiation of the Sun. Russia prepares the launch of two *Interhelioprobe* spacecraft in the end of the 2020s.

9. SOLAR WIND RECONNECTION

Long before the PSP will be launched directly into the solar corona, but soon after the Sputnik launch the solar wind and reconnection in it became accessible to *in situ* observations by space probes. Reconnection was expected to take place, e. g., in the current sheets, which divide sectors of different (due to different sources at the Sun) magnetization of the solar wind. Using magnetic field data obtained by *Pioneer* 6, launched in 1965 on a heliocentric orbit, Burlaga (1968), indeed, observed large magnetic field rotations associated with large decreases of the field strength. The author interpreted them as first magnetic signatures of reconnection in the solar wind. In the mid-1990s additional signatures of reconnection were observed in the solar wind. Fast (Alfvénic) plasma flows where discovered in regions of bifurcated magnetic field reversals (see, e. g. Gosling, 2012 and references therein). After the discovery of CMEs and the interplanetary investigation of magnetic clouds reconnection was conjectured to take place through compressed current sheets at the leading edge of CMEs (e. g., McComas et al., 1994). Later it was shown that reconnection leads to a significant erosion of magnetic flux away from the leading (Lavraud et al., 2014) as well as at the trailing edges of magnetic clouds (Ruffenach et al., 2015).

The four CLUSTER spacecraft (see also below) reached out into the solar wind at 1 AU. Their measurements gave evidence that ion and electron heating occurs at sheets of strong solar wind currents (e. g., Osman et al., 2011). In addition to larger scale reconnection processes typical for the Sun and magnetospheres, in the turbulent solar wind smaller scale current sheets were found to reconnect.

Besides the dependence of magnetic reconnection on plasma beta there is also one on the magnetic shear (or rotation-) angle. The shear is defined as the angle between magnetic field vectors taken at two different opposite sides of the current sheet. Phan et al. (2010) investigated the dependence of reconnection on the magnetic shear (or rotation-) angles across solar wind current sheets. No magnetic reconnection takes place for very small shear angles, in strongly turbulent plasmas and magnetic field shear angles less than 100° the occurrence frequency of magnetic reconnection was found to be reduced as well, i.e. reconnection might even be suppressed.

An even more convenient place to investigate turbulent reconnection is, however, the Earth's magnetosheath, which spacecraft visited very often after the Sputnik launch.

10. TURBULENT RECONNECTION

The solar wind plasma downstream of the Earth's bow shock, but located still outside the magnetopause, i.e. outside the region of dominance of the Earth's magnetic field, is called the magnetosheath. The magnetosheath was reached by the first US-American artificial satellite of the Earth, *Pioneer 1*, launched a year after Sputnik 1 on October 11, 1958. Already these first *in situ* observations in the magnetosheath showed that its magnetic fields are strongly fluctuating (see, e. g., Sonett et al., 1960). The magnetosheath thermal plasma energy density (pressure) is of the same order as the magnetic energy density, i.e. its plasma beta is of the order of unity. And the magnetic Reynolds number is huge. Such plasmas are indeed prone to turbulence. The turbulence in the collisionless magnetosheath reaches out down to the kinetic plasma scale.

Reconnection obviously takes place in small-beta plasmas like the solar corona. In them, the magnetic energy density exceeds the thermal one. But can magnetic reconnection also act efficiently in higher-beta plasmas? Answering this question is of great importance also for astrophysical plasmas, in many of which energy equipartition holds or the plasma beta exceeds unity (see below, section 12). Can reconnection efficiently release magnetic energy in larger-beta plasmas?

The Earth's magnetosheath can be used as laboratory for studying higher-beta reconnection. After the limited-range investigation of magnetosheath phenomena by single spacecraft, multi-spacecraft spacecraft missions could finally be used to investigate quantitatively current sheets and reconnection in the turbulent magnetosheath plasma. CLUSTER was a first small-scale multi-spacecraft mission, with four spacecraft in a tetrahedron arrangement, which enabled a separation of spatial from temporal changes as the suite flies through space. So, CLUSTER revealed a first direct evidence for reconnection in the magnetosheath. Retino et al. (2007) reported about reconnection through ion-scale current sheets in the magnetosheath during the quick passage of the CLUSTER-spacecraft. The sheets were about 100 km thick. Reconnection was identified by the tangential electric field, non-zero normal magnetic field components, plasma inflows and outflows, a Hall magnetic field, the Hall electric field, and the electromagnetic energy conversion $EJ > 0$. Since the current sheet crossing was too short, the plasma speeds could be estimated only using the electric field, which CLUSTER measures only in the plane perpendicular to the spacecraft spin axis. Unfortunately, the four-second time resolution of plasma moments did not allow to study the demagnetization of the electrons and protons.

Another magnetosheath reconnection event was analyzed by Phan et al. (2007) using CLUSTER data. In their case reconnection exhaust was crossed during 15 s (about 10 ion skin depths). In addition to the reconnection signatures already reported by Retino et al. (2007), Phan et al. (2007) also identified rotational discontinuities at the exhaust boundaries and counter-streaming ion beams. They indicated a magnetic connection through the outflow region. They estimated the outflow speed using only four measured values. Unfortunately, the perpendicular to the magnetic field velocity component, i.e. the real reconnection outflow speed, was not obtained. Moreover, not all four CLUSTER spacecraft, separated by a distance of $2R_E$, observed the reconnection signatures. This could be due to the limited spatial extent or the temporary evolution of reconnection. Observations in the upstream solar wind by the ACE and WIND spacecraft recognized the same current sheet before it what observed by CLUSTER. The current sheet was still thick in the solar wind but compressed when carried to the magnetosheath until reconnection is initiated.

Simulations of the turbulent magnetosheath plasma have shown that, since it is stirred around (e.g. by fast jets), vortices, turbulence, wavefronts, magnetic islands (flux ropes), and reconnecting current sheets are generated (see, e.g., Karimabadi et al., 2014). Multi-scale interactions and structure formation occurs in the course of the dynamical evolution of the turbulent magnetosheath plasma. Plasma turbulence locally and spontaneously generates structures like current sheets. In it was suggested already some time ago based on analytical studies of ideal and resistive instabilities that MHD turbulence might develop elongated current sheet structures (Carbone et al., 1990). MHD simulations, which allow to achieve high Reynolds number, confirmed that plasma turbulence may develop into discontinuities, which were identified as ion-scale current density structures. The strongest discontinuities found in 2D MHD simulations were reconnecting current sheets (Servidio et al., 2011). Recent fully kinetic 3D simulations of collisionless plasma turbulence also suggested the development to the current structures as well, indicating that the kinetic current-sheet causes heating and dissipation (Wan et al., 2015). As in the solar wind there is also evidence that in the magnetosheath ion and electron heating occurs at current sheets (Chasapis et al., 2017) and references therein. Some of these current sheets have already been associated with reconnection.

In collisionless plasmas the main non-ideal plasma effects for reconnection take place at electron scales. This required smaller distances between the spacecraft and a high time resolution of the instruments, which became available with NASA's four MMS spacecraft launched March 13, 2015.

The MMS observations lead beyond the CLUSTER results by having a tighter constellation of spacecraft, allowing finer spatial measurements and finer temporary details, e. g., of the current sheets including the electron diffusion region. In fact, MMS provides plasma measurements at an unprecedented high time resolution. Ion and electron moments are obtained by the Fast Plasma Investigation (FPI) Instrument, e. g., at a cadence of 150 ms and 30 ms, respectively. The electric field measurements by the Electric Double Probes (EDP) instrument reaches a time resolution of 8 kHz, magnetic field observations by fluxgate (FGM) and search coil (SCM) magnetometers are fast as well.

Note the difficulty of first finding the reconnection sites in a turbulent plasma. In contrast to the magnetopause and magnetotail with well recognizable large-scale current sheets, the magnetosheath plasma contains numerous current sheets and plasma flows (potential exhausts), which might be associated with a reconnection. In order to find not suppressed in the high-beta plasma reconnection one has to look for current sheets with large magnetic shears angles. It is difficult, however, to obtain the shear angle when the current sheet crossings are not along the normal direction. In such cases, the normal direction has to be determined first. In a 3D-turbulent plasma reconnection might, however, deviate from a quasi-2D geometry (see 3D reconnection, above). So far, the authors of only two studies overcame these difficulties for selected cases.

The first MMS observation of magnetosheath reconnection was published by Yordanova et al. (2016). These authors analyzed an event that occurred in the compressed turbulent magnetosheath, associated with a high-density compressional region at the leading edge of a high-speed solar wind stream. MMS observed strong, quick enhancements of currents at the electron scales, electron heating, fast electron jets, narrow electric field structures and electron pressure anisotropy. The electron inertial length in this magnetosheath region was only 0.7 km, while the distance between the spacecraft was 10 km. All four spacecraft observed the current structures during less than two seconds. While the electron and ion data indicated that the spacecraft did not enter the electron diffusion region itself, the spacecraft encountered the ion diffusion region near an X line. So the ions were demagnetized and organized in a hot and a cold population. Plasma, field, and particle signatures were considered as imprints of the crossing of a reconnection separatrix, although with different signatures as exhaust boundary obtained using CLUSTER observations by Phan et al. (2007).

In a second study, Vörös et al., (2017) presented a study of reconnection signatures in the turbulent magnetosheath at fluid- and kinetic-scales. They found signatures of ongoing reconnection in the high-resolution MMS data using spacecraft observations during crossings of the reconnection in- and outflows regions as well as inside the ion diffusion region. Inside the reconnection outflows D-shape ion distributions were found. Inside the diffusion region mixed ion populations, crescent-like velocity distributions and accelerated ions were observed. One of the four MMS spacecraft skimmed the outer part of the electron diffusion region allowing the observation of parallel electric fields, energy dissipation and — conversion, electron pressure tensor a-gyrotropy, electron temperature anisotropy, electron acceleration and other consequences of kinetic reconnection.

These first detailed and high-resolution investigations of reconnection through thin current sheets in the turbulent magnetosheath have significant implications for the understanding of reconnection in turbulent astrophysical plasmas, which are not accessible for *in situ* investigations. Before returning to this issue let us first shortly mention the achievements reached about laminar, non-turbulent reconnection by spacecraft observations inside the Earth's magnetosphere.

11. MAGNETOSPHERIC RECONNECTION

Obviously, in the space era the best available and most used natural laboratory for *in situ* investigations of magnetic reconnection is near Earth's magnetosphere. Over the six decades, since the Sputnik was launched, many different reconnection signatures have been found mainly at the boundary of the Earth's magnetosphere, the magnetopause and in the magnetotail. A common reconnection-related phenomenon in the Earth's magnetosphere are so-called substorms. It is widely believed the that substorms are closely related to magnetic energy release by reconnection in the geotail. Combining observations of the Soviet INTERBALL-Tail probe and the Japanese GEOTAIL spacecraft it became possible, e.g., to trace down the propagation of a reconnection pulse after the onset of substorms (Petrukovich et al., 1998). The THEMIS (Time History of Events and Macroscale Interactions during Substorms) multi-spacecraft mission verified the relation of reconnection and the onset of magnetospheric substorms. THEMIS space probes, positioned at approximately one-third the distance to the Moon by observing a reconnection event 96 seconds prior to an auroral intensification showed that reconnection triggered a substorms (Angelopoulos et al., 2008).

The big open question is, however, still the quantification of reconnection, its efficiency. After the first surveys of the Earth's magnetosphere by spacecraft it became first possible to estimate an upper limit for the global reconnection rate over the whole magnetotail. Taking a typical time scale of substorm expansions of approximately 30 min, a typical magnetotail (lobe-) magnetic field is $B = 20$ nT and a distance from the plasma sheet to the magnetopause $R = 15R_E$ one obtains for a cross-tail extent $L_{ext} = 30R_E$ (R_E = one Earth's radius) a global cross-tail electric potential of 200 kV. For $V_A = 10^6$ m/s (for a lobe density of 0.1 cm^{-3}) the normalized average global reconnection electric field (reconnection rate) is therefore $E' = 0.053$ (Cassak et al., 2017).

Did spacecraft observations confirm such reconnection electric fields locally as well? In the collisionless plasmas of the magnetosphere, reconnection electric fields in non-ideal regions of reconnection must be balanced at kinetic scales. This could be due to, e. g., the non-gyrotropy of the electrons that causes off-diagonal elements of the electron pressure tensor, the electron inertia may play a role or the interaction of electrons with self-generated plasma-microturbulence. Lower-hybrid turbulence was found, e. g., by the INTERBALL mission (see, e. g., Klimov et al., 1986). This could explain anomalous resistivity. The CLUSTER mission allowed to determine for the first time the properties of ion-scale current sheets in the Earth's magnetosphere, mainly also for the dayside magnetopause and in the magnetotail. CLUSTER has unambiguously disclosed reconnection near the polar cusps. i.e. reconnection of Earth's tail magnetic fields with northward Interplanetary Magnetic Fields (IMF). The latter causes sunward convection in the Earth's ionosphere. Dayside reconnection leads to the interconnection of the Earth's magnetic field with that of the solar wind (IMF), the consequent particle and energy entry into the Earth's magnetosphere and tail reconnection that allows the release of energy stored in the tail to inject particles deep into the magnetosphere and causing auroral substorms — all at ion scales.

CLUSTER allowed to investigate, e.g., the ion-scale-thin current sheets of the Earth's magnetopause (e. g., Panov et al. 2006-1 and references therein). The intensity of the magnetopause turbulence can explain the thickness of the magnetopause due to micro-turbulent transport (e. g., Panov et al., 2006-2). More magnetopause-reconnection-related discoveries of spacecraft until the CLUSTER era are reviewed by Paschmann et al. (2013) findings about reconnection in the Earth magnetotail were reviewed, e. g., by Nakamura et al. (2006).

As for the magnetosheath plasma, the ongoing MMS mission with its high spatial and temporal resolution allows also a better investigation of electron scale magnetic reconnection. Up until now this work concentrated on magnetopause reconnection (e. g., Burch et al., 2016), while now *in situ* investigation of electron scale magnetotail reconnection processes by MMS has started.

12. RECONNECTION AT OTHER PLANETS

Already in 1983, much before the first spacecraft had reached the Jupiter, Vasyliunas (1983) predicted the specifics of strangely formed Jovian reconnection X-line due to Jupiter's fast rotation. Years later these predictions were verified by *in situ* measurements of the *Galileo* mission. The *Galileo* spacecraft explored Jupiter's magnetotail along a low-inclination orbit, where it detected the signatures of tail reconnection. Looking for dipolarizations, strong northward B_y excursions, tailward-moving plasmoids and planetward-moving plasmoid, Ge et al. (2010) inferred that most probably magnetic reconnection is located in the Jovian magnetotail near 02:00 LT at a planetocentric distance of 80 Jovian radii. For the Mercury Büchner et al. (2017) obtained an efficient electron acceleration by turbulent magnetic reconnection, to be verified by the ESA-JAXA mission *BepiColombo* in a few years, after its launch in 2018 and arrival at the Mercury in 2025. Hence, reconnection can play a role not only at planets with a strong internal magnetic field, but as well as at comets and planets with an induced magnetotails like Venus, which reconnection can disrupt.

13. ASTROPHYSICAL RECONNECTION

Efficient reconnection is expected in all low-beta plasmas of the Universe, in stellar coronae, magnetospheres of compact objects, accretion disks coronae or the lobes of radio jets out of active galactic nuclei.

Very common for astrophysical plasmas are, however, higher plasma beta of the order of unity or even above. Not only the thermal but also the kinetic energy of moving astrophysical plasmas might exceed the magnetic energy density.

High plasma-beta are typical for the interior of stars and compact objects, for parts of accretion disks, for supernova remnants and the Inter-Stellar Medium (ISM). The plasma-beta of the Inter-Cluster-Medium (ICM) is, perhaps, much larger than unity. The properties of those plasmas remind rather those of the Earth's magnetosheath, i.e. they are, perhaps, highly turbulent so that a large number of current sheets is presumably formed which reconnect at plasma scales.

Although the detailed properties of the ISM are not well known, yet, numerical simulations reveal the plasma density and magnetic field strength in the ISM (see Fig. 6 taken from de Avillez and Breitschwerdt, 2005) for which the plasma beta is of the order of unity. Note that the plasma of star-forming galaxies consists of a multi-component (-phase), highly compressible magnetized plasma, of high-energy particles (cosmic rays), electromagnetic radiation, and dust. Its dynamical evolution is driven by energy input and loss on vastly different scales as well as by supersonic turbulence. The primary sources of this turbulence are supernova explosions at large injection scales (~100 pc). They generate a turbulence cascade of fluctuations spanning more than 12 orders of magnitude with a Kolmogorov scaling, called "The Great Power Law In the Sky". The turbulence involves, however, magnetic energy conversion into plasma bulk motion, heating, and particle acceleration, perhaps by means of reconnection, modifying the topology of the magnetic field on fast time scales (e.g. Zweibel and Yamada, 2009). Hence, although small-scale observations of the ISM are not available, the importance of reconnection for the ISM cannot be overestimated. The magnetic energy of the ISM, comparable to the thermal and kinetic energies of the photon fields and the cosmic rays is, finally, dissipated at the end of the turbulence-cascade. The corresponding magnetic fluxes are finally dissipated at the end of the turbulence-cascade. There reconnection contributes to heating and particle acceleration. Since the ISM plasma is dilute, the turbulence is collisionless, favoring small-scale CS formation and magnetic reconnection at small scales as it is known from the investigation of solar wind and magnetosheath around the Earth. The investigation of the consequences of CS reconnection for the ISM has been started, however, only recently. Assuming dissipation due to Ohmic resistivity the heating was obtained, which is needed to ionize the gas in the galactic halo to the observable levels, but without detailing the energization processes (e.g., Hoffmann et al., 2012). The investigation of the influence of microphysical kinetic phenomena on magnetic reconnection, dissipation and heating in the ISM has not even been started, yet.

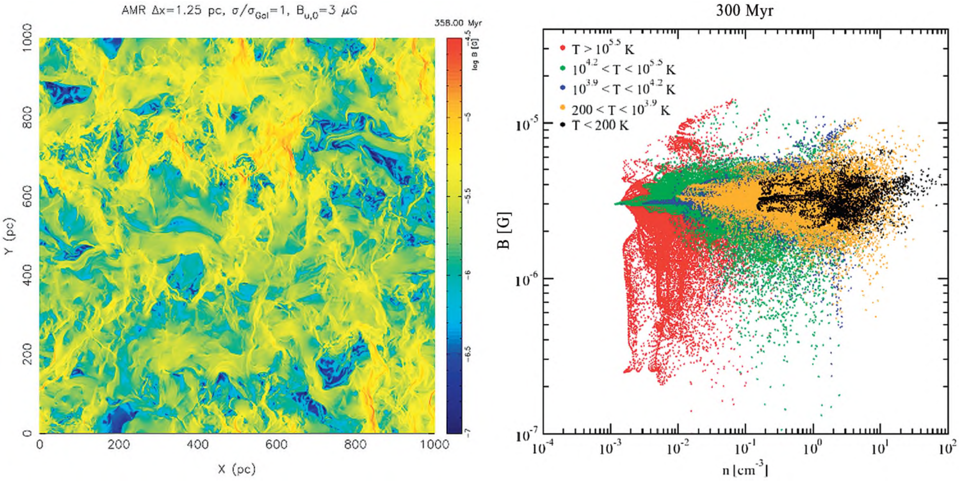

Fig. 6: Left panel: spatial structure of the magnetic field in the turbulent ISM, 2D cut through the 3D MHD-simulated plasma and field evolution. Right panel: scatter plot of magnetic field and plasma density. Image courtesy de Avillez and Breitschwerdt (2005)

CONCLUSION

More than 10 years before the Sputnik was launched a notion of eruptive magnetic energy release — reconnection — was conjectured for our star, the Sun. But only after the Sputnik opened the way for *in situ* space observations it became possible to look for direct evidence of reconnection. Meanwhile space observations have verified the very existence of reconnection. Nevertheless, despite of its importance for the space weather and, presumably, many other astrophysical objects as well as hot laboratory plasmas, however, the physical nature of reconnection in collisionless plasmas is still puzzling, a prediction of its breakout and efficiency for a given macroscopic situation is still impossible. Open are the nature of dissipation and electric fields heating the plasmas and accelerating particles, the efficiency of reconnection in the real, three-dimensional world, the role of turbulence. Currently ongoing multispacecraft *in situ* observations and coming new experiments combined with advanced numerical simulations will, hopefully, help us to better understand the role of reconnection in the plasma Universe.

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SPACE AND PLANETARY MAGNETISM: FROM 1958 TO THE PRESENT

While terrestrial magnetism had its roots centuries ago, when it was realized that the Earth is a magnet, the soon-to-be space faring nations were caught off guard without the techniques and instrumentation needed to explore the magnetism of space. Quickly, scientists and engineers sprang to attention, at first adapting terrestrial instruments. Some of these, notably by S. S. Dolginov and by C. P. Sonnett, involved mechanically-driven, moving sensors, but as time evolved, new generations of magnetometers arose that were simpler and more effective, including the use of a gradiometer configuration to identify the magnetic fields arising from the space platform and to remove them dynamically. Modern instruments are small and robust and have low impact on spacecraft design. Below we review why we explore magnetism in space and how it has been approached on different missions. We cover the early exploration of the Earth's magnetic field, the lunar magnetism program, and our later exploration of the magnetic fields at Venus, Mars, Mercury, Jupiter, Saturn, Uranus, Neptune, and now the asteroid belt.

1. MAGNETIC FIELDS IN SPACE

The universe is pervaded by magnetic fields; they are everywhere. While the inhabitants of this planet now do not use them as frequently for navigation and orientation as they did in those centuries in which the Earth was being explored with sailing ships, they are still important. Magnetic fields penetrate planet interiors and tell us about their internal processes and structure. They also shield the planet from stellar winds and energetic particle outbursts. Magnetic fields can be generated deep in planetary interiors while influencing the regions well above the planet's surface. They can be generated in stellar interiors, notably our own. While the Earth's magnetic field changes slowly, stellar magnetic fields are quite dynamic and produce high fluxes of energetic charged particles that can be harmful to both living creatures and their technological devices. The Earth's magnetic field, in contrast, is a shield that, with the Earth's atmosphere, helps protect the Earth from these energetic charged particles. Thus exploring planetary magnetic fields is intellectually stimulating, but studying the Sun's field and its surrounding interplanetary magnetic field is mandatory. Today space weather is an important component of the natural environment in which we live that requires constant vigilance.

When the space age began, magnetic fields were one of the first geophysical quantities measured, even though they are not the easiest parameter to measure from a spacecraft. Spacecraft are made of materials that may carry magnetic fields, and there are electrical circuits that carry currents. Thus there is a need to separate the spacecraft's magnetic field from that of the environment surrounding the spacecraft. Fortunately early space experimenters stepped up to the challenge and magnetic fields have been studied around the Earth, on the Moon, at the planets and throughout interplanetary space.

2. THE BEGINNING OF THE EXPLORATION OF THE EARTH'S MAGNETIC ENVIRONMENT

The exploration of space began with Sputnik 1 on 4 October 1957, carrying a transmitter that Konstantin Gringauz [personal communication, 1976] had chosen to operate in the HAM amateur radio band so that the entire world could share in this new adventure. It was not long thereafter, on 15 May 1958, when Sputnik 3 was launched carrying S. S. Dolginov's magnetometer with a self-orienting saturable core magnetometer [Dolginov et al., 1960]. This was a very ambitious investigation that was later followed by the development of magnetometers with fixed triaxial saturable cores that measured the components of the magnetic field. We now use descendants of these in most of our planetary and interplanetary exploration. For several years before saturable cores were available, search coil magnetometers were used on spinning spacecraft to measure two of the three components. One such investigation was the search coil magnetometer on *Pioneer 5*, which carried it into deep interplanetary space inside 1 AU where it saw a 'steady' (about 5 nT) field [Coleman et al., 1960]. For most purposes, all three components of the magnetic field are needed.

On 16 August 1961, *Explorer 12* became the first mission to attempt the three-axis saturable core measurement in the Earth's magnetosphere, out to $13.2R_E$ geocentric distance. This trajectory took the spacecraft out of the magnetosphere proper and into the shocked solar wind and occasionally the unshocked solar wind [Cahill, Amazeen, 1963]. The bow shock itself was not detected until 1965, with the spinning search coil magnetometer on the first orbiting Geophysical Observatory [Holzer et al., 1965]. We will return to the Earth's magnetosphere later to prepare us for the discoveries at the planets, but the next chapter in our exploration involves our closest neighbor in space, the Moon.

3. TO THE MOON

Mankind had realized for a long time that the Moon was an airless body trapped in orbit about the Earth and carried around the Sun by the Earth in its annual journey. Its proximity had encouraged science fiction writers throughout the early part of the 20th century to describe trips to the Moon. Finally in the second half of the 20th century, it became possible to fly to the Moon, and various Moon races began. *Luna-1* carried a saturable core magnetometer on 2 January 1959, past the Moon, and reported no magnetic field as did *Luna-2* on 12 September 1959, that impacted the Moon. To properly characterize the magnetic field of a planetary body with a possibly weak field, it is necessary to orbit it, and this finally occurred on 31 March 1966, with the injection of *Luna-10* into orbit around the Moon. *Luna-10* reported at most the possible existence of a very weak magnetic field.

It was not until 19 July 1967, that the US entered the competition with the *Explorer 35* mission to explore the lunar magnetic field [Colburn et al., 1967]. The magnetometer, provided by C. P. Sonett, had 3 saturable cores and a flipper mechanism that rotated a sensor from the spin plane to along the spin axis, so it made measurements with quite accurate zero levels, but from lunar orbit *Explorer 35* could infer only that there were weak magnetic fields on the lunar surface. Its six-year lifetime, until 24 June 1973, allowed an estimate of those weak fields because the solar wind was deflected when the weak fields were at the lunar terminators.

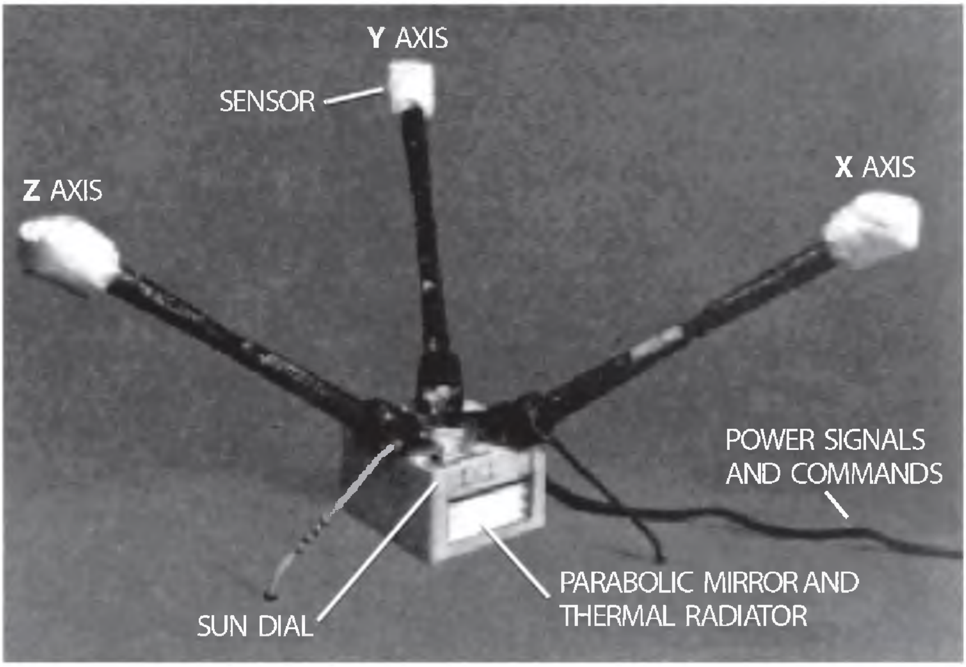

Fig. 1: Lunar surface magnetometer
[Dyal et al., 1970]

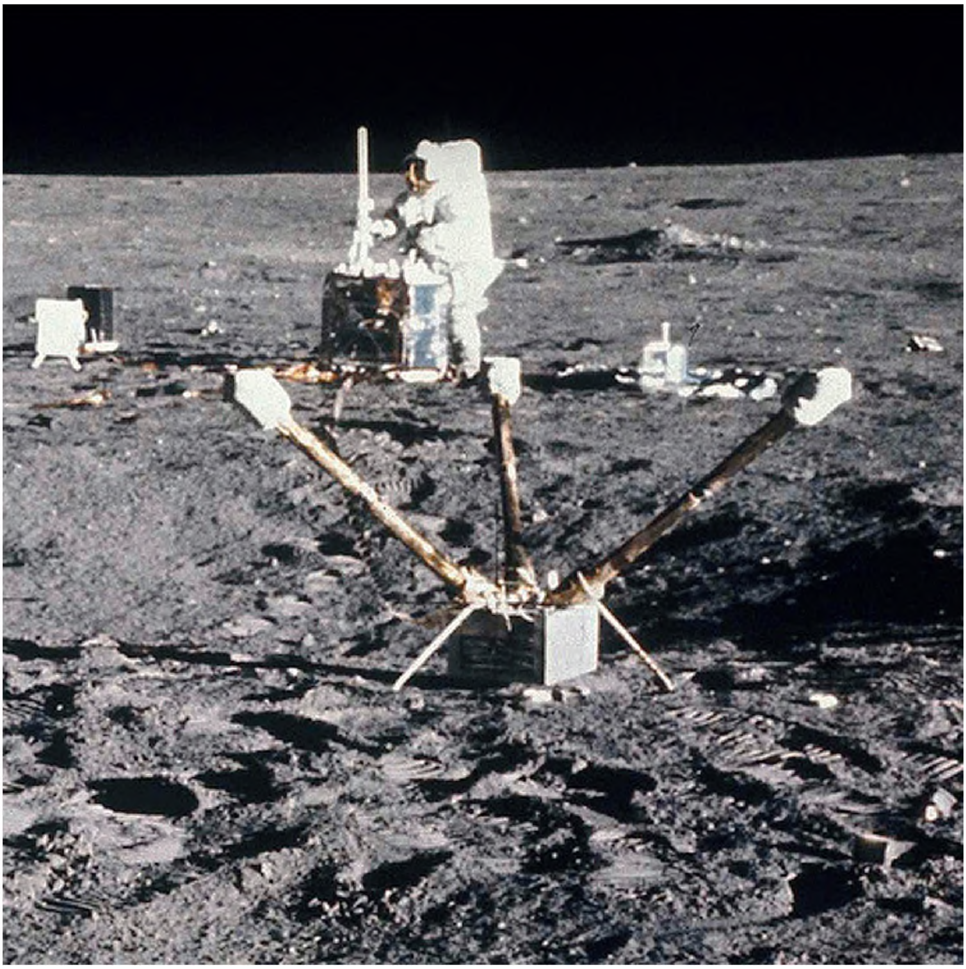

Fig. 2: The *Apollo 12* lunar surface magnetometer deployed on the moon in the Ocean of Storms [Dyal et al., 1970]

It was left to the *Apollo* program to descend to the lunar surface with another complicated mechanical magnetometer system designed by C.P. Sonett and confirm the lunar surface was magnetized. On 9 November 1969, the *Apollo 12* mission delivered the Sonett's ALSEP magnetometer to the lunar surface where it measured magnetic fields of about 36 nT in strength [Dyal et al., 1970]. This was followed by an ALSEP magnetometer on *Apollo 15* and *16* and a portable magnetometer on *Apollo 14* and *16*. These found magnetic fields as high as 103 nT in Fra Mauro (*Apollo 14*) and as low as 6 nT at the *Apollo 15* Hadley site. The *Apollo 16* magnetometers covered a baseline of 7.1 km at Descartes with fields from 112 to 327 nT [Dyal et al., 1974]. *Apollo 15* and *16* also carried magnetometers that were released from the orbiting command module on a small spacecraft about the size of a large loaf of bread, the cubesat of its day. These spacecraft allowed the mapping of the magnetic field from orbit over a portion of the lunar surface [Russell et al., 1975]. This mapping was later completed by the US *Lunar Prospector* mission [Hubbard et al., 1998] and the Japanese *Kaguya* mission [Kato et al., 2010].

Magnetometers can also be used to electromagnetically sound the interior. The terrestrial planets and some asteroids have iron cores that are highly electrically conducting. When the Moon was behind the Earth, it passed through the long steady magnetic tail of the Earth. On the time scale for passage through the tail, the magnetic field was excluded from the Moon's iron core [Russell et al., 1981]. The estimated core radius of 400 km was not confirmed until many decades later, when the seismic data were carefully analyzed with modern techniques.

4. THE EARTH'S MAGNETOSPHERE

The *Explorer* series of spacecraft were, for many years, the series of spacecraft used to study the Earth and the region around the Earth. The *Interplanetary Monitoring Platform* (IMP) series of spacecraft [Watts, 1971] (IMP1 to IMP8) were part of the *Explorer* series and very helpful in exploring the boundaries of the magnetosphere, the magnetopause where the Earth's magnetic field ended, and the bow shock where the supersonic solar wind was decelerated and deflected. However, these small spinning spacecraft did not support instruments that required pointed observations, so the Orbiting Geophysical Observatories (Scull and Ludwig, 1962) were developed and launched into highly elliptical orbits (OGO-1, -3, -5), and low-altitude polar orbit (OGO-2, -4, -6) with a launch each year from 1964 to 1969. None of the first 3 launches worked as planned, but each new launch provided a better platform than the previous until good observations were obtained. OGO-5 showed that the magnetosphere was affected not just by the flowing (dynamic) pressure of the solar wind plasma, but also by the north-south component of the interplanetary magnetic field. Further, it found that the mysterious behavior of aurora (northern and southern lights), that are dramatically activated in what became known as substorms, were associated with storage and release of magnetic energy from the Earth's magnetic tail [cf. Russell, McPherron, 1973].

This mission was followed by the three-spacecraft ESA-USA mission, the International Sun-Earth Explorers with ISEE 1 and 2 in the same highly elliptical, low-inclination Earth orbit with variable separation and ISEE-3 around the L-1 libration point over $200R_E$ closer to the Sun [Russell, 1976]. In the early 1990's, Japan and the USA launched the *Global Geospace* mission to the magnetotail, middle magnetosphere and solar wind [Russell, 1995]. These were followed by other increasingly sophisticated multispacecraft missions to the outer magnetosphere. In 2000, ESA launched the four-spacecraft CLUSTER mission into a closely spaced tetrahedron to study the high-latitude polar cusp where the solar wind plasma penetrates to the ionosphere [Escoubet et al., 1997]. In 2007, the USA launched the 5-spacecraft THEMIS probes that were each maneuverable over a wide range and eventually separated into a lunar-orbiting pair and a magnetospheric triad [Burch and Angelopoulos, 2008]. In 2012, the USA launched the dual-satellite *Van Allen Probes* to study the radiation belts, and in 2015, the four-spacecraft tightly grouped *Magnetospheric Multiscale* (MMS) mission to study magnetic reconnection. While magnetic fields were important on all the magnetospheric missions, they were even more so on the MMS mission that carried 8 fluxgate magnetometers and four search coil magnetometers to measure magnetic fields to an accuracy of 0.1 nT and a frequency of 8000 Hz [Burch and Torbert, 2016].

5. VENUS

America and the Soviet Union began the race to Venus in the early 1960's, and the least ambitious program arrived first with the *Mariner 2* flyby probe arriving on 14 December 1962, carrying two radiometers, a micrometeorite sensor, a solar wind plasma sensor, a charged particle sensor, and a magnetometer. The magnetometer saw no planetary magnetic field during the flyby, putting an upper limit on the Venus magnetic moment of 0.1 of the terrestrial moment [Smith et al., 1963]. The larger *Venera* spacecraft were designed as atmospheric probes and later landers. *Venera-3* was the first spacecraft to enter Venus' atmosphere on 18 October 1967. *Mariner 5* flew by the next day and, like *Mariner 2*, detected no Venus magnetic field [Bridge et al., 1967].

The detailed exploration of the planet began in October 1975, when both a lander and an orbiter launched on a single Russian rocket arrived at Venus. The magnetometer on the orbiter mapped the solar wind interaction but did not report a planetary magnetic field. *Venera-10* arrived shortly after *Venera-9*. It, too, saw the solar wind interaction but did not detect a planetary magnetic field. *Venera-11* to *-14* also carried magnetometers but did not try to orbit Venus.

The first American orbital mission to Venus was the *Pioneer Venus* Orbiter arriving on 4 December 1978, carrying a magnetometer and a wide complement of particles and field instruments [JGR, 1980]. Its orbit carried it as low as approximately 150 km for part of the time in orbit about Venus, allowing a quite stringent upper limit to be placed on the Venus magnetic moment [Phillips, Russell, 1987]. The lack of an active dynamo like that of the Earth has been attributed to the weak heat flow in the hot, thick, dry Venus crust. A dynamo, like a heat-engine, requires a transfer of thermal energy, and Venus' thick dry crust should not transfer as much heat from the core as the Earth's wet crust. *Venus Express* arrived on 9 November 2005, entered a 24-hour orbit complementary to that of *Pioneer Venus*, and also failed to find evidence for an intrinsic magnetic field. The *Venus Express* magnetometer was a very successful gradiometer design [Zhang et al., 2006] that removed the spacecraft magnetic field so well that even the ELF signals from lightning could be detected while the magnetized reaction wheels were spinning [Russell et al., 2013].

6. MARS

The first successful Mars mission was the *Mariner 4* mission that flew by Mars on 14 July 1965. It carried a magnetometer and detected the solar wind interaction, but no unambiguous intrinsic magnetic field [Smith, 1969]. The Russian *Mars-2* and *Mars-3* missions were inserted into Mars orbits on 27 November and 2 December 1971. Both carried magnetometers and definitely detected the solar wind interaction signature, but evidence for an intrinsic magnetic field was scant. *Mars-5* successfully entered orbit on 12 February 1974, and completed 22 orbits. Again, evidence for a solar wind interaction was clear, but no clear evidence for an intrinsic field was obtained. The Russian *Phobos-2* mission was successfully inserted into Mars orbit on January 29, 1989, and slowly nudged to a rendezvous with the moon Phobos. The mission obtained data close to Phobos, but was not able to unambiguously measure a Mars or Phobos intrinsic field. However, the later-discovered martian crustal magnetic fields probably did contribute to the Phobos measurements.

Thirty-two years after their first magnetic measurements on *Mars-4*, the US once again flew magnetometers on the *Mars Global Surveyor*, arriving on 12 September 1997, but could not begin orbital operations until March 1999. Nevertheless, the initial low-altitude data immediately revealed a strong crustal magnetic field in some regions of the planet [Acuna et al., 1998]. The most recent mission to Mars, the American MAVEN orbiter mission, carries a magnetometer used mainly in support of other payload measurements [Connerney et al., 2015]. No lander or rover to Mars has carried a magnetometer. Currently, the US Mars lander *InSight* is scheduled to carry a fluxgate magnetometer to the surface.

7. MERCURY

Only two Mercury missions have thus far been attempted: the American *Mariner 10* multiple-fly-by mission in 1974 and 1975 [Ness et al., 1975], and the American MESSENGER mission that was inserted into orbit on 30 April 2015 [Solomon et al., 2007]. *Mariner 10* found clear evidence for an intrinsic magnetic field with a measurable offset of the magnetic moment. MESSENGER confirmed these conclusions, especially the surprise that Mercury had a dipole offset 484 km northward along the rotation axis, and tilted less than 3 degrees from the rotation axis and a magnetic moment of $2.8 \cdot 10^{12}$ Tm^3 [Anderson et al., 2011].

8. ASTEROIDS

The *Dawn* mission had been designed to measure the magnetic fields of Vesta and Ceres, but NASA dropped the magnetic investigation during implementation. Even with no magnetometer, the orbital nature of the mission enables limits to be placed on the magnetic moments using the energetic particle detectors associated with the GRaND gamma-ray and neutron detector. A magnetic moment of $6{\cdot}10^8$ Tm^3 would be sufficient to stand off the average solar wind pressure at Vesta and generate "Fermi" electrons that would be detected on the spacecraft at orbital altitude above Vesta. Since no such electrons were seen at Vesta, the upper limit on the vestan moment is about 10^9 Tm^3. Fermi-accelerated electrons were detected at Ceres [Russell et al., 2016], but these occurred only when a Solar Energetic Proton event had occurred and disappeared after a week. Hence these have been interpreted as a comet-like interaction with the asteroid with the water supplied by subliming ice [see also, Villarreal et al., 2017]. No evidence of a cerean magnetic moment has been found except during and immediately after a solar energetic proton events, and the limit on the intrinsic magnetic moment of Ceres is $3{\cdot}10^9$ Tm^3.

Galileo flew by a small asteroid Gaspra, in 1991, and a signature in the magnetic field was interpreted as an intrinsic field deflection of the solar wind [Kivelson et al., 1993]. However, based on the expected signature of such an interaction from hybrid simulations, Blanco-Cano et al. [2003] found that such an interpretation was questionable, as Gaspra is too small to produce the postulated whistler-mode wave.

9. THE OUTER PLANETS AND THEIR SATELLITES

The exploration of the outer Solar system has been much simpler than the exploration of Mars. To date, there have been five fly-by missions with *Pioneer 10* flying by Jupiter on 4 December 1973; *Pioneer 11* flying by Jupiter on 3 December 1974; and Saturn on *Voyager 1* flying by Jupiter on 5 March 1979, and Saturn on 12 November 1980. *Voyager 2* flew by Jupiter on 9 July 1979; Saturn on 25 August 1981; Uranus on 24 January 1986; and Neptune on 25 August 1989. *Ulysses* flew by Jupiter on 8 February 1992. The *Pioneer 10* and *11* missions each carried at least a Vector Helium Magnetometer [Smith et al., 1974]. The *Voyager* mission carried dual fluxgate magnetometers [Behannon et al., 1978].

Only Jupiter and Saturn have been studied with orbiters. *Galileo* carried a fluxgate magnetometer into Jupiter orbit and also flew by Io, Europa, Ganymede, and Callisto [Kivelson et al., 1992]. Io, Europa, and Ganymede have sufficient atmospheres that they do affect the interaction of the rotating magnetosphere with these moons. The volcanic moon Io has sufficient atmosphere that becomes ionized in the strong radiation belt of Jupiter that it forms a dense plasma disk that drifts outward and powers a circulation in the magnetosphere that has geomagnetic activity driven by internal processes unlike the Earth's externally driven processes. The moon Ganymede has an intrinsic field. It is possible that this field is an amplification of the jovian field since it is in the same direction as such an amplified field would be [cf. Kivelson et al., 2004].

The planetary magnetic field has been now studied additionally with the *Juno* spacecraft that, in theory, should be quite accurate because of its low periapsis altitude, but the analysis is still at a preliminary stage at this writing [Connerney et al., 2017]. The magnetic dipole moment is $1.55{\cdot}10^{20}$ Tm^3 based on *Galileo* data with a tilt of the dipole axis of 9.7°. An important parameter for gas giants is their rotation rate that may not be obtainable from optical measurements that are affected by winds. The dipole longitude of Jupiter's magnetic dipole tilt axis had drifted 2° since the flybys of *Pioneer* and *Voyager*, suggesting that the official rotation rate may be incorrect [Yu, Russell, 2009]. This drift is illustrated in Fig. 3.

The *Cassini* mission arrived at Saturn on 1 July 2004, and continued measuring Saturn's magnetic field until 15 September 2017. It found an extremely symmetric magnetic field with no discernable tilt of the magnetic axis from the rotation axis. Such an alignment makes it impossible to measure the rotation period of Saturn from its magnetic field. It also is very much a surprise, as many have assumed that the Cowling theorem required some asymmetry

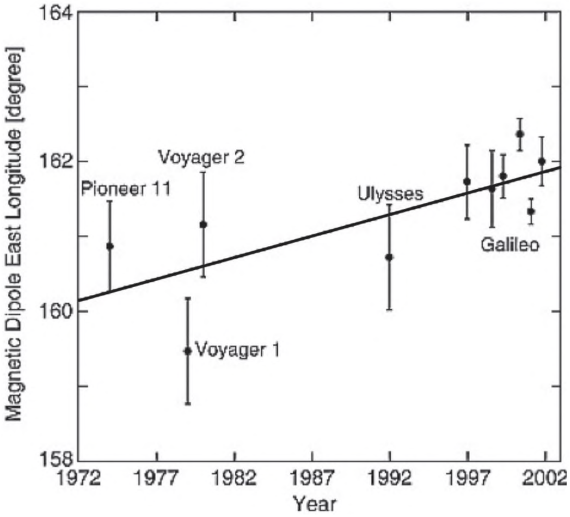

Fig. 3: Longitude of the dipole axis of Jupiter with the current rotation rate of Jupiter, indicating that the spin period based on earlier radio measurements needs adjusting [Yu, Russell, 2009]

to allow the magnetic field to be generated by a dynamo [Russell, Dougherty, 2010].

Only the *Voyager 2* flybys of Uranus and Neptune have given us measurements at these planets. Both are less dipolar and more multipolar than Earth, but the fields seem clearly dynamo-driven [Connerney et al., 1987, 1991].

10. COMETARY MISSIONS

The least massive solar system bodies with significant magnetospheres and solar wind interactions are comets that have reservoirs of frozen gases that sublimate when the comet enters the inner heliosphere. The first cometary fly-by mission was the International Cometary Explorer, a repurposed solar wind monitor, nee ISEE-3, that was redirected from Earth-Sun orbit to fly by comet Giacobini-Zinner in 1984 [Smith et al., 1986]. The spacecraft flew through the tail 7800 km downstream from the nucleus and found an induced tail about 8000 km wide with a strength of up to 60 nT.

The most ambitious exploration of a single comet was mounted by the flotilla of spacecraft that flew to intercept comet Halley in 1985. This consisted of the Russian *Vega-1* and *-2* spacecraft [Sagdeev et al., 1986], the Japanese *Sakigake* and *Suisei* spacecraft [Itoh, Mirao, 1986], and the European *Giotto* mission [Reinhard, 1987]. The *Suisei* mission monitored the upstream solar wind conditions as it and *Sakigake* flew by Halley. *Vega-1* and *-2* flew through Halley's coma and the *Giotto* took close-up pictures inside the coma. The *Deep Impact* mission carried an impactor to comet 9P Tempel 1 [A'Hearn et al., 2005]. Its goal was to learn about the nucleus and not about the solar wind interaction. In particular, the crater size was of high importance, but this proved difficult to determine.

The most recent cometary mission was the *Rosetta* mission to 67P/Churyumov-Gerasimenko. This mission included the *Philae* lander with a magnetometer and other instruments, and a well-instrumented comet orbiter [Russell et al., 2007]. The lander did not land as planned, but did reveal that the comet was not magnetized. It was also determined through isotopic studies that the water on Earth did not arrive from comets like 67P/C-G.

11. THE FUTURE OF SOLAR SYSTEM MAGNETIC OBSERVATIONS

The exploration of the magnetic fields of the Earth and planets and the regions in between has been extremely rewarding, but the exploration is not complete. The planetary dynamos of Uranus and Neptune have not been explored to date. To do so requires planetary orbiters with low periapsis. The interaction of Pluto with its solar wind environment was not attempted despite

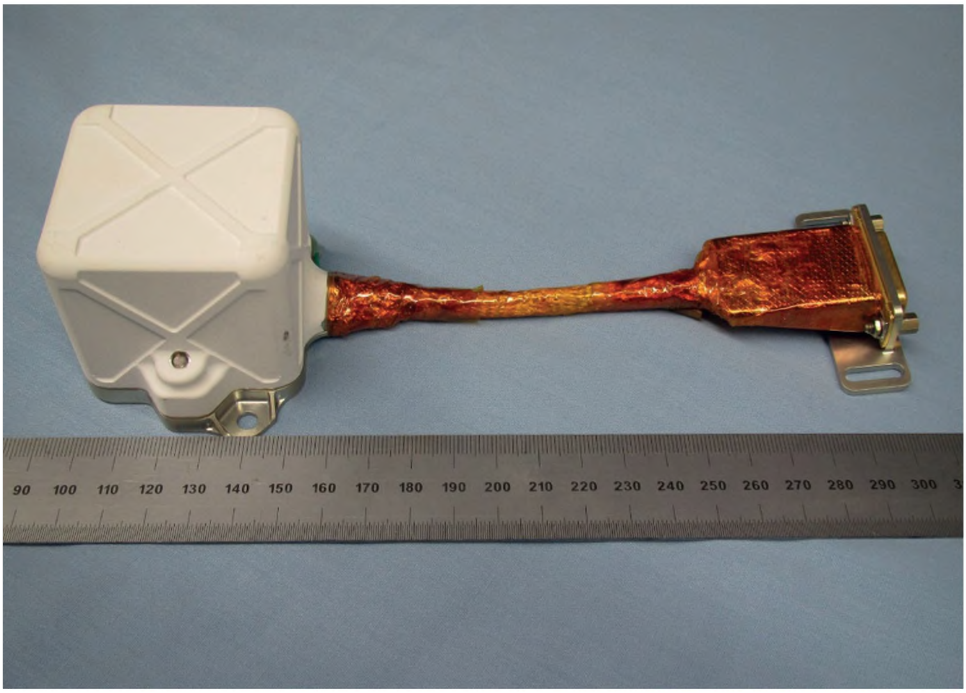

Fig. 4: Magnetometer sensor for the *InSight* lander weighing 100 g. The electronics, a single card on the lander, also weighs 100 g. In this application, the sensor has a dust cover

New Horizon's close flyby. Closer to the Sun, further exploration is needed both at Mercury and Venus, where the high-surface temperatures make their highly desirable electromagnetic induction studies difficult.

These temperature limitations could be overcome with new high-temperature technology. In the regions between Earth to Saturn, work remains and research continues. Plans are being developed for landing on the Moon and a Mars lander, *InSight*, is scheduled to land in November 2018, with a fluxgate magnetometer. The state of the art in sensor design has advanced rapidly. The sensor shown in Fig. 4 has a ±20,000 nT range and sensitivity equal to any of those described above. Similar sensors are scheduled to be flown to asteroid 16 Psyche and on the Europa mission in the next decade. Joining the Europa mission will be the JUICE mission to orbit Ganymede. Soon to be on their way to the inner solar system are *BepiColombo* to Mercury with a European and a Japanese component; and *Solar Orbiter* and *Solar Probe*, the latter going in to 10 solar radii. The age of exploration of the magnetism of the Solar system is far from over.

CONCLUSIONS

The study of the magnetic fields of solar system bodies has been an active area since the beginning of the space age. There is no evidence of active dynamos at Venus and Mars, but certainly there was once such a dynamo at Mars and most probably at Venus. The Earth's dynamo is perhaps normal with a tilted dynamo and secular variation. The jovian dynamo may also be topologically similar to that of the Earth. Uranus and Neptune have fields reminiscent of those of Earth and Jupiter, but with greater tilt and less dipolar dominance. Mercury and Saturn have dynamos too, or once did. Today they have aligned symmetric offset magnetic fields that are deemed to be the odd fellows in the dynamo club. Ganymede also has a strong magnetic field, possibly dynamo-driven [Kivelson et al., 1996].

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RADIATION IN SPACE: DRAMATIC WAYS OF SOVIET AND AMERICAN PIONEERS OF SPACE EXPLORATION

The paper examines thoroughly the very first "great discovery" of the Space Age — radiation zones embracing the Earth. Found with the help of first artificial Earth satellites, Sputnik 2 and 3 and *Explorer 1* and following, they were studied both theoretically and experimentally throughout the following decades. The paper describes the first explanation for a physical mechanism underlying a newly discovered natural phenomenon; active and passive experiments in space and their implications; mechanisms, which form spatial-energy structure of radiation zones and sources of the particles of the radiation belts of the Earth. We conclude with the present state of these studies and the questions still unanswered.

INTRODUCTION

The emergence of a new science — space physics — took place only 12 years after the end of the Second World War and during the "cold war". Even though the purposes, which two world superpowers: the USSR and the USA — pursued in nuclear‑rocket‑space race, were military, they provided, nevertheless, to scientists of these countries unique opportunities for fundamental scientific researches. It did not take long to wait for the first discoveries in space. Radiation belts of the Earth — the first natural phenomenon discovered by scientists of the USSR and the United States in the dawn of the space era, gave rise to space physics. The pathways of space pioneers research of the two countries were independent of each other, accompanied by dramatic moments, but led to the results that enriched the world science of outer space.

1. THE FIRST DISCOVERY IN SPACE: "...SPACE IS RADIOACTIVE!"

2017 year — 60-year anniversary of the beginning of the space age: namely on the 4th of October, 1957 the first artificial Earth satellite was launched. There was no scientific equipment aboard it, but the data of its radio transmitter were used by scientists to study the properties of the ionosphere (Report…, 2012).

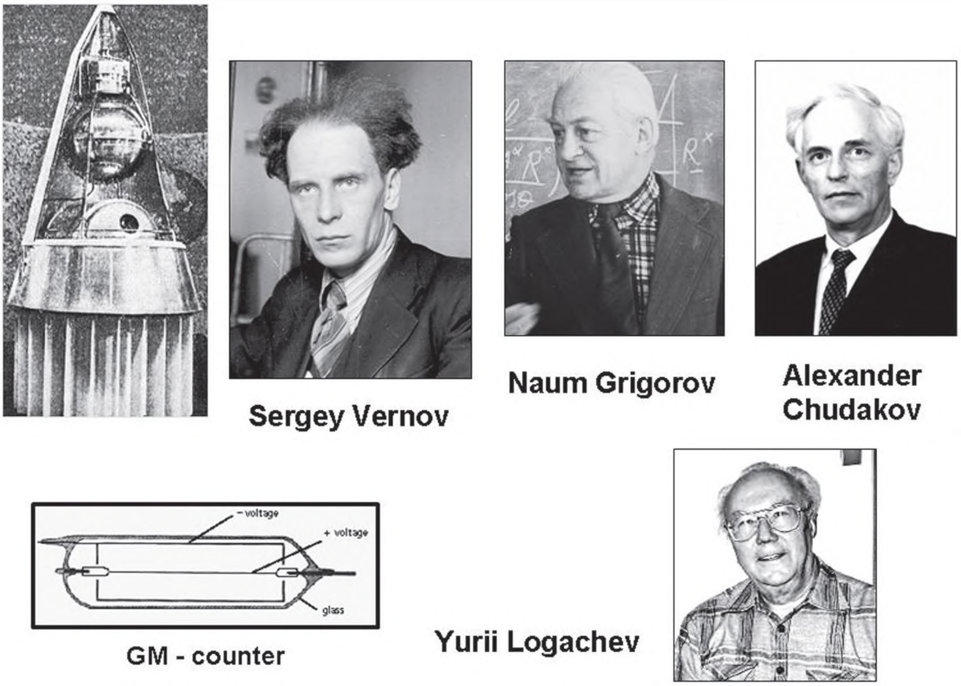


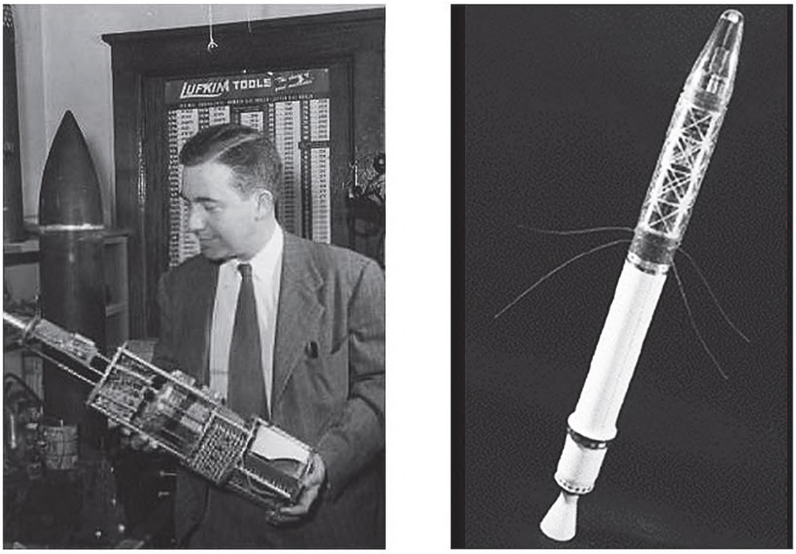
Fig. 1: Sergei Vernov's team from Moscow University, who installed the first physical instrument (Geiger-Mueller counter) aboard the second Soviet satellite — Sputnik 2

However, already the Second Soviet satellite (Sputnik 2), which was launched just a month after the First, carried the payload installed by the scientists from the Moscow University led by Professor Sergei Vernov (Fig. 1). It was the world's first scientific instrument — Geiger-Mueller counter to study cosmic rays — charged particles of high energies originating in the Universe (Vernov et al., 1958a, 1960).

Their American colleagues from the team led by Professor James Van Allen (Fig. 2) from the University of Iowa in January 1958 launched a similar device aboard the American *Explorer 1* — a Geiger-Mueller counter for the study of cosmic rays as well (Van Allen et al., 1958, 1959).

Experiments of Vernov and Van Allen led to the first discovery made by humans in space — "radiation belts" surrounding our planet. In fact, these experiments served as the beginning of a new direction in science — space physics, which began to develop rapidly since then.

The path to this discovery was brief and dramatic. In November 1957 in the Soviet Union and in January – February 1958 in the United States scientists received the first information from near-Earth orbits, but neither Vernov, nor Van Allen and their teams were able to give the correct physical interpretation of the observed phenomenon on the basis of the first data of experiments. Vernov and his team, after seeing the first data from Sputnik 2, comparing them with the activity in the Sun, came to the conclusion that their instrument, which demonstrated large variations of count rates (Fig. 3), registered energetic solar particles from the small solar flare, which was observed then. That was wrong. Here isolation of Soviet science from the other world also played a role. For the sake of secrecy, scientific data exchange was limited, and Soviet scientists could not obtain the data from Sputnik 2, which were dropped to the Australian receiving station. This inevitably affected the interpretation of the experimental results.



James Van Allen **Explorer - 1**

Fig. 2: James Van Allen of the University of Iowa, who installed his instrument (Geiger-Mueller counter) aboard the first American satellite *Explorer 1*

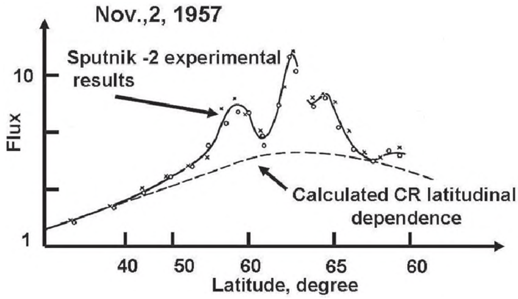


Fig. 3: The first results from Sputnik 2: fluctuations in the counting rate of the Geiger-Mueller counter were observed compared to the expected latitudinal dependence of the Galactic cosmic ray flux

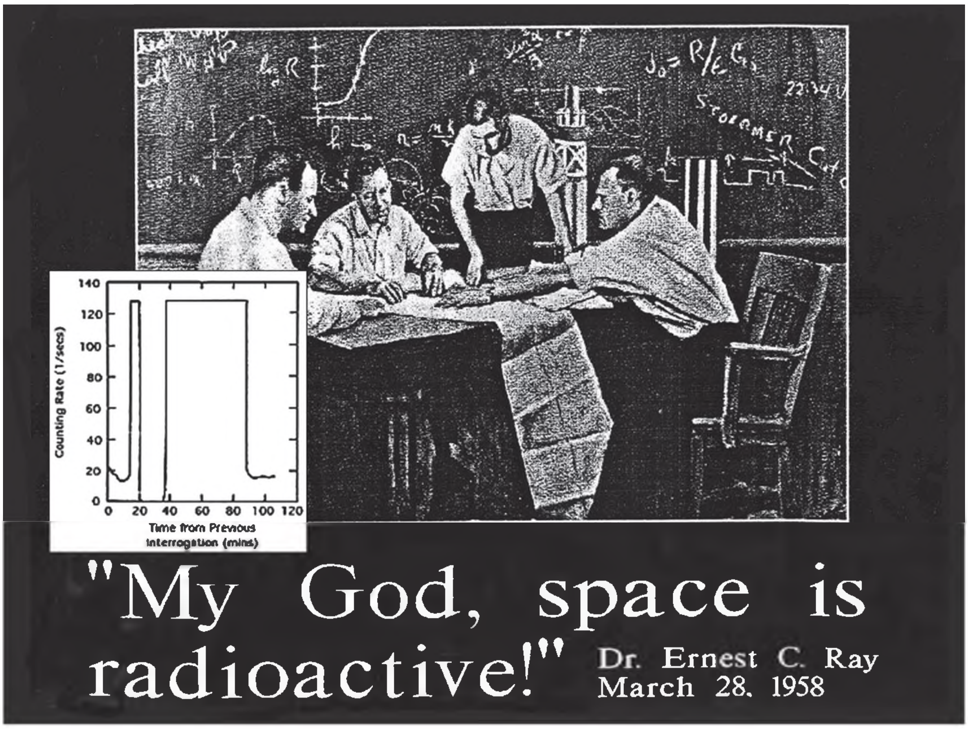


Fig. 4: The first results from *Explorer 1*: the count rate of a Geiger-Muller in several regions of the orbit was surprisingly large — there was "overload" (the inset). Van Allen's team was surprised by the results of the first experiment, and one of them said the phrase, which became famous: "My God, space is radioactive!"

However, Vernov's counterpart Van Allen also came to wrong conclusions originally. Seeing the first data of his instrument, which showed unexpected high speed count rates of the detector along the orbit of *Explorer 1* (Fig. 4, separate panel), he and his colleagues were so surprised that one of them exclaimed the phrase that has become a cruise since then, "My God, space is radioactive!" Flux of particles registered by Geiger-Muller counter was so big, that the instrument was saturated (see Fig. 4). Van Allen interpreted this as the registration of auroral particles (those, which caused aurora) with an energy of only 30 keV. And that was a mistake.

Nevertheless, by mid-1958, i.e. just a few months after the beginning of space experiments, the understanding of the physics of the new phenomenon became clearer.

Subsequent experiments, aboard the American *Explorer* series spacecraft and Soviet Sputnik 3 launched in May, 1958, followed the route to determine the nature of that phenomenon. Sputnik 3 carried a variety of equipment developed by different institutes of the Soviet Union (see, e.g. Vernov, et al., 1958b). Aboard the spacecraft MSU scientists installed for the first time a scintillation detector. Its data revealed the existence of two spatially separated regions of trapped radiation in the near-Earth space: an external zone filled with electrons with an energy of ~100 keV and above and an internal proton one. The proton energy of the inner belt was significantly higher (up to ~100 MeV and more) than that of the electrons in the outer belt.

In addition, high-altitude flux dependence was found indicating the capture of particles in a magnetic trap. The Van Allen group, based on data from the *Explorer* satellites, came to similar conclusions.

In fact, what Van Allen and Vernov discovered are high-energy particles filling a magnetic trapping region around our planet. This is a single formation, but within it the spatial structure is different for protons (ions) and electrons (Fig. 5). For electrons, unlike protons, there is a slot between the belts (see Section 5). This led to the initial interpretation of the structure of radiation zone as consisting of internal and external regions. American scientists at the *Explorer 1* could not register particles of the external radiation zone, due to the peculiarities of the spacecraft's orbit. The external electron zone was registered for the first time with Soviet Sputnik 3 by Vernov's group in May, 1958 (Vernov, et al., 1959).

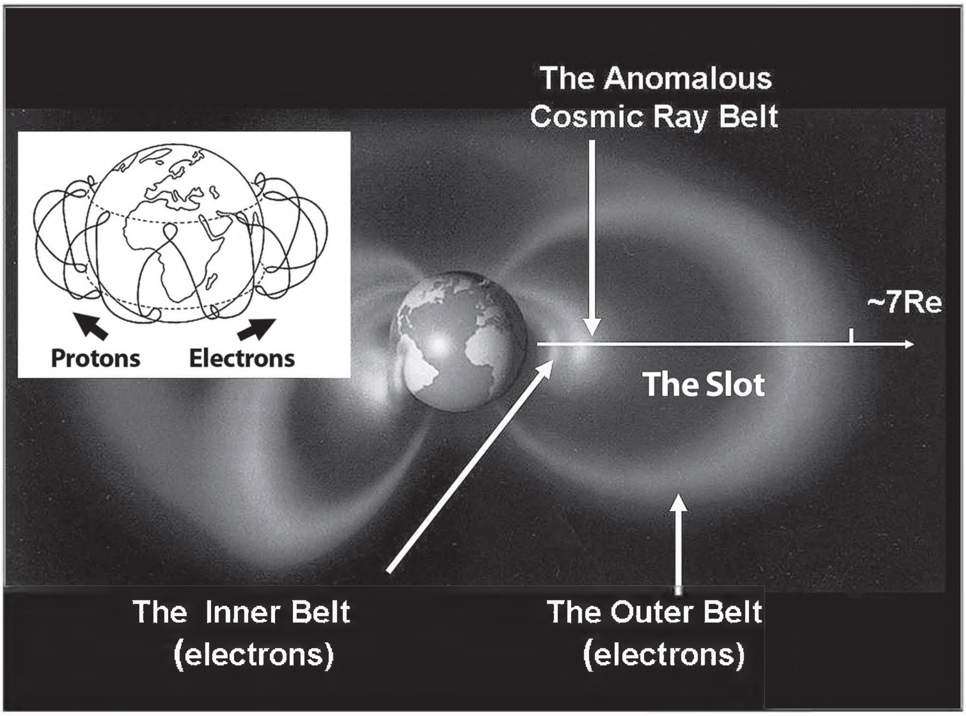


Fig. 5: Radiation zones of electrons (internal and external) with a slot between them. The position of the belt formed by anomalous cosmic rays is also shown (see Section 4)

Van Allen with the typical Americans' inherent desire for healthy advertising was able to gather a press conference on May 1, 1958, where he was the first to announce the opening of a new natural phenomenon, immediately voiced by journalists as a "belt" of radiation. This is how "Van Allen's radiation belts" were born. In this sense Soviet scientists lost the priority.

Now it is obvious that the first Soviet and American experiments in space complement each other. However, specifics of international relations of that era almost excluded international cooperation, and space physics was born in the conditions of a sharp competition between the two superpowers. This, of course, was the Nobel result, but the history has done its job differently…

Even a joke was born among American physicists: "it is quite natural that Americans opened an internal radiation zone, and Russians — external one. In the conditions of "cold war" it had to be like that: the area of American influence — the internal radiation zone, and of the Soviet — the external one. They shall be separated by a "demilitarized zone" — "the slot" between them".

So, the beginning of space research led to the first remarkable result in the field of physics of near-Earth space — the discovery of radiation zones and that, in fact, gave rise to new science — "space physics".

This stage of the Soviet researches of the radiation belts ended with the flight of automatic space probes of *Luna* series to the Moon. With the help of the onboard instruments MSU scientists were able to describe a complete spatial and energy pattern of the radiation belts. In addition, temporary changes in the external zone of radiation were found, which determined the new direction of radiation belts physics — the study of their dynamics depending on solar and geomagnetic activity. It's amazing, but as it was in the case of the launch of the first satellites, American scientists turned out to be quite a bit behind: their space probe *Pioneer 4* flew to the Moon just two months later the Soviet *Luna-1* (March and January 1959 respectively). Aboard the probes Geiger-Mueller counters were installed, which helped in getting the full picture of particles' spatial distribution in the radiation belts of the Earth.

2. THE FIRST PHYSICAL MECHANISM OF THE FORMATION OF A NEW NATURAL PHENOMENON

By mid-1958, the essence of the first discovery made with the help of the first satellites became apparent. The radiation belts surrounding the Earth consist of protons and electrons in a wide energy range. Calculations showed that this is a stable formation: the lifetime of particles in the inner belt could reach tens of years.

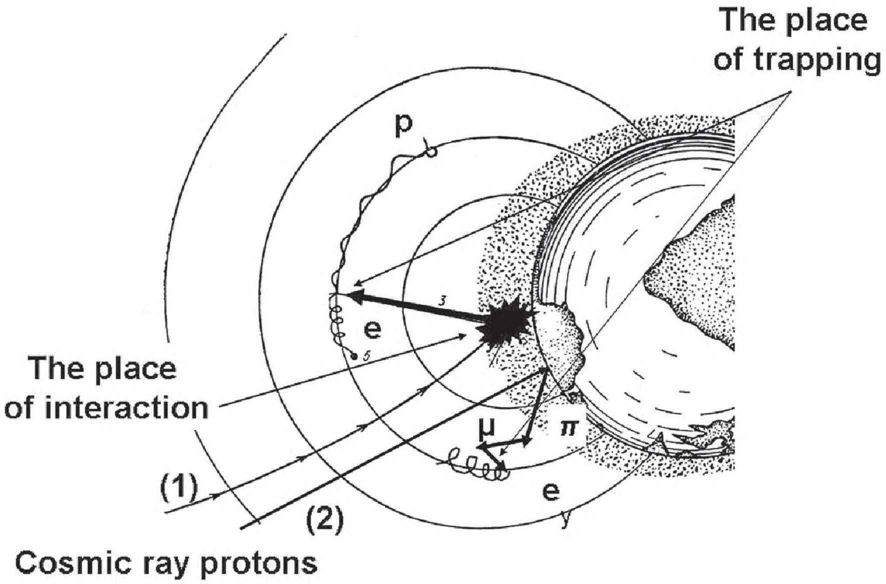


Fig. 6: The mechanism of proton and electron formation in the inner zone thanks to galactic cosmic ray capture by protons, proposed by S. Vernov, A. Lebedinsky, and F. Singer, as well as electrons (the mechanism of pion's decay), proposed by N. Grigorov (see Section 4)

It was necessary to understand the nature of these particles: their sources and acceleration mechanisms. This went on for the next 20–30 years. However, the first model, offering a mechanism for the formation of particles of radiation zones, appeared almost immediately after their opening. This was formation of secondary energetic protons in the decay of albedo neutrons arising in the interaction of primary cosmic rays with the atmosphere (Fig. 6). This model was subsequently named CRAND (Cosmic Ray Albedo Neutron Decay).

It turned out that cosmic ray (protons), reaching the atmosphere and interacting with it, form secondary particles — products of nuclear reactions. Among them are neutrons, some of which fly into outer space. Neutrons are unstable, with the lifetime of ~15 min. They decay according to the known scheme, forming protons, electrons, and antineutrinos:

$$n \rightarrow p + e^- + \tilde{\nu}.$$

The decay products of charged particles: protons and electrons — fill up the radiation belt.

The authors of this idea was Vernov and his colleague Alexander Lebedinskii from MSU (Vernov et al., 1958c). It is interesting to note that almost at the same time (just two weeks later) and regardless of the mechanism of the formation of the inner radiation belt was proposed by American scientist Fred

Singer (Singer, 1958). The mechanism of albedo neutrons decay made it possible to explain the existence of high-energy protons (and, as it turned out, subsequently, electrons) in the inner belt, near the Earth, but in a limited energy range (for electrons: no more than hundreds of keV; for protons: tens of MeV), determined by the energy of albedo neutrons.

Then it was necessary to determine the mechanisms of filling particles as well as the external radiation zone.

After the *Explorer 1* Van Allen's team launched a series of *Explorer* satellites to study radiation in near-Earth space. Gradually, other groups of American scientists became involved in the research of radiation belts.

In the USSR, under the initiative and the leadership of Vernov, series of *Electron* satellites was launched in 1964, carrying a variety of the scientific instruments. They played an important role in making the knowledge about the structure and dynamics of trapped radiation systematic. Thanks to the well-chosen orbits and the composition of the payload, almost the entire area of radiation zones was studied for the first time: energy and spatial distributions of protons and electrons in a wide range of energies, as well as their temporal variations. Results of *Electron* satellites have become a significant contribution of Russian space physics to the world's knowledge of the Earth's radiation zones (see, e. g. Vernov et al., 1970).

The first studied of the radiation belts showed multi-scale temporal and spatial variations of the particle flux. The question arose as to what type of variations and how stable the radiation belts are, how their characteristics change, depending on solar and geomagnetic activity. The first experiments of 1950–60 were run at the maximum of the solar activity cycle, so the question of their stability throughout the cycle remained.

The result of studies of radiation zones in the 60's was a final understanding of their spatial and energy structure. Scientists have found that the belt, in fact, is a single formation of charged particles (mainly protons and electrons), captured in the magnetic field, within a very large range of energies. The electron energy can reach the order at least of 10 MeV, and protons up to 1000 MeV. The upper limit of the energy of the trapped protons coincides with the energy of Galactic cosmic rays at the maximum of their intensity. The difference in the spatial structure of proton and electron radiation zones consisted, in fact, in the existence of a gap (see Fig. 5) — a local decrease of particle fluxes at a distance of $(2–3)R_E$ in the equatorial plane. From the point of view of theoretical models (see Section 5 below), it was found that clearance is the domain of lesser dominance of the electron component.

So, in addition to determining the mechanisms of particle losses in the belts, the model of their formation should answer the question of how trapped particles acquire such significant energy.

3. NUCLEAR EXPLOSIONS — THE FIRST ACTIVE EXPERIMENTS IN SPACE AND VIOLATION OF THE OUTER SPACE ECOLOGY

In 1958, the American physicist Nicholas Christofilos offered the American military to conduct a bold experiment: to use the possibility of capturing charged particles with a magnetic field of the Earth to defeat the enemy's space vehicles, i.e. intercontinental ballistic missiles (ICBM) and satellites in space. To do this, he proposed to blow up nuclear explosive in space (Christofilos, 1959). From the military point of view, they were of interest, because secondary radiation — the decay products of radioactive substances, especially the MeV-energy electrons, could lead to the changes in the ionosphere's properties, increasing its ionization and, subsequently, hampering radio waves propagation, as well as capturing relativistic electrons in the magnetic trap and increasing radiation doses compared to their natural level. The latter factor, along with the electromagnetic pulse from the explosion, was considered to be a method of active influence on spacecraft and ballistic missiles of the enemy, while radiation could damage electronics and individual units of satellites and missiles.

Such experiments on high-altitude nuclear explosions began in the US in the spring of 1958. The first explosions were low-power (1.7 kt), produced at a relatively low altitude (tens of km) and had no noticeable effect on the background of natural electron fluxes in the radiation zones of the Earth (Van Allen, 1997).

But the subsequent experiment *Argus 1* was made at a higher altitude of several hundred km and, although it was of a relatively low power, produced the observed effect against the background of the natural radiation environment. It were those experiments *Argus 1* and the following *Argus 2*, which proved it possible to inject particles into the geomagnetic trap and to capture them steadily in it. Really, *Explorer 4* spacecraft registered a new artificial belt of electrons, which existed for about three weeks (see, e. g., Van Allen, 1997).

The most powerful explosion was *Starfish*, which the United States produced in 1962 at an altitude of about 400 km. It made the most noticeable changes in the spatial and energy structure of radiation belts, for a long time violating, in fact, the natural ecology of the radiation environment of outer space. Fission products of radioactive substances — remnants of a nuclear explosion — were relativistic electrons fluxes with energy up to several MeV. In the inner zone of radiation zones their concentration significantly exceeded the radiation levels observed before explosions, making it impossible to observe them up to 1966 (Fig. 7). On the same figure variations of the counting rate of the Geiger-Mueller detector aboard the Soviet *Cosmos-5* are shown (Galperin, Bolyunova, 1964) are shown, which was 7,500 km from the epicenter of the explosion over

Johnston island. We see that a beam of relativistic electrons has increased by more than 3 orders of magnitude.

The Soviet Union tested nuclear weapons in space as well. The most powerful had the power of 150 kt (“K3”) and 300 kt (“K4”) and were blown at altitudes of about 300 km, which caused significant changes of the particle flux in the inner zone of the natural radiation belts, although not as extensive as the *Starfish*.

The main purposes of the US and USSR nuclear tests in space were, of course, military. And in this respect they were very successful: the damaging effect of artificial radiation on satellites was demonstrated. In (Gombosi et al., 2017) the statistics are as follows: as a result of nuclear explosions, 11 satellites where damaged when they crossed the regions of the most intense fluxes of artificial radiation zones. In general, solar panels where damaged due to exposure to significant doses of radiation (Hess, 1963, Gombosi et al., 2017).

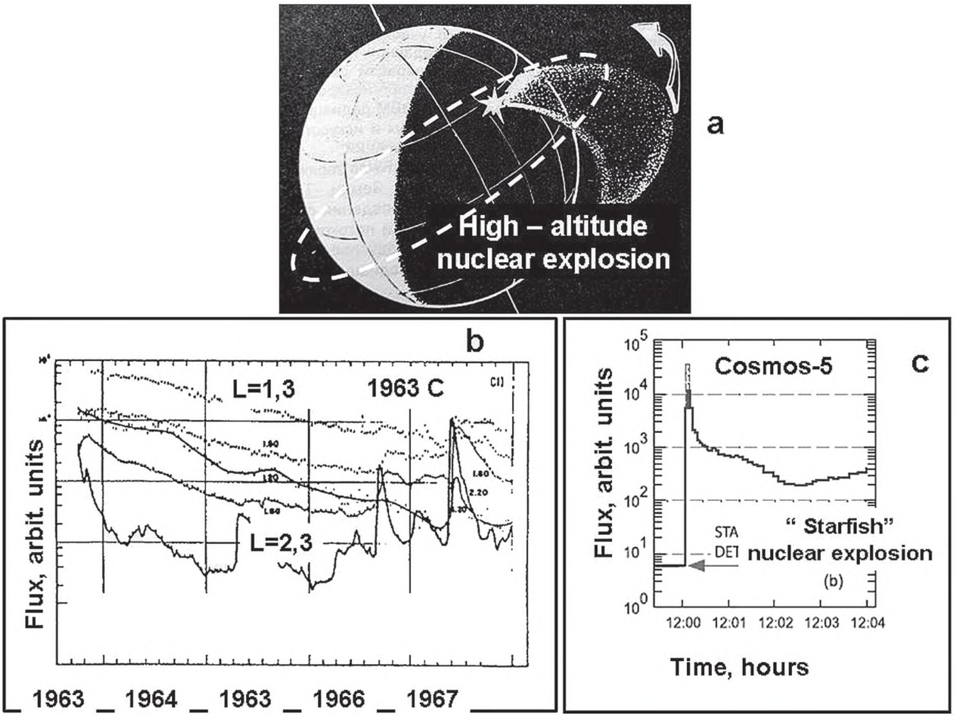


Fig. 7: Effects in near-Earth radiation environment caused by the most powerful high-altitude nuclear explosion *Starfish*; b) variation of the detector counting rates, recorded subrelativistic electrons with energy >400 keV on the American satellite 1963C; c) significant, more than 3 orders of magnitude increase in the electron flux directly after the explosion, as registered by Soviet *Cosmos-5* spacecraft. It can be noted that artificially injected electron fluxes from a nuclear explosion exceeded the natural ones in the inner belt for several years, up to 1967

However, these tests, in addition to military purposes, were immensely important for fundamental science. This was the first active geophysical experiment in space, and it demonstrated the validity of the model of stable trapping of charged particles in space, already developed by that time. The characteristic dependences of particle fluxes along the magnetic field line and the typical for the stable trapping pitch-angular distributions of particles with maximum intensity in the direction perpendicular to the magnetic field line were experimentally found.

Nevertheless, and now it is obvious that the nuclear tests of the end of 50' and the beginning of 60' led to a large-scale harm to ecology of near-Earth space: the spatial structure of the inner zone of electrons with energy >5 MeV of radiation belts. *Explorer 15* data relating to 1962 differs significantly from the modern structure of 2015, according to *Van Allen Probes*, by presence of high-intensity streams of relativistic electrons (from Gombosi et al., 2017).

Scientific resonance from the results of nuclear tests was great. American scientists in the late 50's even discussed actively the possibility of the formation of radiation zones of the Earth as a result of Soviet nuclear weapons tests in space (Lemaire, 2000). Realizing the immense importance of nuclear tests in outer space for fundamental science, Van Allen in 1958 proposed to declassify their results as having, from his point of view, great importance for fundamental science. This was done, but later (Gombosi et al., 2017).

4. ION AND ELECTRON TRANSPORT: FORMATION OF THE SPATIAL-ENERGY STRUCTURE OF RADIATION ZONES

As noted above, by the beginning of 60's there was a problem of search for an accelerator mechanism transforming a small energy of a solar plasma (about 1–10 keV) into energy of particles, which reach in radiation zones about 1000 MeV for protons and 10 MeV for electrons. This mechanism was found only a few years after the discovery of the radiation zones.

Theoretical model, which could explain almost the entire spatial-energy structure of radiation zones, was created by the mid-60's. It was based on the diffusion mechanism of particle transport across the magnetic field, which occurs because electric and magnetic fields fluctuations in near-Earth space. The efficiency of this approach can be seen from the fact that the mechanism of such "radial diffusion" is currently considered as main for explaining experimentally observed spatial and energy distributions of trapped particles inside the radiation belts.

Particles radial transfer is caused by electric and magnetic fields fluctuations in the magnetosphere, and fluctuations — by changes in solar wind pressure

(Fig. 8). Induced electric field lead to particles drift in crossed magnetic and electric fields and, hence, to diffusion transport of particles across magnetic power lines. Particles moving inside the trapping region increase their energy *E* by means of a betatron acceleration mechanism while maintaining the magnetic moment μ of the particles with pitch-angle =90°

$\mu = E/B = \text{const},$

where *B* is magnetic field induction, which decreases during the particles drift inward the radiation belts.

Thus, particles from the tail of the magnetosphere, which is a kind of reservoir or "warehouse" for solar wind and ionospheric plasma particles, fall into the magnetic trapping region, where they are accelerated during the transport.

Parker (Parker, 1960) expressed the idea of particle diffusion inside a magnetic trap for the first time under disturbances of a magnetic field of type of sudden pulses. Then, the ideas of diffusion transport were developed in the works of scientists both in USSR and USA practically simultaneously and independently (Tverskoy, 1964; Tverskoy, 1965; Nakada et al., 1965).

Particle transport is described by Fokker-Planck equation, the solution of which is a picture of the spatially-energy structure of the captured particles in the form of a particle distribution function for the given μ and *L*-shells (for ions):

$$L^2 \frac{\partial}{\partial L}\left|\frac{D_{LL}}{L^2}\cdot\frac{\partial f_i}{\partial L}\right| - \frac{G}{\sqrt{\mu}}\cdot\frac{\partial f_i}{\partial \mu} - f_i\Lambda_{ce} = 0.$$

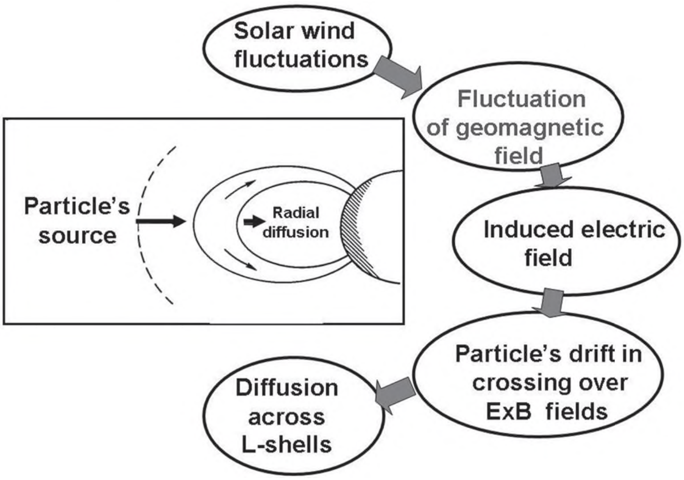


Fig. 8

In this stationary equation of radiation belts: Λ_{fi} — distribution function for I-type ions; μ — magnetic moment; G — Coulomb factor that determines the losses of the particles; Λ_{ce} — charge-exchange term, which also determines particle losses, but at energies less than hundreds of keV, and D_{LL} — the radial diffusion coefficient.

It is D_{LL} term that determines the speed of the particles transport in depth in the radiation belts. Particles (ions in this case), as they approach the Earth closer, more and more "feel" the effects of Coulomb scattering during their interaction with cold electrons in the plasmasphere, which is described by the Coulomb term G and charge exchange with atoms of a neutral exosphere surrounding the Earth. In this case, from the point of view of the radial diffusion model, the formation of the maximum ion intensity in the radial profile of their intensity (Fig. 9) corresponds to a characteristic place in space where the transport rate determined by D_{LL} is compared with the rate of ions losses due to Coulomb interactions and charge exchange process (respectively, the terms G and Λ_{ce} in the Fokker-Planck equation). For electron radiation belts, additional losses — interaction with electromagnetic waves (see below) — must be taken into account, as well as neglect of the charge-exchange process. In the framework of this model for radiation zones formation, determination, and evaluation of the particle diffusion coefficient D_{LL} become central problem of any modeling.

D_{LL} depends on the heliophysical conditions, both comparatively short (e.g. coronal mass ejections, CMEs) as well as long-term (e.g. variations during solar cycle). It is defined as the amplitude and frequency of magnetic and/or electric fields disturbances, dependent, in turn, on the parameters of the solar wind in the interplanetary medium.

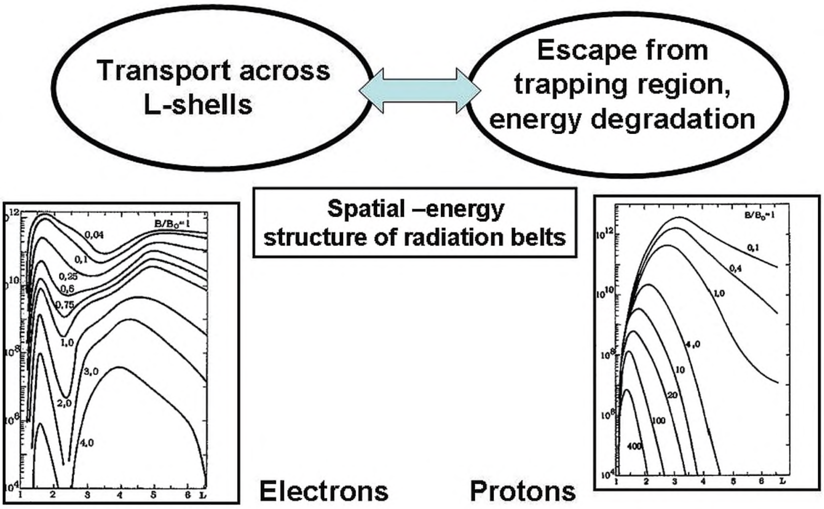


Fig. 9

From late 60's quantitative models of radial diffusion were developed by many. Among them, the model by (Tverskoy, 1965), differed significantly from the others. For example, the main difference between the first models of radial diffusion developed in (Tverskoy, 1965) with that by (Nakada, 1965), was that the latter used D_{LL} on the order of greater magnitude than (Tverskoy, 1965). Both models include Fokker-Planck equation D_{LL} defined just only fluctuations of magnetic field (so-called "magnetic diffusion"). As a result, the calculation of (Tverskoy, 1965) showed the better agreement with the experimental data than (Nakada, 1965). Tverskoy's model gave a good quantitative agreement with the experiment and allowed explanation of many characteristics of the spatial-energy structure of both proton and electron radiation zones.

Main paradigm of the first models was existence of magnetic diffusion only. Later, (Falthammer, 1966) proposed — unlike the first models — considering "electric diffusion" of particles, arising under action of large-scale magnetospheric electric field fluctuations. Later, many others picked up the idea and developed a lot of models taking into account not only "magnetic" D_{LL}, but the composition of "magnetic" and "electric" ones (see, e.g., Haerendel, 1968, Schulz, 1974, Spieldvik, 1977).

Coefficient of "magnetic diffusion" proposed in (Tverskoy, 1965) matched the average-perturbed geomagnetic situation and, accordingly, determined the "average" spatial and energy structure of the belts. On the other hand, "electric D_{LL}" in the models of other authors were chosen more by intuition, because the power spectrum of electric field fluctuations was not studied experimentally (Panasyuk, 1984).

Main experimental data, confirming the model of Tverskoy, came from *Electron*. The spatial and energy distributions of protons of different energies obtained in the experiment aboard this and then other spacecraft were in good agreement with the model of particles radial diffusion arising only from magnetic fluctuations. However, in a number of works by foreign authors published in those years, many experimental data were consistent with the model of "symbiotic" effects of fluctuations of electric and magnetic fields, or only electric ones.

The contradiction was resolved by the mid-80s, when, after a series of experiments on radiation belts studies, a lot of experimental data appeared, which concerned not only protons and electrons, but also heavier ions, which played an important role in determination of the sources and mechanisms of particles' acceleration and transport inside the geomagnetic trap. That became possible since the end of 60', when first in the US and in the USSR, and later in other countries, instruments were made to identify energetic ions (from tens keV up to MeV) by mass and energy and later by charge state.

Soviet experiments in this direction became possible in 1970s. The first Soviet experiment on the study of energetic heavy ions in radiation belts was carried out aboard *Molniya-2* in 1972 (Panasyuk et al., 1977). Similar American experiments began earlier, first in 1967 aboard low-Earth orbit spacecraft *Injun 4* (Krimigis, 1967) near equatorial plane in 1972 aboard *Explorer 45* (see e.g. Fritz, Spieldvik, 1978). Experiment aboard *Molniya-2*, along with more recent, made it possible to construct the spatial and energy structure of the equatorial ion belts, which served as a testbed for different models of radial diffusion. All these experiments determined the databases on the spatial-energy structure of radiation zones, which were used to establish the limits of applicability of different models of radial diffusion.

Solar wind consists of, along with protons, helium, carbon, oxygen, and heavier elements. Their relative concentration does not exceed a few per cent (for helium) and even lower for heavier particles. However, despite this, the study of heavy ions played an important role for the physics of radiation belts, as it helped in testing various models for radiation belts formation, which would be impossible with the experimental data on proton and electron component only. The reason for that is that the diffusion coefficients in the Fokker-Planck transport equation in general depend on both energy and the type of particles (i.e. their mass and charge state). Therefore, heavy ions proved to be an extremely important tool to verify various models of radial diffusion.

In addition, heavy ions are a kind of indicator of what is the source of energetic ions in the geomagnetic trapping region. For example, the presence of carbon or multi-charged heavy ions is sufficiently convincing evidence in favor of solar wind as a source of captured particles. (Panasyuk, 1980). Quantitative estimation of the adiabaticity limit of particle motion was decisive to determination of the nature of the captured heavy ions in the radiation zones. According to the criterion of Alfven (see e.g. Alfven, Falthammer, 1967; Morfil, 1973; Il'in et al., 1984):

$$\frac{\rho_L}{\rho_m} \approx \rho_L \frac{|\nabla B|}{B} = \varepsilon \ll 1,$$

where ρ_L — Larmour radius; ρ_m — magnetic field line curvature; B — magnetic field magnitude. Since ρ_L is determined by the momentum and charge state of the ion, using to experimental data on spatial distribution of ion fluxes it is possible to determine their charge states. It turned out that the charge state of energetic ions (MeV's energies) such as oxygen, carbon, iron, populating the radiation belts is close to that observed for the solar plasma and energetic particles (i.e. multiply charged). This was evidence in favor of the solar origin of captured ions with energies over hundreds of keV (Panasyuk 1980, 1983).

As for the problem of dominance of "magnetic" or "electric" diffusion in the process of particle transport it turned out (Panasyuk, 1984) that "magnetic diffusion" with the diffusion coefficient proposed in (Tverskoy, 1965) describes most of the spatial-energy structure of radiation zones. Fluctuations in the magnetospheric electrostatic field also take part in the formation of the radiation belts. However, their effectiveness is limited to only small particle's (ions) energies (less than hundreds of keV) in the external radiation zone and, possibly, in the internal zone for ion energies of more than several MeV.

Studies of heavy ions in the radiation zones made it possible to find another mechanism of their existence in the geomagnetic trapping region. It was found that the protons of the inner radiation zone in the loss cone (in the area of the South Atlantic anomaly) create new secondary particles (e.g. helium) as a result of interactions with atmospheric atoms. The latter, being trapped, form an additional component to the main (i.e., created by radial inward transport of particles belt of trapped particles). This phenomenon was first discovered in an experiment on the low-altitude satellite *Interkosmos-17* (Vandas et al., 1988). Thus, another source and mechanism of formation of the radiation belts was found.

The structure of electron radiation belts is fundamentally different from the ion belts because of the gap between the outer and inner electron belts.

Why there are no electrons in the slot?

Already in the end of 60's publications showed the loss of particles as the reason, their "precipitation" from the area of stable capture as a result of electrons' interactions with electromagnetic waves such as "whistlers", which belong to a special type of waves generated in the field of thunderstorm activity near the Earth's surface. These waves, spreading along the magnetic lines of force, resonantly interact with moving particles, changing their directions. As a result, part of electrons appears in the "loss cone", providing their directed "precipitation" into the atmosphere (Fig. 10). This was the first model interpretation of the gap formation between two of the belt's regions, which attributed it to the dominance of electron losses over the diffusion inward transport.

Electrons, unlike ions, are more susceptible to the effects of electromagnetic waves (mainly in the Very Low Frequency, VLF, range) than ions. If for ions the main mechanism of losses is ionization charge-exchange process (for relatively small energies less than hundreds of keV), for electrons the Coulomb scattering and interaction with waves become essential. In the Fokker-Planck diffusion equation electron losses are described by the introduction of an additional term for the loss in the wave-particle interaction. As a result of cyclotron resonance, electrons of up to sub-relativistic and relativistic energies can scatter on these waves and, once they get into the loss cone, perish in the atmosphere. This factor, along with the Coulomb scattering, determines their lifetime in a magnetic trap. Electromagnetic radiation that causes electron scattering can be generated as the particles themselves, which inhabit the radiation zones, for example, particles of the ion ring current amplifying during magnetic storms and causing instability of the plasma, as well as electrostatic oscillations of the plasma. The models, developed later, were also based on resonant "wave-particle" interaction.

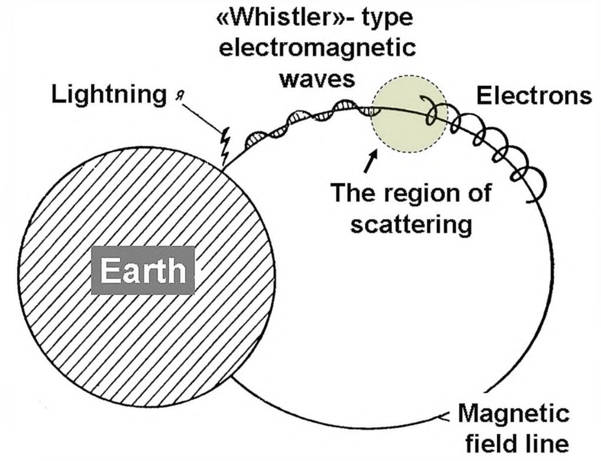


Fig. 10: Scattering mechanism (changing the direction of the particles' velocity vector under the influence of electromagnetic waves): a certain portion of the particles interacting with the waves changes their initial direction along the magnetic field line and "dies", penetrating into the atmosphere of the Earth

However, perhaps the most surprising was the understanding that the humans can be involved in the appearance of a slot between the belts. Powerful ground-based low frequency transmitters, operating in the kilohertz frequency range, can also cause the electrons to precipitate from radiation belts! It is important to emphasize that both model calculations and direct results of correlated experiments on particle measurements, which were run aboard spacecraft and ground-based transmitters, confirm this. Moreover, in the mid-70's there were some papers arguing for exclusively anthropogenic origin of the slot in electron radiation belts. It is necessary to underline that the problem of relationship between natural and anthropogenic impacts on electron radiation belts requires further research.

Publications on this subject first appeared in the late 60's – early 70's, although the first studies of anthropogenic effects on electronic component of radiation belts date to 1957. Then first evidence appeared for the impact of the powerful radio transmitter *Creecy* (1–12 kHz), located in Antarctica, on the electron radiation belts and precipitation of the particles into the atmosphere from the zone of stable capture.

One of the first works pointing the possibility of modification of the space-energy structure of the electrons of the outer belt were studies published in the mid-60's (see, e.g., Imhov et al., 1966). In it, on the basis of measurements of the energy spectrum of electrons in the inner radiation belt, it was demonstrated that local maximum in the spectrum of relativistic electrons at an energy of about hundreds keV and more is a result of the resonant "wave-particle"-type interaction in the periods when the spacecraft crossed the region of space near the longitude of the Soviet VLF radio transmitter nearby the city of Gorky (now Nizhny Novgorod). The result of this interaction was a resonance acceleration of the particles.

Following these studies, numerous others demonstrated the reality of anthropogenic impact in the “ecology” of the electron radiation belts. The reason for this was the powerful VLF navigation radio transmitters on different continents, which operated in the kHz range. Currently, the most powerful (1 MW) of them, Naval Communication Station Harold E. Holt, is located in Australia.

However, not only the radio emission from powerful ground-based radio transmitters can trigger electron precipitation from radiation belts. The lines represent the antenna radiating at frequencies 50–60 Hz, and related harmonics. This radiation can be a source of more broadband, “trigger” radiation, leading to the development of interactions such as “wave-particle” over areas of advanced industrial human activity. It was indeed proved in a number of satellite experiments. For example, in experiments aboard the Soviet *Cosmos-484* spacecraft (see, e. g., Grigoryan et al., 1981), it was found that electrons poured into tens or hundreds of keV at latitudes of localization of the outer electron belt over North America, which is an experimental evidence in favor that humans are capable to influence near-Earth radiation environment.

Papers began to appear, which explain the formation of the spatial-energy structure of the inner electron belt and the gap as a result of the anthropogenic impact. In other words, this could mean that in the 19th century and earlier, when radio communication had not been yet invented, the gap between the electronic belts could not exist. This point of view probably deserves attention, but it is certainly impossible to ignore natural interaction of electrons with waves in the same frequency range, such as “whistlers” during lightning discharges, which occur inside radiation belts as a result of plasma instabilities.

Precipitation of the electrons from the radiation belt under anthropogenic factors (VLF radio transmitters, electric power lines), indicated in number of studies, is no doubt now. Still, a model, which accounts for simultaneous existence of both anthropogenic and natural sources of electron losses in the gap region, is considered to be more attractive.

The slot between the electron radiation belts is not always empty. In this regard, it is interesting to recall briefly the initial history of the study of the relativistic electron component in the gap of radiation belts.

Already in 1964, it became clear that the slot between the belts is sometimes filled with very energetic electrons. This is the phenomenon of filling MeV’s electrons of gap at $2 < L < 3$ shells. It was found by the Soviet team headed by Vernov from Moscow State University aboard *Electron* spacecraft. This “new” belt in the gap between the more stable inner and outer belts existed for about a month. Unfortunately, these results were published only in the proceedings of the conference (Vernov et al., 1965, 1966).

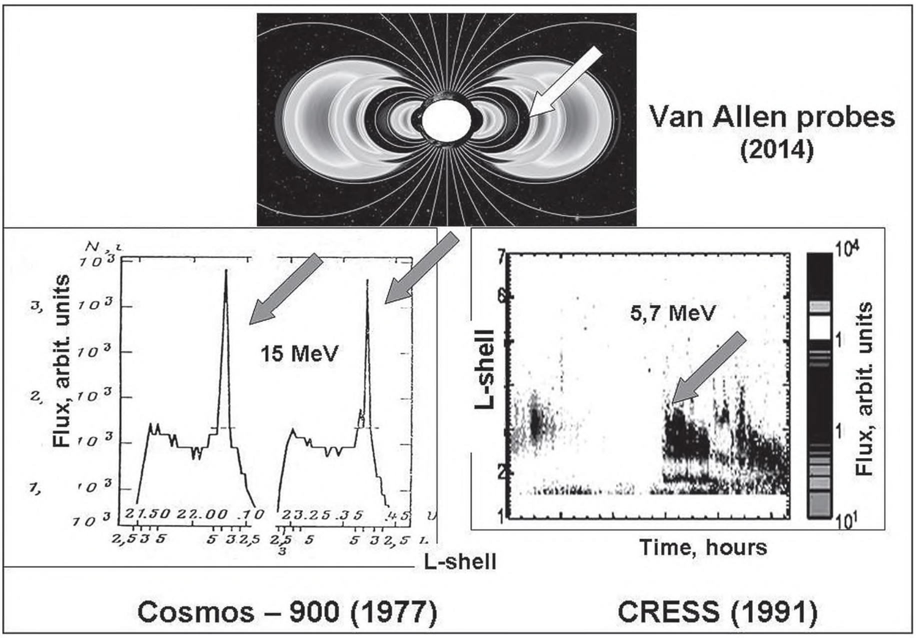
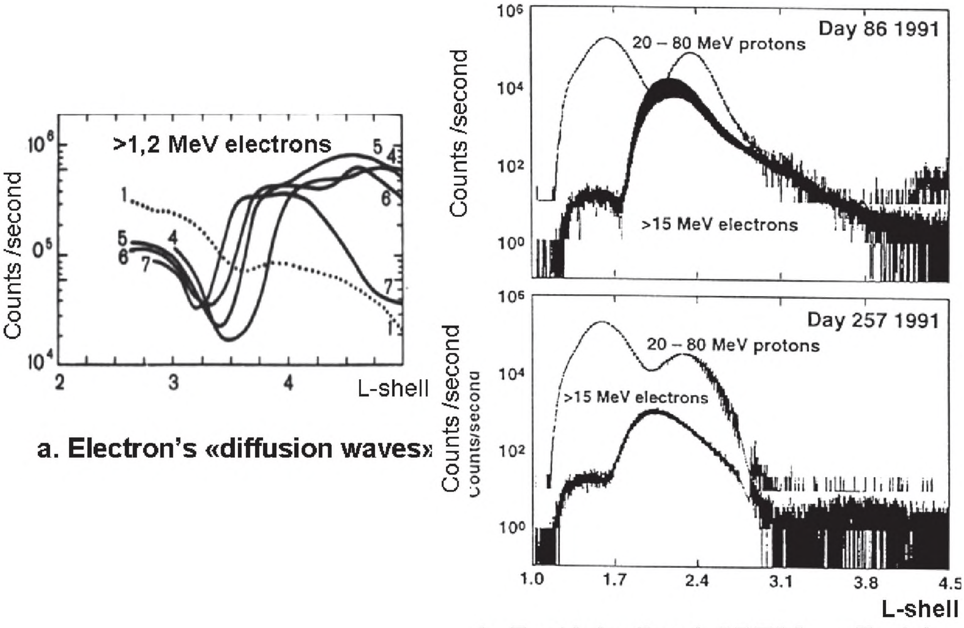


Fig. 11: Injection of relativistic electrons into the slot between the belts according to observations aboard *Cosmos-900*, CRESS, and Van Allen Probes (marked with arrows)



a. Electron's «diffusion waves»

b. Fast injection («CRESS – effect»)

Fig. 12: Two types of variations of relativistic electrons in the outer belt: (a) "diffusion waves" and (b) abnormally fast injections of protons and electrons ("CRRESS-effect")

Subsequently, Evgeny Gorchakov with his team (Gorchakov et al., 1981) also from Moscow University installed a Cherenkov detector aboard *Cosmos-900* spacecraft, which had the highest sensitivity to relatively small fluxes of high-energy electrons of the radiation belts. During this experiment, scientists from MSU were able to register for the first time the appearance in the slot of electrons with energies exceeding 15 MeV (Fig. 11a). From these data, one can clearly see the existence of a belt of 15 MeV electrons (marked with an oval) during the passage of *Cosmos-900* through the radiation belts on April 1977. This belt of relativistic electrons lasted a few days and then disappeared. Later the same group of MSU scientists managed to register few more cases of emergence of relativistic electrons of so large energies in radiation belts during 1977 and 1978 (Gorchakov et al., 1984).

Having analyzed these results, the authors concluded that all these cases relate to time intervals during the recovery phase of geomagnetic storms and correlate with the increase in solar wind speed. However, the nature of the accelerator mechanism responsible for the appearance of these electrons in the radiation zones were still unclear.

One can nothing but regret that, because of the isolation of Soviet space science, these remarkable results were not made known to the world scientific community in due course. In fact, these studies were the beginning of an intensive study of relativistic electrons in the geomagnetic trapping region. The problem of relativistic electrons generation is still discussed today.

The outer electron radiation belt, unlike the inner one, is very non-stationary. One of the most striking manifestations of its “non-stationarity” is so-called “diffusion waves”, studied in detail in 1960–1970 (see, e.g., Frank, 1965). Diffusion waves of electrons observed in the recovery phase of geomagnetic storms (Fig. 12a), demonstrated the movement velocity in accordance with the “medium-perturbed” model diffusion coefficient, which confirmed the validity of the concept of magnetic “diffusion” of radiation zone particles (see, e.g. Tverskoy, 1965).

However, in the early 90’s it became obvious that rapid changes of electron (and also proton) fluxes can be associated with the influence of single pulses of high-amplitude solar plasma pressure on the magnetosphere, which lead to anomalously fast particles’ movement inward the trapping region compared to the transport rate determined by the “medium-perturbed” diffusion coefficient. This became apparent after in 1991 (Blake et al., 1992) an effect was observed with CRESS spacecraft of fast resonant electron and proton acceleration during the second time intervals to energies up to 7–15 MeV and 40 MeV respectively at $L = 2{,}2–2{,}6$ (see Fig. 14). Such rather rare phenomenon in the radiation zones was caused, as was shown in (Pavlov et al., 1993) and simultaneously (!) by (Li et al., 1993), by emergence of a powerful specific bipolar pulses of the geomagnetic field. Further, these effect of acceleration was observed with *GLONASS* and *Meteor* spacecraft and others. In general, variations of electrons of this type fit into the model of particle acceleration under the action of sudden pulses, but with amplitude and shape rarely observed in nature.

The non-stationary belt of relativistic electrons in the gap was recently observed by a scientific team with the *Van Allen Probes* (Baker et al., 2013). It should be noted that the sensitivity — the geometric factor of instruments aboard *Cosmos-900* and CRESS was much higher than that of Relativistic Electron Proton Telescope (REPT) aboard *Van Allen Probes*. As a result, the instrument was able to register the injection of electrons into the gap between the belts up to 15 MeV.

Electrons of sub-relativistic and relativistic energies play an extremely important role both in the development of ideas about physical processes that determine the dynamics of particles in a geomagnetic trapping region and for applied problems — their effects over electronics and materials of spacecraft. It is enough to note that the problems of sources, mechanisms of transport and losses of these particles are still not fully understood and research continues.

5. HOW MANY SOURCES THERE ARE OF THE EARTH'S RADIATION BELTS' PARTICLES?

The first mechanism of the Earth's radiation belts formation — CRAND, proposed by Vernov, Lebedinsky, and Singer (see Section 2 above) just after they were discovered, did answer the question about the sources of particles of radiation belts, but only partially. Among the cosmic ray protons penetrate into the atmosphere due to nuclear reactions, generating neutron albedo, which, in turn, decay into protons and electrons, replenishing the radiation belts. However, the energy of these particles, as noted above, cannot exceed several hundred keV for electrons and tens of MeV for protons. In addition, albedo belts cannot extend to equatorial distances beyond $2R_E$, i.e. further than the inner zone. However, the radiation belts extend up to $7R_E$ and their energy range exceeds that of purely "albedo component". Therefore, the question of the sources and accelerators of all other particles — in fact, the bulk of the radiation zones, — remained open.

It should be noted that CRAND mechanism is not limited to the role of cosmic rays in the formation of the radiation environment of the Earth. The fact is that the primary component of cosmic rays, interacting with the atmosphere, generates "bottom-up" fluxes of secondary neutral pi-mesons (π^0). These particles are short-lived and decay into mu-mesons (μ) and electrons. Some of the electrons can run out into space, creating an albedo flux (see Fig. 6 (2)). Calculations show that the energy of these electrons reaches hundreds of MeV and these electrons at low altitudes form some kind of "halo" of particles, drifting around the Earth and contributing to the radiation environment. For the first time this mechanism of replenishment of radiation zones with particles was proposed by scientist from Moscow University Naum Grigorov (Grigorov, 1985).

It was necessary to find sources of particles In addition to the "albedo" sources. It is quite natural that such a candidate could be the plasma of the solar wind. An important role here played the experiments of Konstantin Gringauz, who with the help of plasma instruments aboard Soviet *Luna-2* space probe, launched in 1959 (Gringauz, 1961), for the first time proved the existence of a continuous solar plasma outflow from the atmosphere of the Sun.

But in 1972 there were experimental data obtained by American scientists with the low-altitude polar satellite 1971-089A (Shelley, et al., 1972), which showed that in addition to solar plasma particle in radiation belts come from terrestrial ionosphere. This was a kind of sensation, because before this discovery no one expected that there could be another source of plasma in the vicinity of the Earth except the solar one. This was done with the help of an energy-mass spectrometer — a device capable of discerning particle fluxes by their energies and mass. It turned out that the ionosphere "gushes" oxygen with energy 0.7–12 keV into the surrounding space (Fig. 13). Moreover, this oxygen has a charge of 1+ — that is, it is weakly ionized, in contrast to the solar ions, which have practically no electronic shells, being multiply-charged.

For example, solar oxygen (essentially "stripped" ions) has a charge close to 8+. Thus, another, additional source of particles of the radiation belts was discovered — the Earth's ionosphere.

Solar wind plasma fills the outer regions: between the shock wave and the boundary of the magnetosphere, the polar regions and the tail of the magnetosphere. The tail of the magnetosphere is a huge reservoir in which the both solar and ionospheric plasma accumulate; it plays an active role in replenishing the radiation zones with particles. During magnetic storms, powerful deformations of the magnetic field occur here, leading to the generation of induction electric fields, which accelerate particles of both solar plasma and terrestrial ionosphere. Some of these particles, already accelerated in the tail, reach the outer boundary of the radiation belt and here another process starts, their inward transport, in the direction of the Earth (see Section 4). The "driver" of this process is also solar wind, namely, its fluctuations: both large-scale (such as CMEs) and weaker, almost constantly existing in the interplanetary medium. Fluctuations of the solar wind create fluctuations of the Earth's magnetic field, which, in fact, inject particles into the magnetic trap. During their transport to the Earth via radial diffusion mechanism (see Section 4), their energy increases, conserving the first magnetic invariant of movement $\mu = E/B = \text{const}$, where E — kinetic energy of particle and B — induction of the local magnetic field (so called betatron acceleration).

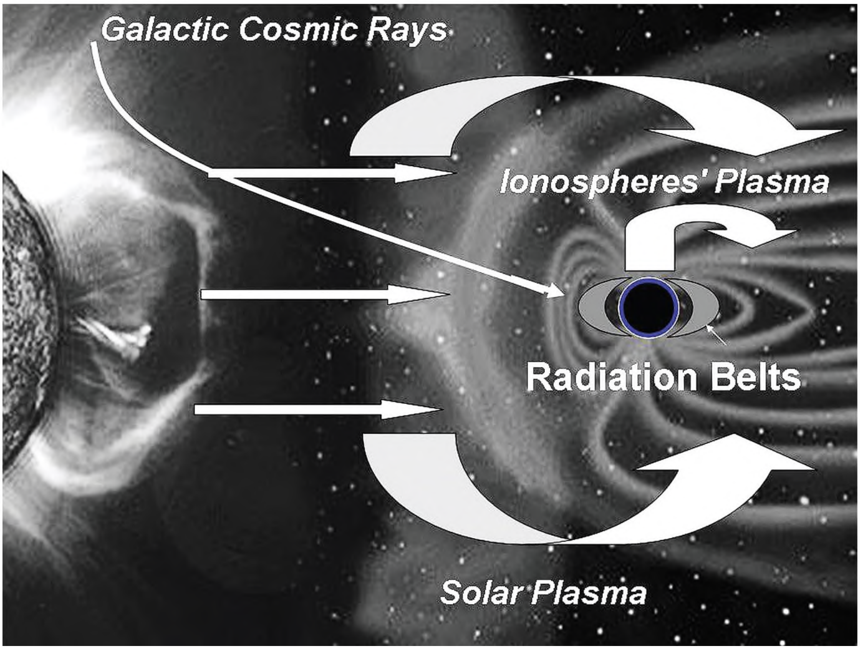


Fig. 13: Main sources of particles of radiation zones of the Earth: galactic cosmic rays (including anomalous component), solar and ionospheric plasma

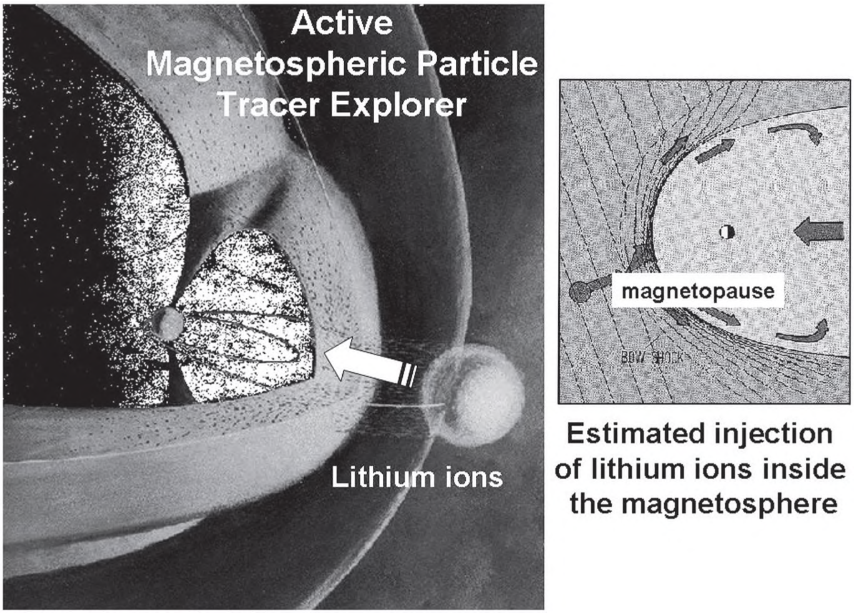


Fig. 14: Active experiment AMPTE (Active Magnetospheric Particle Tracer Explorer) on lithium ions injection in front of the bow shock of the magnetosphere with the aim of verifying the possibility of transport of these ions inside the magnetosphere

However, doubts about the validity of the particle source model in radiation belts as a mixture of solar and ionospheric plasma arose in 70's-80's.

To that time already experimental data appeared, both from foreign (see, e. g. Lennartson et al., 1982) and Soviet (see, e. g. Belousova et al., 1986) spacecraft, on the energy and composition of the ring current — particles inside the magnetic trapping region with energies from 1 to 100 keV responsible for the development of the main phase of the magnetic storms. It turned out that during strong magnetic storms ionospheric plasma plays a dominant role in the formation of the ring current, thus determining the magnitude of the magnetic storm. It was, in fact, a revolution. Doubts arose whether one should consider solar plasma as the dominant source of particles in the internal magnetosphere. According to some researchers the significance of solar matter for internal magnetosphere, and radiation belts in particular, could be overestimated.

This led to the idea of new active experiment — AMPTE (Active Magnetic Particle Tracer Explorer). Its main purpose was to test the possibility of solar plasma injection into the magnetosphere (Haerendel et al., 1985). This was carried out as follows. Aboard one of the two satellites, which were launched outside of the magnetosphere, the container with lithium was installed, which is also known to be a component of the solar plasma, but in extremely small quantities. It was assumed that after the explosion of the container in front of the bow shock of the Earth's magnetosphere on the dayside, part of the lithium ionized by solar ultraviolet would penetrate the tail of the magnetosphere in the plasma flow of the solar wind and there it would be registered by instruments aboard other small spacecraft in the tail. Of course, only if the very injection of solar plasma into the magnetosphere is possible (Fig. 14).

The experiment ended with a negative result: no lithium ions were registered aboard the spacecraft inside the magnetosphere! It seemed that the supporters of the idea of the dominance of ionospheric plasma in the inner magnetosphere would triumph. However, it turned out that the penetration of lithium into the magnetosphere did not occur because of the unexpected effect of electric polarization of the fiery lithium cloud immediately after the explosion and the development of Rayleigh-Taylor instability type (Hassam, Huba, 1987). As a consequence, solar wind flow could not catch these particles and transport them further into the Earth's magnetic field. The project AMPTE was one in a series of active experiments involving injection of chemicals in near-Earth space for various purposes, including military applications. In this project, as well as in earlier experiments with nuclear explosions, this applied goal stimulated the development of fundamental science.

But not only solar and ionospheric plasma were sources of particles inhabiting the radiation zones.

In 1990 joint Soviet-American experiments began (see e. g., Adams et al., 1991) the study of the so-called Anomalous Cosmic Rays (ACR). Earlier, in the mid-70's, the American IMP-8 space experiment (Garsia-Munos et al., 1973) clearly demonstrated that there is a component of cosmic rays with energy about 10–15 MeV/nucleon, exceeding the Galactic Cosmic Rays (GCR) of the same energy range in intensity. Its composition was dominated by heavy elements such as oxygen and nitrogen. In 1974 Lennard Fisk proposed the model (Fisk et al., 1974), according to which these energetic particles are interstellar dust that penetrates the heliosphere, gets ionized by ultraviolet radiation near the Sun and, once again getting out, is accelerated by stochastic acceleration of Fermi-type at the termination shock of Solar system boundary in the region of about 100 AU. Some of them return to the inner heliosphere. Particles accelerated at the front of the heliospheric shock wave are ACRs.

The experimental proof of this model could be the detection of single-charged oxygen ions in the composition of the cells. It is the weakly ionized atoms of the interstellar substance, in contrast to the fully peeled nuclei of the GCR, should represent the ACR. Such evidence was obtained during a joint US-Soviet experiments to study the penetration of ACR inside the magnetosphere from the interplanetary space. Indeed, it turned out that the Soviet spacecraft of the *Cosmos* series registered fluxes of a single-charged oxygen at low altitudes in the magnetosphere, which, in turn, were simultaneously registered in the interplanetary space aboard IMP-8 (Adams et al., 1991).

But the unexpected result was the discovery of the radiation belt consisting of this, in fact, by interstellar matter.

It was shown that as a result (Fig. 15) of charge-exchange process in the Earth's atmosphere ACR charge-state increases, and consequently radius of trajectory curvature sharply decreases. Thereby, conditions for a stable capture are provided. It turned out that it is located at a distance slightly greater than $2R_E$ from the surface into the plane of the equator (Grigorov et al., 1991).

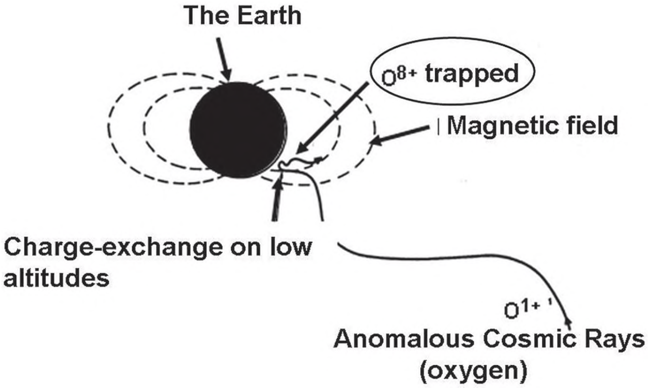


Fig. 15: The mechanism of anomalous cosmic rays' (ACR) radiation belt formation is penetration of single-charged ACR ions into geomagnetic trap with their subsequent reloading, conversion into multi-charged ions, and capture by magnetic field

It should be noted that our joint experiment with the Americans on the study of ACR was successful and very fruitful in scientific terms, but, perhaps, was the exception in terms of bilateral cooperation in the whole early history of space physics.

Thus, by the end of 1980 the stable point of view on multi-component composition of particles of radiation zones of the Earth was formed, among which are solar and ionospheric plasmas, and also GCR (including ACR) —main sources of their replenishment (see Fig. 13).

CONCLUSION

The history of Earth's radiation zones research counts more than six decades. The studies so far provided a fairly consistent model of its description — the result of the impact on its spatial and energy structure of the external environment — solar wind and interplanetary magnetic field, leading to geomagnetic disturbances, and internal — low-frequency natural and anthropogenic oscillations of the electromagnetic field, leading to acceleration, transport, and particles escape from the trapping region.

With the first discovery of the radiation belts space physics began. The surprising fact was that the basic physical laws of particle acceleration, transport, and loss in the inside of the magnetic trap was understood soon after their discovery. Most likely, this contributed to the fact that among the pioneers of studies of the near-Earth radiation proved to be many researchers with a wealth of knowledge in the field of plasma physics, nuclear, and fusion research. Of course, the enthusiasm of the pioneers of space exploration at the beginning of the space age played an important role.

Soviet and American researches in the field of space physics developed independently in the era of the "cold war", secrecy and distrust of each other. Leaving aside the issue of priorities, it can be noted that Vernov and Van Allen together with their teams went in parallel ways and came to similar results independently from each other. These two scientists have launched space physics researches of near-Earth space and interplanetary environment, science, which continues to be relevant and intensively develops now.

In 2012, American scientists launched a pair of spacecraft to study the radiation belts, calling them in honour of James van Allen. In Russia in 2014 we launched a satellite to study energetic particles in the inner magnetosphere and named it in honour of Sergey Vernov.

…Many years later, not terrestrial, but space orbits of these two great scientists — pioneers of space researches, crossed (Fig. 16).

Fig. 16: Studies of the radiation belts continues: in 2012 American scientists launched the space mission named in honour of Van Allen, and in 2014 Russians — Vernov space mission

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SOLAR SYSTEM — INTERSTELLAR MEDIUM CONNECTION: PAST AND RECENT ASPECTS

There are several and very different types of links between the Solar system and the Milky Way interstellar medium and I briefly discuss three aspects here. Although being of very different kinds, these aspects are interestingly all related in minor or major extent to comets, *messengers of science*. (1) The most direct link is the *solar motion* link, i.e. the formation of our *heliosphere* that is due to the interaction between the solar wind and the ambient interstellar matter of the small interstellar cloud our Sun is presently crossing (the Local Cloud). Russian scientists and space missions have played a major role in the observational and theoretical studies of the heliosphere. The Russian-French collaboration on this topic has started early in the seventies and is still ongoing*. This science has been with time more and more fascinating and culminates today with the exploration of the solar wind boundary by the two *Voyager* US spacecraft and the recent entry of *Voyager 1* in the Galactic gas of the Local Cloud. (2) The soft X-ray emission due to the solar wind encounter with neutrals from the interstellar space has been discovered more recently and serendipitously. It is again a consequence of the Sun's motion in interstellar gas but does not have any impact on the heliosphere, instead, it contaminates all diffuse X-ray astronomical observations, calling for corrections. More important, the consequences of the mechanism at work, overlooked in the past, are still under study and may influence various fields in astrophysics. (3) Our Sun and Solar system planets and minor bodies were born in a collapsing interstellar cloud, this is the *parental* link. Understanding all phases and processes of Solar system formation is by many ways mandatory, but some steps of the interstellar and proto-solar physics and chemistry are still largely unknown. Small Solar system objects, the comets, may bring in future clues on the nature of the gigantic reservoir of organic interstellar matter associated with the so-called *diffuse interstellar bands*, a 70-years long observational mystery, and tell us whether this organic matter has been delivered to Earth during comet infall.

1. INTRODUCTION: THE MYSTERIOUS COMET SHADOW?

I would like to introduce the heliospheric interface, i.e. the most direct imprint of the Sun-Interstellar Medium (ISM) interaction, in a non-classical way. Fig. 1 shows the image of a large fraction of the sky (about 90 by 90 square degrees) recorded by the SWAN instrument on board the ESA-NASA SOHO satellite that is posted at the Lagrangian point L1, 1.5 million kilometers from

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* This article is dedicated to the memory of our dear colleague Youri Malama.

the Earth. SWAN (which is still operating today in 2018) is sensitive to the Lyman-alpha (121.6 nm) radiation in the ultraviolet, a radiation emitted when neutral hydrogen atoms are illuminated by a source at the same wavelength and then de-excite (resonance scattering). Like all instruments in space sensitive to Lyman-alpha, SWAN is detecting Lyman-alpha from all the directions, with some large-scale variations. The brightness is represented by the blue-white color scale. We call this sky background the *Lyman-alpha glow*.

Let's suppose that at the time this image was recorded, i.e. in 1997, we were totally ignorant about the origin of this Lyman-alpha glow, i.e. we did not know whether it is emitted far away in the Milky Way or much closer, and what is the source of the H atom excitation. This particular year, a conspicuous source started to be detected in addition to the glow, and became a very bright and wide spot seen in white at the center of the image. This spot was coinciding with the location of comet Hale-Bopp and it culminated in brightness when the comet was close to its perihelion. The interpretation was quite simple: close to the Sun, the iced water from the comet nucleus is heated and sublimates, water molecules H_2O are decomposed into H and OH under the action of the solar UV radiation, and escaping H atoms are resonantly excited by the strong solar Lyman-alpha emission.

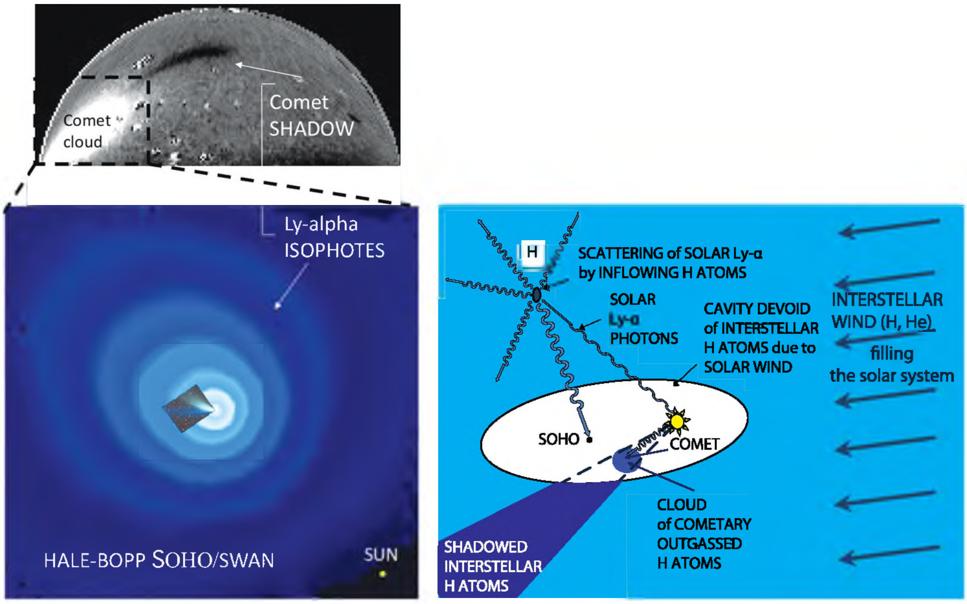

Fig. 1: A hundreds-million-km-wide shadow: the comet shadow on the interstellar gas. Inflowing interstellar H atoms distributed in space scatter the solar UV Lyman-alpha photons, producing the UV H glow. At the time of comet Hale-Bopp, those solar photons passing through the cloud of outgassed cometary H atoms served to excite them and the cloud became opaque to the radiation. Interstellar atoms behind the cloud are no longer illuminated and there is a lack of backscattered emission from the shadowed region. Image courtesy Lallement et al. (2002)

Their de-excitation produces a huge Lyman-alpha bright cloud around the comet nucleus. Note that, if our eyes were sensitive to the ultraviolet radiation, in addition to the visible light, we would have seen Hale-Bopp illuminating half of the sky during months!

Totally unexpected was the dark feature in the upper part of the image. This elongated area of low intensity was moving in the sky from one day to the other but remained constantly attached to the comet emission. Inspecting more closely this strange feature, we noticed that it was always oriented along the projection onto the sky of the Sun-comet axis and visible only in the direction opposite to the Sun as seen from the comet (see Fig. 1). This implied that H atoms located behind Hale-Bopp along this Sun-comet axis (and only those atoms) were no longer emitting at Lyman-alpha, and therefore no longer excited. In other words, what we were seeing was a shadow cast by the comet cloud on the interstellar H gas, producing *dark* interstellar atoms that in the absence of the comet shadow would have been observed through their Lyman-alpha emission. Again, imagine that at this time we did not know anything about the location of the H atoms producing the glow and what excites them: in this case the "shadow" observation would have been a revelation: if the non-emitting ("dark") atoms were those, for which the Sun is masked by the comet, then two conclusions could be drawn: first, the source of excitation of these atoms is the Sun, and, second, this population of atoms must be located close to our star, otherwise far away the solar radiation would be too faint to produce a non-negligible emission, that is, in the Solar system and NOT at astronomical distances.

Because H atoms cannot stay long in the Sun's vicinity without being ionized by the solar flux below 91.2 nm, this in turn implies an external source of atoms able to replenish permanently the interplanetary space, in other words a permanent flow of interstellar H atoms. In reality, we already knew in 1997 that the H atoms producing the glow are within the Solar system. This was deduced in 1971 based on parallax effects, and it was already understood that interstellar atoms enter the Solar system in response to the motion of our Sun in interstellar gas. However, with this single observation of the comet shadow we would have made an important step in the understanding of the Sun-ISM interaction, with some similarity with the discovery of the solar wind based on the comet radial tail of ionized plasma.

2. THE HELIOSPHERIC INTERFACE

In the early seventies, at the time the interstellar wind was discovered, the actual characteristics of the Milky Way ISM immediately around our Sun was unknown, and as a consequence there were only speculations about the shape and size of the heliosphere, the volume occupied by the solar wind in the ambient ISM. Models had been developed, however they were assuming a fully ionized interstellar gas, and in this case this gas cannot penetrate the solar wind volume and flows around the heliosphere. After the stimulating discovery of the interstellar neutral atom flow, it became clear that the cloud encountered by the Sun is at least partially neutral and consequences in terms of physical processes at work in the interaction region were studied. The Sun's gravity, its radiation, and its wind interact with the encountered interstellar gas, cosmic rays, and magnetic field and create a perturbed and complex area that follows the star along its trajectory: the heliosphere and its boundaries.

It is during this interesting period that the collaboration between the Russian team led by Vladimir Baranov and the French group at Service d' Aéronomie in France strengthened. The Moscow group (Fig. 2) was developing the most sophisticated models of interaction between a partially ionized interstellar flow and the solar wind, with in particular state-of-the-art Monte-Carlo methods developed by Youri Malama to represent the neutrals and iterative methods to couple them with the ionized gas, the latter being modeled with hydrodynamical codes (see Fig. 4).

In parallel, the implementation of hydrogen absorption cells in front of the UV photometers flown on board the *Prognoz-6* and *-7* spacecraft became a crucial point. The photometers were built in France, following agreements between V. Kurt and J.E. Blamont (see Fig. 2). The principle of resonance scattering and its application to absorption cells were derived from the pioneering theoretical and experimental work in the laboratory of Prof. Kastler, and Prof J. Blamont had the very judicious idea to equip the photometers with these new cells. Acting as negative spectrometers, they for the first time allowed for the deriving of kinematical properties of interstellar flow, something none of the other experiments had achieved before, and, especially, observations ideally adapted to test the new Moscow models. As a matter of fact, observations of stellar spectra had clearly shown that our star, like all others, is traveling in space with its own specific velocity, but the relative motion between our star and the local ISM was unknown, both in modulus and direction. Moreover, the density, temperature, and ionization state of the surrounding ISM were also unknown. Intense work to interpret the *Prognoz* observations was done in the eighties. The French group had also started spectroscopic observations of nearby stars, with the goal of detecting signatures of the ambient gas, i.e. the gas in the cloud crosses by the Sun.

Combination of those observations, *Prognoz* data, sophisticated Moscow models and, later, the results of the *Ulysses* mission is at the origin of several important advances. They are the determination of the precise direction of the interstellar flow, the measurement of the neutrals' deceleration through charge-exchange reactions with the ionized gas, the identification of the cloud absorption lines in star spectra and subsequent measurements of its ionization state, and, last but not least, estimates of the size of the heliosphere.

During the 90's and later, the French-Russian collaboration continued. Along the years, students of V. Baranov and Y. Malama become talented scientists and continued to develop the models and interpret the data (Fig. 3).

Fig. 2: *Prognoz-6* and *-7* and the Russian-French collaboration that started around the Lyman-alpha photometer and the hydrogen cell and is still continuing today. Top from left to right: a *Prognoz* spacecraft; Academician I. Shklovsky who was leading the project; Academician V. Kurt who initiated the collaboration; Academician G. Petrov (sitting) with colleagues V. Baranov, Y. Malama, S. Chalov in the Institute for Problems in Mechanics; our dear colleague Youri Malama. Bottom from left to right: Nobel Prize winner A. Kastler, whose discoveries were at the origin of the H-cell; Prof. J. Blamont and Dr. J. L. Bertaux celebrating the launch at the CNES headquarters in Paris; V. Baranov explaining the physics of the heliosphere

Fig. 3: From the first to the second and third generations of the heliospheric Russian-French team. Top from left to right with Vladimir Baranov: Rosine Lallement, Elena Provornikova; Eric Quémerais. Bottom from left to right: Olga Katushkina, Dmitri Aleksashov, Sergey Chalov, Vlad Izmodenov

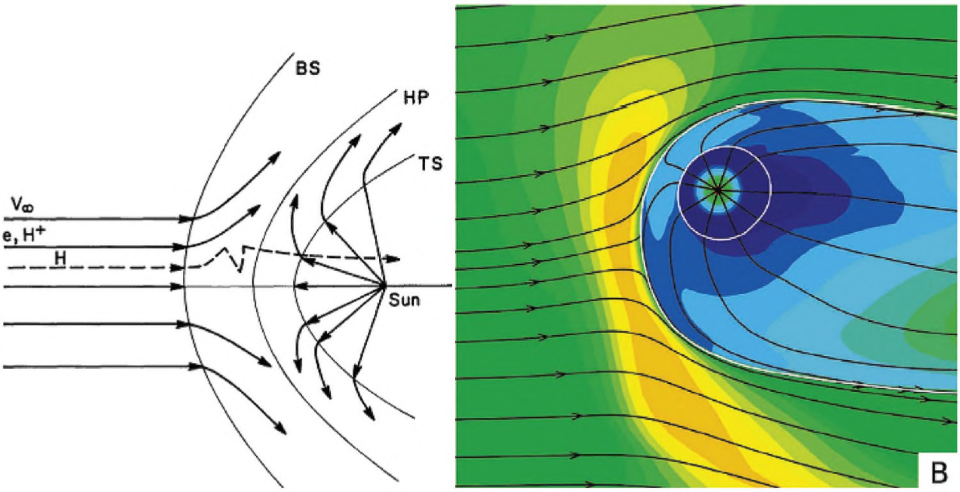

Fig. 4: From the first kinetic models of the heliosphere (Baranov, Malama, 1991) to today's sophisticated hydro-kinetic self-consistent models (Izmodenov et al., 2015)

The collaborative work led to the measurement of the influence of the interstellar magnetic field on the shape of the heliosphere and constraints on the field direction. The two *Voyager* spacecraft has started the second phase of their fantastic adventure, the exploration of the solar wind outer boundaries, and the collaboration continued based also on the new *Voyager* data. It led to the discovery of the so-called “Hydrogen Wall” — accumulated neutral gas at the periphery of the heliosphere (Quémerais et al., 2010), and the one of the Galactic weak counterparts to the signal (Lallement et al., 2011). In particular, Vlad Izmodenov started to lead a very productive group at IKI. Vlad, S. Chalov, D. Aleksashov produced and are still producing the most detailed multi-population models of the heliospheric interface and the best models of propagation of low and high energy particles in the heliosphere. An example of the spectacular evolution of the former models is illustrated by Fig. 4 .

3. OUR INTERSTELLAR ENVIRONMENT, THE LOCAL INTERSTELLAR BUBBLE, THE FUTURE HELIOSPHERE AND OTHER ASTROSPHERES

Stars are traveling through very different types of interstellar media, ranging from ultra-compact cold clouds to very tenuous and hot gas of the cavities blown by supernovae. All along its journey within the Milky Way, the Sun similarly crosses various types of ISM. As we said above, it is presently moving in a region of very low density, a region called the *Local Interstellar Bubble*. The cavity is filled with low-density clouds and our star is presently crossing one of them. Fig. 5 shows a planar cut in the three-dimensional map of the nearby ISM synthesized based on absorptions measured in the light of nearby stars (Capitanio et al., 2017). The absorption is produced by interstellar dust particles associated with the clouds. Such three-dimensional maps reveal dense clouds and cavities of tenuous, generally hot gas blown by stellar winds and supernovae.

The Solar system, and again a comet have unexpectedly played a fundamental role in the understanding of the nature of this *Local Interstellar Bubble* (hereafter LB). In the 90’s, after the success of the German X-ray satellite ROSAT, it was believed that the diffuse soft X-ray emission (energy in the order of 0.25 keV) that was observed from all directions had its origin in the LB (at the exception of the Galactic halo directions where additional non-local emissions do exist). The temperature of 1 million K and the density were consistent with the hot gas blown by an old supernova. There was, however, an embarrassing discrepancy between the hot million-K-pressure in the LB and the pressure derived from stellar observations in the local cloud crossed by the Sun. And then came comet Hyakutake, and it was found to shine in soft X-rays. This was a big surprise since comets are frozen objects, far from the condition required to emit in X-rays!

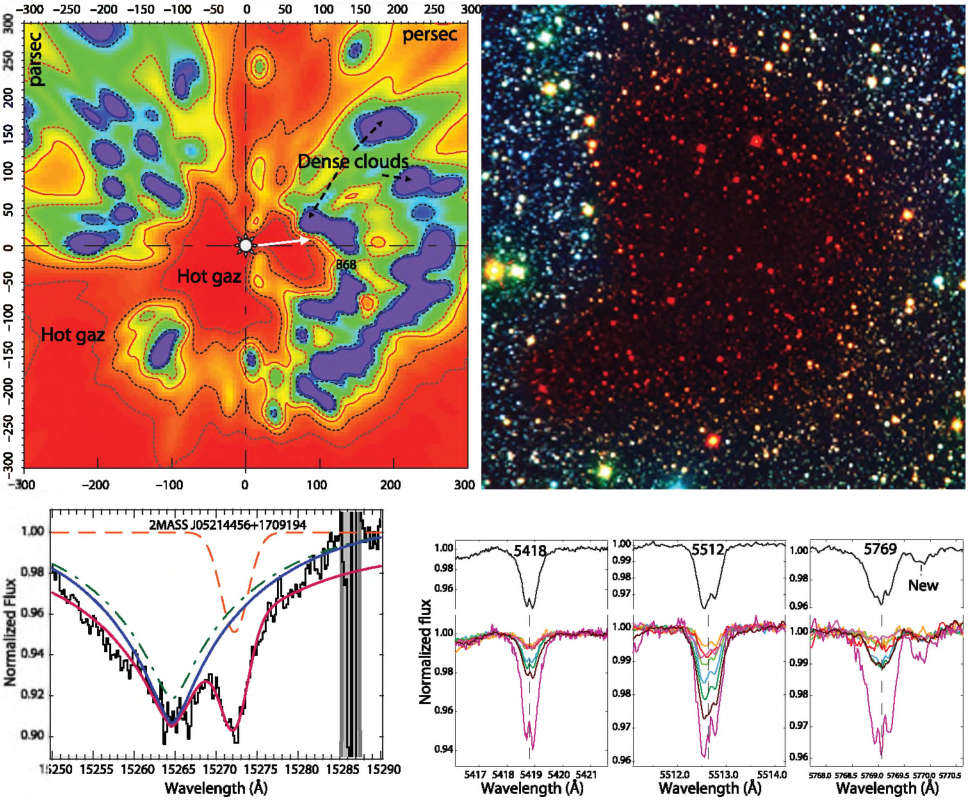

Fig. 5: Top left: The distribution of interstellar clouds in the Sun vicinity. Shown is a planar cut along the Galactic Plane within a reconstructed 3D distribution of interstellar matter, based on absorption towards 80,000 stars. The Sun (white star) is in the middle of the figure and the Galactic centre direction is to the right. Units are parsecs. Red areas correspond to cavities devoid of dense matter, while violet regions are dense clouds. The Sun lies within the volume devoid of dense matter called the Local Interstellar Bubble (LB). At the periphery of LB are dense cloud complexes. White arrow: projection onto the plane of the Sun's motion with respect to the bulk of interstellar matter, the motion will bring it through the clouds seen at about 100 pc to the right, in the Scorpius-Centaurus group of cloud. The compact cloud Barnard 68 is indicated as a black square. Image courtesy Capitanio et al. (2017). Top right: the dark cloud Barnard 68 in infrared: stars located behind the cloud are invisible at optical wavelengths because of the strong dust absorption. Only red giant stars can be detected in the near-IR. 1.5273µ diffuse interstellar bands (DIBs) level off with respect to the dust grains in cloud center, showing that the organic macromolecules responsible for the DIBs disappear, potentially due to accretion onto grains. Image courtesy Elyajouri et al. (2017). Bottom left: A typical 1.5273µ infra-red DIB from the SDSS/APOGEE survey. Image courtesy Elyajouri et al. (2016). Bottom right: Example of weak DIBs and their spectra profiles detected in high quality, high resolution spectra. The structures suggest different molecular carriers in the gaseous phase of the interstellar medium. Image courtesy Cami et al. (2018)

The US physicist T. Cravens was the first to understand the mechanism at work: charge-exchange between solar wind high-charge-state ions and neutrals outgassed by the comet (Cravens, 1997). After a solar wind ion has captured the electron from the neutral, the newly formed ion is excited and de-excites by emitting soft X-rays and EUV lines.

However, if this mechanism is at work, it must be applicable to any neutral encountered by the solar ions, in particular interstellar neutrals flowing in the Solar system. Computations of the corresponding spectra and emission pattern started and it was found that the emission pattern and the brightness of the solar wind charge-exchange emission (SWCX) are compatible with the background observed by ROSAT (Koutroumpa et al., 2009). Finally, and more recently, thanks to improved models and charge-exchange cross-sections, and new data and shadowing techniques, the situation was clarified: the LB is filled with hot gas, but about half of the emission is due to the solar wind and subsequently the hot gas pressure is smaller, in better agreement with the embedded clouds.

Today, the Solar system X-ray emission is removed from the astronomical X-ray observations of diffuse objects. Moreover, SWCX emission was detected from Mars, Venus, Jupiter, Saturn, and an ESA-CAS space mission is under preparation to observe the X-ray emission from the Earth magnetosheath. But the story does not end here: the CX mechanism can be applied in principle to any type of dynamical interaction between hot gas with charged ions and cool gas, at least partially neutral (Lallement, 2004). There is a growing number of evidences that it is the case in some active star-bursting galaxies, some supernovae, or even within galaxy clusters.

According to the 3D maps of the interstellar clouds, the motion of the Sun, and the motion of the nearby clouds, the trajectory of our star will bring it in about 6 million years in much denser regions, namely those that are at the periphery of the LB (and to the right in Fig. 5, top-left). Hopefully, it will avoid the (fortunately rare) dark clouds, in which light is so strongly absorbed by dust that humans living at this time would be deprived of starry nights, i.e., night skies would show planets only.

Other potential and more dangerous consequences of dense cloud crossings have been investigated. As a matter of fact the properties of the encountered circumsolar ISM govern the strengths of the interactive processes at work in the solar wind-ISM transition region, the resulting shape and size of the heliosphere and the distance at which the solar wind is stopped in its expansion and repelled, the boundary of the "heliosphere". During the encounter with a compact cloud, the heliosphere may shrink within the Earth orbit in response to the high interstellar pressure in the dense cloud, removing the protection brought by the solar wind *cocoon* against most of the Galactic cosmic rays. Accretion of interstellar matter onto the Earth through gravitational focusing is also to consider.

On the other hand, of more interest today is the observation of other *astrospheres*, i.e. interfaces between stars and the surrounding ISM they are traveling through. The Moscow team has started today to extend the modeling of our heliosphere to astrospheres observed by new generation instruments. They may teach us a number of interesting properties of both the stellar winds and the physical parameters of the clouds, providing interesting perspectives (Izmodenov et al., 1999; Katushkina et al., 2018).

4. COMET SAMPLE RETURN: A CLUE TO THE 70-YEAR-OLD MYSTERY OF THE DIFFUSE INTERSTELLAR BANDS?

In future, Solar system observations may bring answers to crucial and longstanding questions on the interstellar matter, again in an unexpected way and again thanks to comets. The recent spectacular and very successful ESA *Rosetta* mission to comet 67P/Churyumov-Gerasimenko has changed our view on comet formation. First, the unexpected measurements of volatile gases such like argon strongly favour the so-called *gentle hierarchical accretion* scenario (Davidsson et al., 2016). According to it, comets start to form through coagulation of small grains from the proto-solar nebula, followed by continuous accretion and coagulation of solids of increasing size. Indeed, the two-lobe shape of comet 67P in this case would be the latest step of accretion of large solids. Others scenarios that invoke violent collisions and fragmentations of Trans-Neptunians Objects (TNOs) to form comets cannot account for the presence of noble gases such as argon because they would have fully evaporated. The second major result from *Rosetta* is the very large fraction of organic matter. Composition measurements of the grains with the COSIMA ion beam and time-of-flight mass spectrometer show that the ratio of organic to mineral matter reaches ~80 % (Bardyn et al., 2017). Third major result is high abundance of very large organic molecules (Fray et al., 2016). The molecules are not directly characterized, however, this result can be deduced from the measurements of the fragments ejected from the grains by the ion beams, namely CH^+, CH_2^+, and CH_3^+, similarly to what is obtained using the most primitive parts of meteorites.

This ensemble of results has interesting implications. Since it leaves room for the presence of unaltered interstellar material in the comet nucleus, it opens new perspectives for interstellar matter studies. In a recent paper, it was suggested that the 70-year-old puzzle of the yet-unidentified diffuse interstellar bands (DIBs) could be at least partially solved by a comet sample return mission (Bertaux, Lallement, 2017). DIBs are hundreds of absorptions observed in the light of stars that are located behind one or more interstellar clouds. Despite 70 years of stellar spectroscopic observations and laboratory experiments, none of the DIBs could be assigned a specific carrier, except, very recently, for the quasi-certain identification of the buckminsterfullerene CH_{60}^+, a cage-like macromolecule that resembles a soccer ball (see, e.g., Cordiner et al., 2017; Lallement et al., 2018). Importantly, the shapes of the DIBs and their variety favour their origin in a very wide population of large organic molecules distributed in interstellar clouds. Because such molecules are key species in the chain of processes that affect interstellar grains from their birth sites around evolved stars to collapsed dense clouds, and finally to proto-solar, proto-planetary matter, their identification is mandatory to understand this otherwise still uncertain cycle. Recent studies of the links between DIBs and reddening show that DIBs attenuate strongly and almost disappear in the densest cores of the interstellar clouds. This is observed statistically and also for individual clouds (Lan et al., 2015; Elyajouri et al., 2017) and it has been interpreted by Bertaux and Lallement (2017) and Elyajouri et al. (2017) as the coagulation-accretion of the DIB molecular carriers onto the grains and participation to the observed grain growth in the cloud cores. In addition to the DIB disappearance, Bertaux and Lallement (2017) show a positive link between this disappearance and the fraction of small grains that produce the so-called UV-rise in the interstellar reddening curve and they go one step further. Estimating the amount of interstellar carbon locked in DIB carriers they find it compatible with the amount of carbon of interstellar origin in comet 67P and argue that this similarity favours the presence of the DIB carriers, possibly unaltered during the *gentle hierarchical accretion*, in the coagulated material of the comet. According to this view, it is foreseen that a cometary sample return mission followed by state-of-the-art laboratory analyses of the sample could lead to the identification of the organic molecules that are present in interstellar space and are responsible for the DIBs.

CONCLUSION

Science around the Solar system-ISM connection, and especially served by pioneering space experiments, has been the opportunity to start a fruitful, exciting and friendly collaboration between Russian and French scientists, and colleagues from other countries. This collaboration is continuing today, and is taking various and new forms, which is a sign of good health... Several projects are in preparation, a long way to go… but this is beyond the scope of this presentation in the frame of the celebration of 60 years of Space age: so lets celebrate first how far we've come already together in this scientific adventure!

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PLANETS AND THEIR SATELLITES: 60 YEARS OF SOLAR SYSTEM EXPLORATION

The historic Soviet Sputnik mission in 1957 began a spectacular era of space exploration. With the tremendously successful flyby of the Pluto system by the *New Horizons* spacecraft in July 2015, humankind completed its initial survey of our Solar system within the first 60 years. Solar system exploration has always been and continues to be a grand human adventure that seeks to discover the nature and origin of our celestial neighborhood and to explore whether life exists or could have existed beyond Earth. Before Sputnik, everything we knew about our Solar system came from ground-based telescope observations and from analysis of meteorites. This limited perspective couldn't begin to reveal the diversity and the rich nature of the planetary environment. This short overview will address how space agencies have approached a comprehensive series of missions, heralded in by Sputnik, for the last 60 years and makes some new assertions as to how Solar system exploration will continue over the next 60 years.

INTRODUCTION

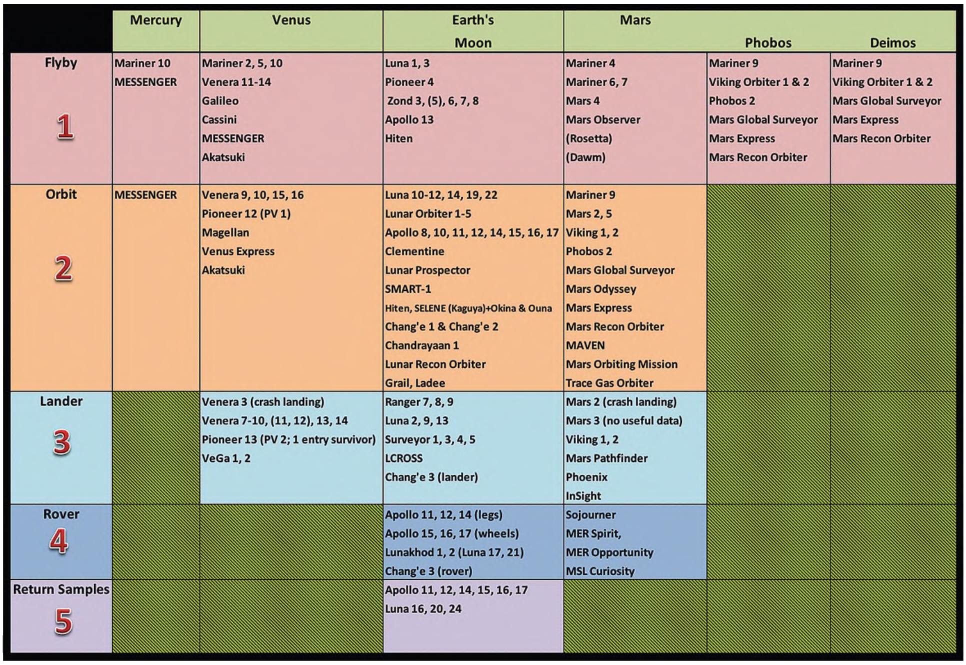
Solar System exploration has followed a general mission paradigm of "fly-by, orbit, land, rove, and return samples". A complete campaign may not be performed for each object in the Solar system, since not all pertinent scientific questions can be studied at all objects, and there are difficult technological challenges and financial obstacles to overcome depending on the mission and/or the destination. Moreover, a healthy program of Solar system exploration requires a balance between detailed investigations of a particular target and broader reconnaissance of a variety of similar targets. This mission paradigm approach is summarized in Fig. 1 for the inner Solar system and Fig. 2 for the outer Solar system, showing progress made in our exploration efforts.

By following the above paradigm, the space agencies have forged a path of significant progress in our knowledge and understanding and developed a strategy for future exploration as well. For the past 60 years, key scientific goals have been focused on advancing scientific knowledge of the origin and evolution of the Solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space. The quest to understand our origins is universal. How did we get here? Are we alone? What does the future hold? Modern science, and especially space science, provide extraordinary opportunities to pursue these questions.

1. FLYBY MISSIONS

Flyby missions are designed to obtain the most basic information on their target bodies. Early flyby missions also enabled space agencies to navigate between planets. This early trek into the Solar system was accomplished with flybys to each planet in our local neighborhood as shown in Fig. 1. U. S. *Mariner* and Soviet *Venera* missions surveyed and inventoried the inner planets Mercury, Venus, and Mars. For the National Aeronautics and Space Administration (NASA), *Mariner 2* was just the first robotic space probe to conduct a successful planetary flyby, and the first step in a long journey. The scientific instruments on-board were two radiometers (microwave and infrared), a micrometeorite sensor, a solar-plasma sensor, a charged-particle sensor, and a magnetometer. These instruments measured the temperature distribution on the surface of Venus, made basic measurements of Venus' atmosphere, discovered the solar wind (the first experimental observation of solar wind was made by the instruments on-board Soviet *Luna 2* in 1959. — *ed.*), and determined that Venus, unlike Earth, has no intrinsic magnetic field.

The first two *Venera* spacecraft were designed as flyby missions, but after several flyby failures the Union of Soviet Socialist Republics (USSR) began targeting *Veneras* directly into the planet Venus, using the planet's extensive atmosphere to slow them down during entry.



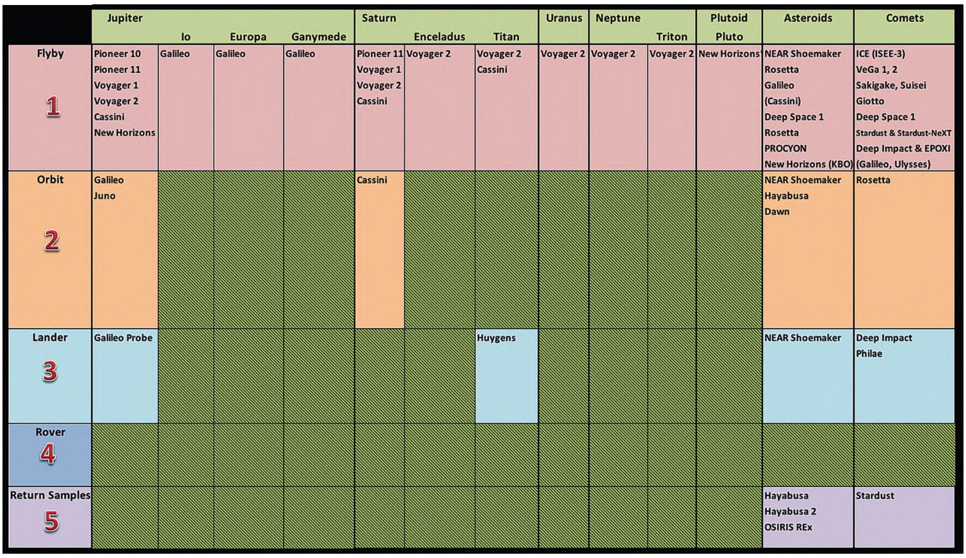
	Mercury	Venus	Earth's Moon	Mars		
					Phobos	Deimos
Flyby 1	Mariner 10 MESSENGER	Mariner 2, 5, 10 Venera 11-14 Galileo Cassini MESSENGER Akatsuki	Luna 1, 3 Pioneer 4 Zond 3, (5), 6, 7, 8 Apollo 13 Hiten	Mariner 4 Mariner 6, 7 Mars 4 Mars Observer (Rosetta) (Dawm)	Mariner 9 Viking Orbiter 1 & 2 Phobos 2 Mars Global Surveyor Mars Express Mars Recon Orbiter	Mariner 9 Viking Orbiter 1 & 2 Mars Global Surveyor Mars Express Mars Recon Orbiter
Orbit 2	MESSENGER	Venera 9, 10, 15, 16 Pioneer 12 (PV 1) Magellan Venus Express Akatsuki	Luna 10-12, 14, 19, 22 Lunar Orbiter 1-5 Apollo 8, 10, 11, 12, 14, 15, 16, 17 Clementine Lunar Prospector SMART-1 Hiten, SELENE (Kaguya)+Okina & Ouna Chang'e 1 & Chang'e 2 Chandrayaan 1 Lunar Recon Orbiter Grail, Ladee	Mariner 9 Mars 2, 5 Viking 1, 2 Phobos 2 Mars Global Surveyor Mars Odyssey Mars Express Mars Recon Orbiter MAVEN Mars Orbiting Mission Trace Gas Orbiter	▨	▨
Lander 3	▨	Venera 3 (crash landing) Venera 7-10, (11, 12), 13, 14 Pioneer 13 (PV 2; 1 entry survivor) VeGa 1, 2	Ranger 7, 8, 9 Luna 2, 9, 13 Surveyor 1, 3, 4, 5 LCROSS Chang'e 3 (lander)	Mars 2 (crash landing) Mars 3 (no useful data) Viking 1, 2 Mars Pathfinder Phoenix InSight	▨	▨
Rover 4	▨	▨	Apollo 11, 12, 14 (legs) Apollo 15, 16, 17 (wheels) Lunakhod 1, 2 (Luna 17, 21) Chang'e 3 (rover)	Sojourner MER Spirit, MER Opportunity MSL Curiosity	▨	▨
Return Samples 5	▨	▨	Apollo 11, 12, 14, 15, 16, 17 Luna 16, 20, 24	▨	▨	▨

Fig. 1: The current exploration paradigm of flyby, orbit, land, rove, and return samples for the inner Solar system

The *Venera 5* and *6* atmospheric probes lasted long enough to provide significant atmospheric data. *Venera 7*, designed to survive all the way to the surface, landed and transmitted for about 20 minutes before its battery died. The Soviet *Venera* missions greatly extended our knowledge of Venus and still remain today the most significant lower atmosphere and surface measurements from that planet. These powerful set of observations fueled our fascination with our neighborhood and our desire to learn more.

The principle of gravitational assist was exploited early to provide a method of increasing or reducing the speed of a spacecraft without the use of propellant. The *Mariner 10* spacecraft was the first to use gravitational assist to reach another planet by swinging by Venus on February 5, 1974. This maneuver placed it on a trajectory to fly by Mercury a total of three times, twice in 1974 and once in 1975. The recent MESSENGER mission used the same approach, executing two Venus and three Mercury flybys before entering into orbit around Mercury in March 2011.

As shown in Fig. 2, the outer Solar system had flybys with two *Pioneer* and two *Voyager* spacecraft. The *Voyager* flyby missions completely changed the way we view the outer Solar system. The primary mission of *Voyager 1* and *2* was the exploration of the Jupiter and Saturn systems. After making a string of discoveries there, such as active volcanoes on Jupiter's moon Io and the intricacies of Saturn's rings, the mission was given the approval to continue to the next planet. *Voyager 2* went on to explore Uranus and Neptune and is still the only spacecraft to have visited these outer ice giant planets.



	Jupiter				Saturn			Uranus	Neptune		Plutoid	Asteroids	Comets
		Io	Europa	Ganymede		Enceladus	Titan			Triton	Pluto		
Flyby 1	Pioneer 10 Pioneer 11 Voyager 1 Voyager 2 Cassini New Horizons	Galileo	Galileo	Galileo	Pioneer 11 Voyager 1 Voyager 2 Cassini	Voyager 2	Voyager 2 Cassini	Voyager 2	Voyager 2	Voyager 2	New Horizons	NEAR Shoemaker Rosetta Galileo (Cassini) Deep Space 1 Rosetta PROCYON New Horizons (KBO)	ICE (ISEE-3) VeGa 1, 2 Sakigake, Suisei Giotto Deep Space 1 Stardust & Stardust-NeXT Deep Impact & EPOXI (Galileo, Ulysses)
Orbit 2	Galileo Juno	▨	▨	▨	Cassini	▨	▨	▨	▨	▨	▨	NEAR Shoemaker Hayabusa Dawn	Rosetta
Lander 3	Galileo Probe	▨	▨	▨	▨	▨	Huygens	▨	▨	▨	▨	NEAR Shoemaker	Deep Impact Philae
Rover 4	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Return Samples 5	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Hayabusa Hayabusa 2 OSIRIS REx	Stardust

Fig. 2: The current exploration paradigm of flyby, orbit, land, rove, and return samples for the outer Solar system

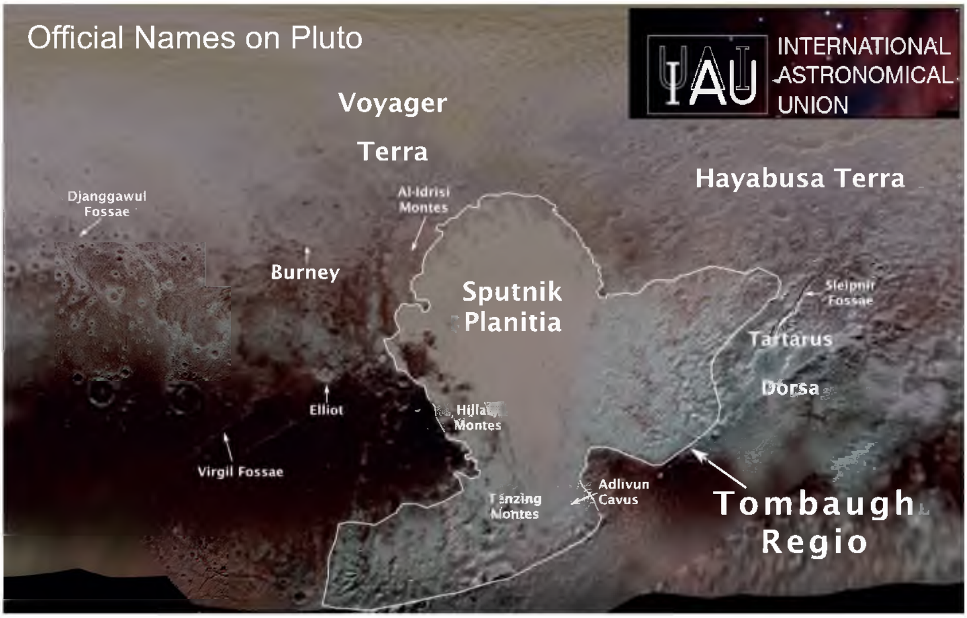


Fig. 3: Official names on Pluto as approved by the International Astronomical Union highlighting a number of historic explorers including Sputnik, which heralded in the space age

Voyager 1 and *2* are still operating and are currently exploring the region near the heliopause, and as of this writing (April 2018) are at 141.3 and 117.1 Astronomical Units (AU) from Earth, respectively, continuing into the fourth decade of their journey since their 1977 launches (see https://voyager.jpl.nasa.gov/mission/status/). In August 2012, data transmitted by *Voyager 1* indicated that it made a historic entry into interstellar space, the region between the stars, filled with the solar winds of nearby stars.

As part of NASA's New Frontiers program, the *New Horizons* mission made the first reconnaissance of the dwarf planet Pluto (at 39 AU from Earth) and is now venturing deeper into the distant, mysterious Kuiper Belt, a relic of early Solar system formation. *New Horizons* was launched on January 19, 2006, from Cape Canaveral, Florida, directly into an Earth-and-solar-escape trajectory with an Earth-relative speed of about 16.26 km/s. After a brief encounter with asteroid 132524 APL, *New Horizons* proceeded to Jupiter, making its closest approach on February 28, 2007. The Jupiter flyby provided a gravity assist that increased *New Horizons*' speed by 4 km/s. The encounter was also used as a general test of *New Horizons*' scientific capabilities, as the spacecraft returned data about the planet's atmosphere, moons, and magnetosphere.

Most of the spacecraft's post-Jupiter voyage was spent in hibernation mode to preserve onboard systems, except for brief annual checkouts. On January 15, 2015, the *New Horizons* spacecraft successfully came out of hibernation and began its approach phase to the Pluto system, which resulted in the first flyby of the dwarf planet on July 14, 2015. In honor of the accomplishments of our early explorers, the official International Astronomical Union designation of the large nitrogen glacial region on Pluto has been named *Sputnik Planitia* as shown in Fig. 3. *New Horizons* has been given the approval to target and flyby another Kuiper Belt Object, nicknamed Ultima Thule which it will flyby on New Year's Day 2019. After this flyby, *New Horizons* will continue on an escape trajectory. Like with *Voyager 1*, scientists hope to learn more when *Voyager 2* and *New Horizons* pass out of the heliosphere and begins measuring interstellar winds.

2. MISSIONS THAT ORBIT

Beyond flybys, the next most sophisticated type of mission is designed to get a spacecraft into orbit around a Solar system object. Data from flyby missions were essential to prioritize which objects to orbit. High-resolution data from an orbiter mission are essential to planning for a future lander or rover mission.

With the Moon as a main target and a precursor to human missions to the Moon, the Soviet *Luna* missions included hard and soft landers, several orbiters, and some sample returns but no flybys; the *Zond* missions included three successful flybys and two successful circumlunar flights. *Pioneer 4* appears to be the only *Pioneer* flyby of the Moon.

After flyby missions, scientists wanted to learn much more about the basic properties of our planetary neighbors such as structure, size, density, and atmospheric and surface composition. NASA's *Magellan*, the European Space Agency's (ESA) *Venus Express*, and the Japanese Space Agency's (JAXA) *Akatsuki* spacecraft have orbited Venus. The world's space agencies have sent armadas of spacecraft to orbit the Moon and Mars. For the outer planets, after the *Galileo* orbiter to the Jupiter system, *Juno*, launched in August 2011, got into orbit in July 2016, while the *Cassini/Huygens* mission orbiting Saturn since the summer of 2004 came to an end by plunging into the planet in September 2017.

As our nearest neighbor, the Moon continues to be a natural laboratory for investigating fundamental questions about the origin and evolution of the Moon and the bombardment history of the inner Solar system. The Moon provides an excellent target for many new space agencies to begin their programs of solar system exploration. Launched to the Moon in 2007, JAXA's *Kaguya* and then *Chang'e 1*, which became the Chinese National Space Agency's (CNSA) first lunar-orbiting spacecraft, part of an extensive Chinese Lunar Exploration Program followed by *Chang'e 2* (launched in October 2010). The Indian Space Research Organization (ISRO) launched their very successful Lunar orbiter *Chandraayan 1* in 2008. Launched in 2009, NASA's *Lunar Reconnaissance*

Orbiter (LRO), a robotic mission that has mapped the Moon's surface at high resolution (~1 m^2), is still operating as of this writing making it the mission that has operated the longest at the Moon (over 109 lunar months). LRO's data are being used worldwide for determining lunar landing sites. These new lunar missions have enabled numerous groundbreaking discoveries, creating a new picture of the Moon as a dynamic and complex body even maintaining volatiles.

The Russian Roscosmos State Corporation is currently planning a new series of lunar missions starting with the soon to be launched *Luna 26*, a lunar orbiter that will perform global studies of the Moon. In addition, South Korea is also planning a Korean *Path Finder Lunar Orbiter* that will be launched within the next couple of years.

Planetary scientists have made significant and steady progress in understanding what Mars is like today and what it was like in its distant past. The exploration of Mars is currently being accomplished by an international array of missions from NASA, ESA partnering with Roscosmos, and ISRO. Orbiter missions operating at Mars include *Mars Odyssey*, *Mars Express*, *Mars Reconnaissance Orbiter*, *Mars Atmosphere and Volatile EvolutioN Mission* (MAVEN), *Mars Orbiter Mission*, and the *ExoMars Trace Gas Orbiter*.

3. LANDER AND ROVER MISSIONS

Lander and rover missions enable scientists to acquire "ground truth" measurements necessary to fully interpret the data obtained from previous orbital missions. It has been the inner Solar system objects, Venus, the Moon, and Mars that have had a number of lander and rover missions. USSR has dominated successful *in situ* surface exploration of Venus, while the US has done the same for Mars, but the Moon has seen a number of highly successful surface and rover missions with China joining Russia and the US as shown in Fig. 1.

More recently, the successful landings of missions such as the one-metric-ton NASA *Curiosity* rover on Mars and the ESA *Rosetta* mission's *Philae* probe on comet Churyumov-Gerasimenko clearly show the ability of our space agencies to explore our Solar system at a new level of intensity. It is steps like these that will allow humans to go beyond this planet and out into the Solar system once again.

Curiosity has been on the surface for approximately three Mars years. From its data we now know that Mars was more Earthlike in its distant past, with rivers, lakes, streams, a thick atmosphere, clouds and rain and perhaps, an extensive ocean. Although today Mars is rather arid, scientists believe that vast amounts of water are trapped under the planet's surface and under the carbon dioxide snow of its northern polar cap. Water is the key that will enable future human activity and long-term presence on Mars.

4. SAMPLE RETURN

Sample return provides scientists with essential data to understand the geological history of a body and in some special cases look for evidence of past life. Up to the present, space agencies have collected samples from several Solar system bodies, as well as samples of the solar wind. The USSR *Luna* and NASA *Apollo* programs in the late 1960s and early 1970s brought back over 850 pounds of Moon rocks, soils, and regolith. These materials are still being analyzed and yielding significant scientific results. Roscosmos has upcoming plans for cryogenic return of lunar samples from the south polar region with Luna 28 in mid-2020s.

It is also important to note that many of the meteorites that have fallen on Earth can now be identified with specific Solar system bodies such as the Moon, Mars, and Vesta. The comet Wild 2 and the asteroid Itokawa were visited by robotic spacecraft from NASA and JAXA, respectively, both returning unique samples. Upcoming missions to very large carbonaceous chondrites include NASA's OSIRIS-REx mission to Bennu and JAXA's *Hayabusa 2* mission to Ryugu. These asteroids are some of the most primitive known and are believed to contain significant complex carbon compounds including amino acids. When these samples will be returned before 2024, it is expected that a new leap in understanding the early formation period of the solar system will emerge.

NASA's *Mars 2020* rover mission, currently in development, is based on the design of the highly successful *Mars Science Laboratory* rover, *Curiosity*. This rover will carry sophisticated hardware and new instruments to conduct geological assessments of its landing site, determine the potential habitability of the environment, and directly search for signs of ancient Martian life by contact instruments as well as by coring and storing rock samples for later return to Earth. In addition, JAXA's *Martian Moons eXploration* (MMX) mission will orbit the Mars moons Phobos and Deimos and bring back samples from Phobos. Other sample return missions are being considered that will usher in a new decade of solar system exploration.

5. THE NEXT 60 YEARS

Our robotic Solar system explorers have gathered data to help us understand how the planets formed, what triggered different evolutionary paths among the planets, what processes are active, and, thus, how our own planet formed, evolved, and became habitable. To search for evidence of life beyond Earth, we have used these data to map zones of habitability, study the chemistry of unfamiliar worlds, and reveal the processes that lead to conditions necessary for life.

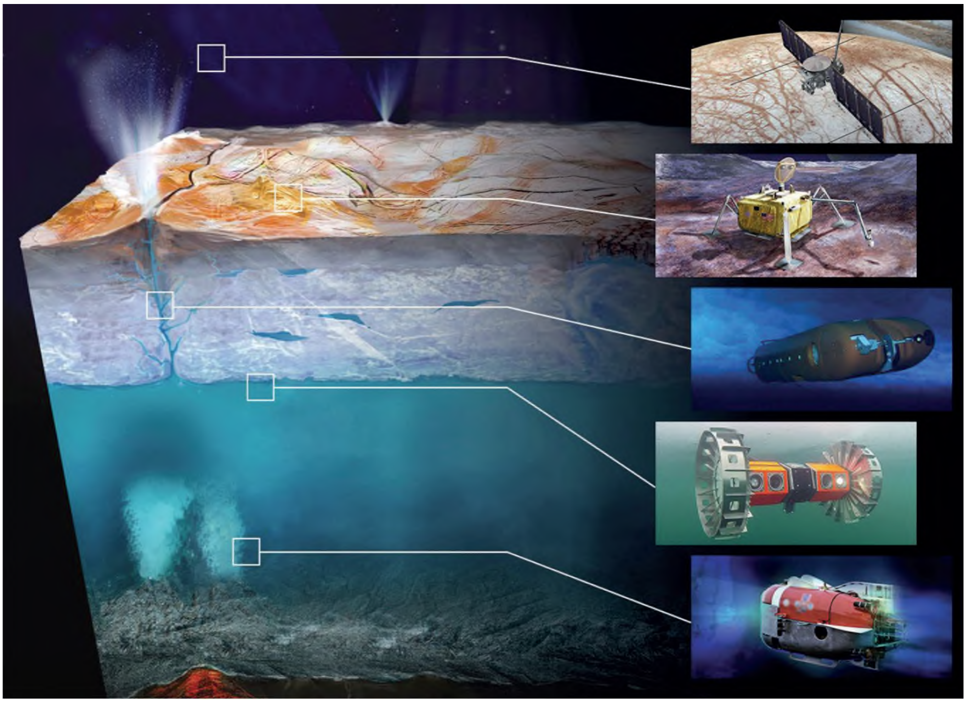


Fig. 4: For the ocean worlds of the outer planets we will pursue a new exploration paradigm encompassing: orbit, land, submerge, and explore their deep oceans with new autonomous submarines

This overview touches on only a few examples in each of the categories that have defined our approach to Solar system exploration for the last 60 years. We are now entering a new era of space exploration as we start to execute more complex missions that will land, rove, and return samples from top-priority targets in the Solar system. Those are the remaining regions in Fig. 1 and 2 that have not had missions to date.

In addition to our current approach of flyby, orbit, land, rove, and return samples, a new paradigm is also emerging. One of the most exciting discoveries has been in the outer Solar system. Missions led by NASA have made a major discovery that there are many large, salt-water oceans inside icy moons of the giant planets. NASA's *Galileo* mission found liquid water under the thick ice crusts of Europa, Ganymede, and Callisto at Jupiter. Europa is particularly enticing, and NASA is currently developing the *Europa Clipper* mission to assess its potential habitability and interrogate the thickness of its ice shell. At Saturn, *Cassini* found that Titan, the only moon in the Solar system with a dense atmosphere, and Enceladus, a tiny moon, also have deep global water oceans. Enceladus spews its ocean water into space in the form of geysers through huge cracks in the southern polar regions. Direct analysis by *Cassini*'s instruments reveals seafloor hydrothermal activity, and organic molecules in its water, but without modern instruments we cannot tell whether its ocean contains life. Is it possible that these hydrothermal vents are essential to life? On Earth, we find rich communities of organisms living off the chemistry of water-rock interactions, and the oceans of both Enceladus and Europa are believed to be in contact with their rocky interiors.

New technologies will enable space agencies to develop and execute an astounding range of more complicated and challenging missions. For these new ocean worlds, we must pursue a new exploration paradigm. Fig. 4 shows that we must orbit, land, submerge, and explore these deep oceans with new autonomous submarines. For these missions, we will depend on how we are exploring our own Earth oceans as a guide. We are at the leading edge of a journey of exploration that will yield a profound new understanding of the Solar system as our home.

Robotic exploration not only yields knowledge of the Solar system. It also will enable the expansion of humanity beyond low Earth orbit. By studying and characterizing planetary environments beyond Earth and identifying possible resources, planetary scientists will enable safe and effective human missions into space. Scientific precursor missions to the Moon will enable the return of humans to explore while we have also made significant progress toward enabling human missions to Mars within the next 60 years. A single-planet species may not long survive. It is our destiny to move off this planet and into the Solar system. We are developing the capability to do it.

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GEOLOGICAL EVOLUTION OF THE TERRESTRIAL PLANETS: 60 YEARS OF EXPLORATION AND DISCOVERY

Sputnik 1 ushered in an intense phase of exploration of the terrestrial, or Earth-like, planetary bodies, the Moon, Mercury, Mars and Venus, and a new era of Comparative Planetology. Each step of exploration in the first 60 years of the Space Age provided insight into the basic themes in planetary formation and evolution, and began to fill in the missing chapters of the formative years of the history of our own Home Planet, Earth. The next 60 years of the Space Age has already been launched, with a census of exoplanets orbiting other stars, and the study of Comparative Planetary Systems.

INTRODUCTION

The launch of Sputnik 1 on October 4, 1957 revolutionized many political, social, and cultural paradigms, and completely changed the personal perspective of humans. No longer were we individuals whose perspectives were dominated by our immediate surroundings, interrupted daily by the arrival of the newspaper to deliver more distant news. Instead, Sputnik 1 ushered in an era global awareness, instant communications, and world citizenship. No astronaut, cosmonaut or taikonaut returns to Earth unaffected by this global perspective, and a sense of awe and alarm at the thin, tenuous nature of the Earth's atmospheric envelope. And *Apollo 8*; images of the entire Earth from space, the "Blue Marble" surrounded by the vast darkness of space. And Earthrise on the Moon! We began to see ourselves as a planet, Planet Earth.

Few scientific disciplines were more affected by this change than geology. Geologists tended to work in the field, studying the outcrops of rocks, their orientation, nature and age, and piecing together the results into a geological map of a "quadrangle", an artificially defined manageable area dictated by latitude and longitude. The perspective of the individual geologist in the field was that of a "personal panorama": What can I see and understand in my field of view, and how is my perspective changed by climbing over the next hill? The more venturesome geologists combined these maps into State geologic maps, and then into National geological maps. Some intrepid geologists even ventured abroad, and found that the geology was often quite different, or revealed a different part of Earth history. But few were brave enough to claim to know or understand the geology of the entire planet.

The launch of Sputnik 1 instantly changed the perspective of the individual geologist from a "personal panorama" to a "global perspective". Suddenly we could view entire mountain ranges, continents, and their relationships. We quickly realized that the Earth was a planet, an entity that could be viewed as an interconnected whole, whose history could not be viewed solely through the lens of a parochial "regional" perspective. Quickly following the appreciation of the global perspective, that of the Earth as a planet, was the realization that the Earth was only one member of a family of planets and satellites in the Solar system, and that these planetary bodies might hold insights and perspectives on the geological processes and history of our own Home Planet, Earth. Thus, the field of Comparative Planetology was born (Fig. 1, 2). What could we learn from the other Earth-like, "terrestrial" planetary bodies, the Moon, Mars, Mercury and Venus? What insights would they reveal about how Earth-like planets form and how they work?

It has been 60 years since the launch of Sputnik 1, the first 60 years of the Space Age. What has comparative planetology of the terrestrial planets taught us about the Moon, Mercury, Mars and Venus, and about the nature and history of our own Home Planet, Earth? In this contribution, we trace the exploration of the terrestrial planets, the findings and insights that have accrued, how they provide perspective on Earth, and where we are going in the coming decades. We accomplish this through a narrative that differs from a traditional scientific paper. It is impossible to cite individually the tens of thousands of scientific papers that have built this paradigm. Instead, we cite a series of books, review papers and synthesis contributions that can lead the interested reader to more details. We hope that this narrative review encourages the reader to seek out the exciting details of the individual building blocks that form the foundation of our new understanding. We challenge the reader to use this as a framework to formulate the critical questions that will propel us to even deeper understanding in the future as we move from comparative planetology to comparative planetary systems.

Fig. 1: The terrestrial, or Earth-like planets in our Solar system, in order of decreasing size; Earth, Venus, Mars, Mercury and the Moon. Image courtesy NASA

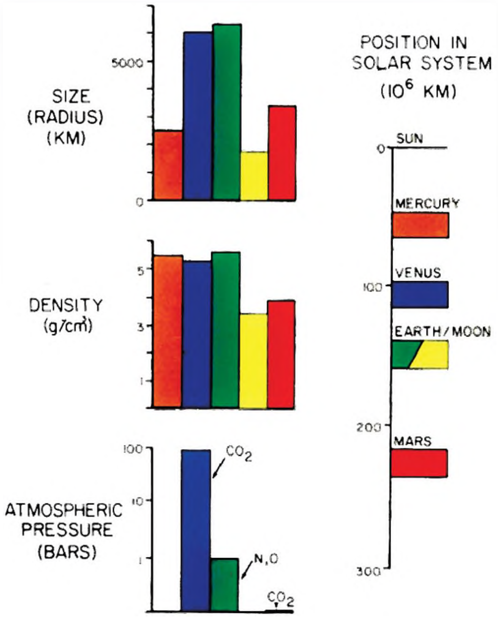

Fig. 2: The basic characteristics of the terrestrial planets: size, density, atmospheric pressure and position in the Solar system

1. EARTH

The launch of Sputnik 1 and the consequent era of planetary exploration caused some, and occurred amidst other, scientific revolutions. Exploration of Earth's seafloor, its topography and magnetic anomalies, began to provide substance to the theory of continental drift and reveal mechanisms, such as seafloor spreading, as the cause of continental separation. This complimented the Sputnik-inspired orbital view of the Earth as a planet, showing how Global Plate Tectonics (seafloor spreading, continental drift, subduction) could account for the globally integrated processes responsible for the current state and recent history of the Earth. The second parallel revolution was the perspective of the Earth in the context of the Solar system, one of many bodies orbiting the Sun, with common starting points, potentially related phases of evolution and a shared fate. The synoptic view of the Earth provided by orbiting spacecraft was duplicated step by step for the Moon, Mercury, Mars, and Venus. With each step, and with the follow-on landers, rovers and human explorers, the terrestrial planetary bodies transitioned from astronomical objects to geological objects.

As exploration of the Earth as a planet intensified (Fig. 3a), it became clear that the newly explored ocean basins were very young geologically (Fig. 3b), less than ~200 million years old, two-thirds of the planet having formed in the last ~5% of the history of Earth! (Fig. 4).

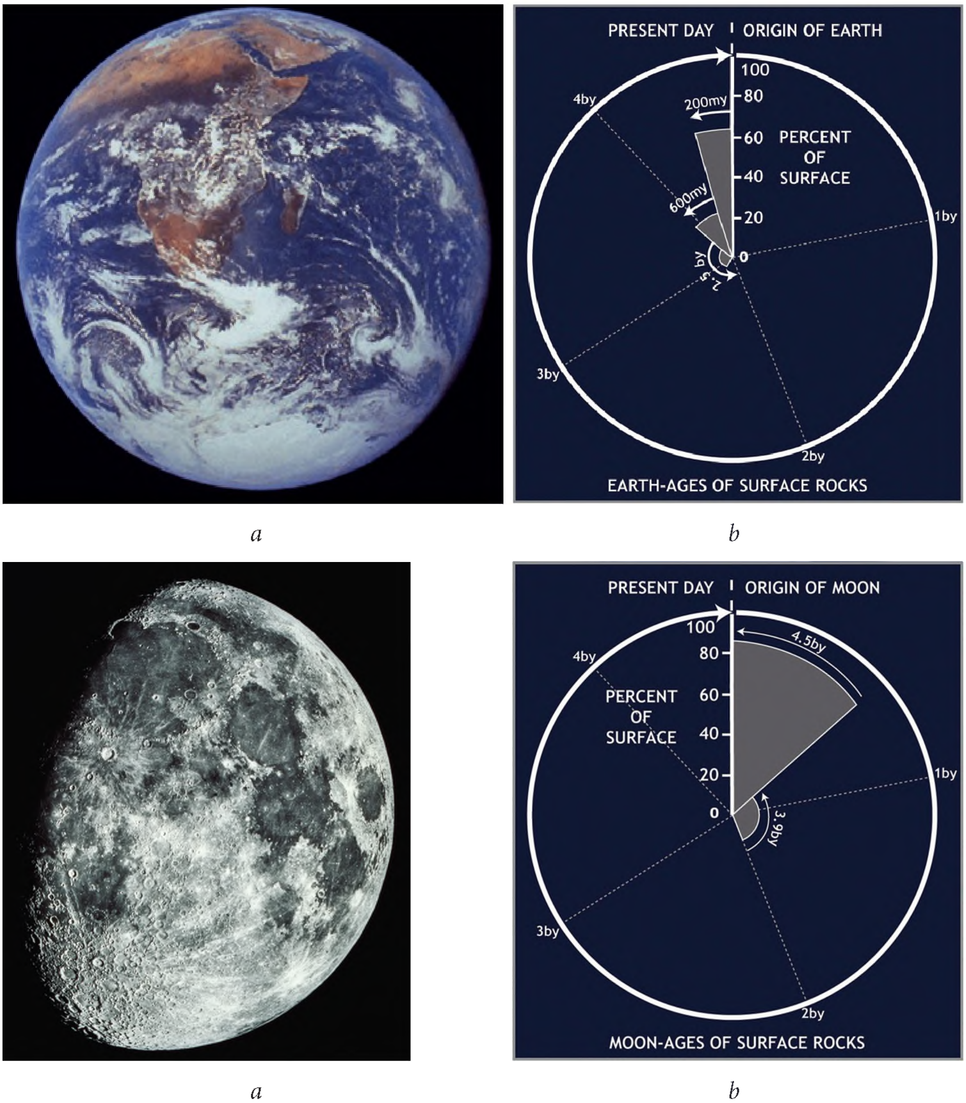

Fig. 3: The Earth and Moon, and the preservation of their geologic records: *a* — the Earth from space. Image courtesy NASA; *b* — the percentage of the Earth's geologic record preserved today as exposed surface rocks, portrayed as a clock. The vast majority of the Earth's surface rocks are very young and little remains from the first half of Solar system history; *c* — the Moon. Image courtesy NASA; *d* — the percentage of the Moon's geologic record preserved today as exposed surface rocks, portrayed as a clock. The vast majority of the Moon's surface rocks are very old, dating from the first half of Solar system history, and providing a complimentary record to the Earth

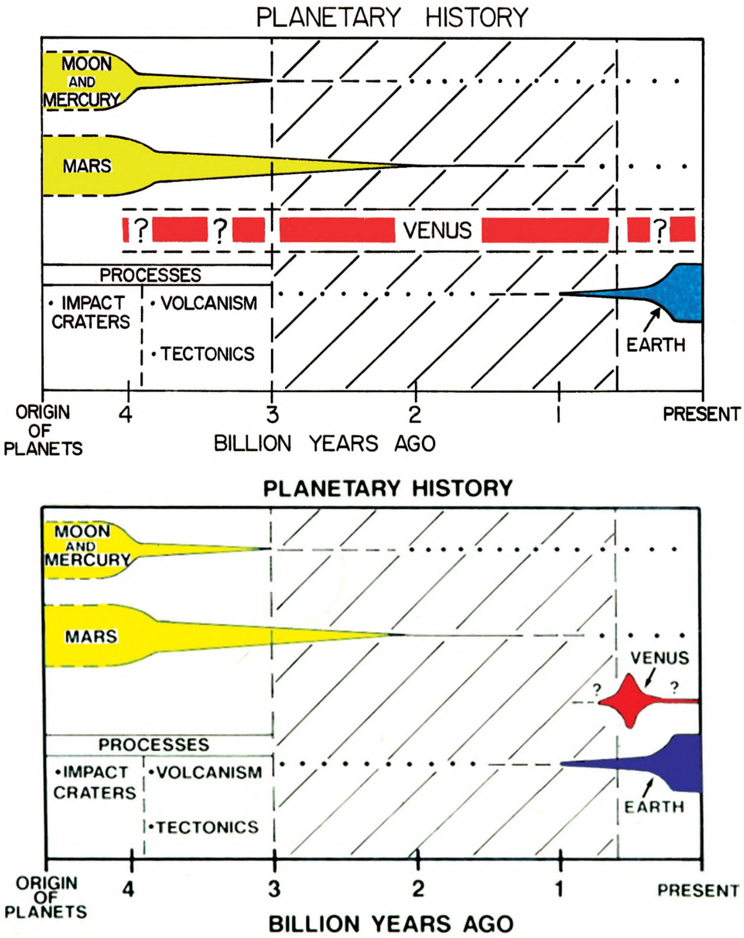

Fig. 4: Geologic history of the terrestrial planets. Plotted is the percentage of the exposed surface record dating from the time of formation of surface rocks (the thickness of the stripe for each planetary body. For example, the Earth's ocean basins make up the majority of the surface and are less than 200 million years old (thick part of the blue stripe), and fewer and fewer rocks are preserve from earlier in Earth history (the decreasing thickness of the line toward the past, left, and finally, dotted). The smaller terrestrial planetary bodies, the Moon, Mercury and Mars, retain exposed rocks from the first quarter of Solar system history (the broad yellow stripes to the left representing heavily cratered terrain) and then decrease in thickness toward the right (younger) as represented by volcanic resurfacing decreasing with time. Preservation of the geologic record on the smaller terrestrial planets reveals the nature of geologic processes operating in the early history (impact cratering, volcanism, and tectonism). (a) Knowledge prior to intensive Venus exploration. Would the surface of Venus be young and dominated by plate tectonics, like the Earth? Would it be heavily cratered and a one-plate planet, like the smaller terrestrial planets? Would Venus be a combination of these two? Would Venus be something completely different? (b) Knowledge subsequent to intensive Venus exploration. The surface of Venus turned out to be something completely different. The surface was young, like the Earth, but there was no evidence for active plate tectonics. The reasons for this remain a mystery

This, together with the very high erosion rate of continental regions caused by the atmosphere, hydrosphere, cryosphere, and biosphere, meant that the geological record of the first half of Earth history was largely obliterated, subducted and destroyed and essentially unavailable for geological study. This raised a series of very compelling questions about Earth: What is the history of the formative years? When did plate tectonics start? How and when did continents form? What was the early atmosphere like? When, and where, did life originate? We needed an understanding of the major processes operating in the first half of Solar system history. Where *is* the record of the major processes operating in the first half of Solar system history? Planets and moons began to join Earth as objects of geological interest and analysis (see Fig. 1, 2). The field of *Comparative Planetology* was born.

2. COMPARATIVE PLANETOLOGY

The geologists who ventured into this field, known variously as astrogeologists, planetary geologists or planetary geoscientists, began to work with new colleagues with a wide variety of backgrounds and training to formulate fundamental questions about the planets: How are they formed? What is their density and internal structure? What factors govern their evolution? How do they gain and lose heat? How do they gain, evolve, and retain atmospheres? What are the basic stages in their evolution? How do planets compare to each other? How do planets evolve together in a system? What environments/conditions are most conducive to life?

How do we gain answers to these questions? It became very clear that a comprehensive national and international planetary exploration program was necessary, but geologists were neither trained nor equipped to make this happen. What was needed was the development of what *Apollo 15* Commander David R. Scott called "science and engineering synergism". Scientists, working shoulder to shoulder with engineers could be mutually inspired and motivated to accomplish larger goals and objectives, and at the same time produce a scientific legacy that would last for generations. The exploration began!

Solar system exploration was not without political context. There were huge fiscal costs involved, and few planetary missions could be justified on the basis of science alone. National leaders realized that space exploration accomplishments were excellent examples of "soft power", demonstrations of technological expertise, organizational ability, and fiscal capability. Successful nations were world leaders, enjoying prestige (how others viewed them) and pride (how the nation viewed itself). Thus, another partnership was forged. How can scientists help national space agencies meet their country's political goals while at the same time optimizing the scientific return? Individual scientists, and national academies of science were to emerge as effective advocates for science in national planetary exploration programs. One of the foremost examples of such effective scientific leadership was Academician Mstislav Keldysh of the Soviet Academy of Sciences.

The culmination of this type of political context was shown in the US-Soviet "Space Race". In response to Cold War rivalry, in 1961 United States President John F. Kennedy challenged the population to land Americans on the Moon and return them safely, all by the end of the decade. This generated the *Apollo* Lunar Exploration Program that saw a politically motivated program become a series of unprecedented scientific expeditions thanks to the influence and efforts of scientists such as Gerald J. Wasserberg, Robert Walker, George Wetherill, James Arnold, Eugene Shoemaker and many others.

3. THE MOON

Prior to Sputnik 1, the farside of the Moon was unknown, and the origin of the dark lunar maria and the multitude of craters on the surface was debated. Was the Moon (Fig. 3c) formed hot or cold, were the craters of impact or volcanic origin, was the lunar surface young or old? *Luna*-3 revealed a lunar farside deficient in the darker maria. Early *Ranger*, *Lunar Orbiter*, *Surveyor*, *Luna* and *Zond* missions significantly augmented the pre-Sputnik telescopic observations and began to reveal the diversity of many of the lunar geologic landforms. The return of lunar soil and rock samples from the lunar surface by *Apollo* (11, 12, 14–17) and *Luna* (16, 20, 24) missions changed the debates almost overnight. The lunar rocks were ancient, all from the first half of Solar system history (Fig. 3d), and the oldest were anorthosites from the bright highlands and relatively younger, but still extremely older, basalts from the darker maria. Angular breccias showed the pervasive influence of hypervelocity impact processes, and soil breccias from the mare regolith showed that this was a continuing and ongoing process.

Assessment of lunar samples, recognition and study of impact craters on Earth, and detailed analysis of lunar landforms showed that impact cratering was the dominant process shaping the lunar surface at all scales. Impact craters, from small "zap pits" on lunar rocks all the way up to giant impact basins in excess of 2000 km diameter, formed the fundamental morphology and topography of the Moon. On the basis of radiometric dates, projectile bombardment and large basin formation peaked early in Solar system history, prior to about 3.7 billion years ago, but cratering subsequently continued to the present. The diversity of impact landforms, and changes in morphology with increasing size (simple bowl-shaped craters, complex flat-floored craters, peak-ring basins and multi-ring basins), augmented by laboratory experiments and study of terrestrial craters, all provided insight into the physics of the impact cratering process. The relatively unaltered lunar impact craters and basins became a baseline for the interpretation of this important process on other planetary bodies. Only a tiny handful of lunar craters were determined to be of volcanic origin. Instead, the large lunar impact basins formed receptacles for the collection of lunar basalt eruption products to form the circular lunar maria.

Volcanism was almost exclusively basaltic in nature and was often characterized by unusually high titanium content. Beginning at about the time of the decline in impact basin flux about 4 billion years ago, and often covered by basin ejecta (the cryptomaria), volcanic activity peaked between 3 and 4 billion years ago, and resurfaced about 20 percent of the Moon, predominantly on the nearside. The total volume of erupted maria is only a few percent of the total lunar crustal volume and records the generation, ascent and eruption of large-volume individual eruptions. Surface manifestations of eruptions include distinctive lava flow fronts, small cones and domes, and several volcanic complexes. Most interesting are the sinuous rilles, several hundred meandering river-like channels that are interpreted to represent thermal erosion associated with very high effusion rate, long duration basaltic eruptions. Missing is evidence for large Hawaii-like shield volcanoes and shallow magma reservoirs, testimony to the high magma ascent rates and large volumes of individual eruptions relative to those on Earth. Also of interest are the "dark mantles", deposits of pyroclastic beads that cover underlying topography and are interpreted to represent widespread explosive eruptive products caused by the volatiles forming, exsolving and erupting in a 1/6th Earth's gravity environment in the absence of an atmosphere. Although unusual features called "irregular mare patches" have been hypothesized to have been emplaced in the last tens of millions of years, the vast majority of lunar volcanic activity appears to have been emplaced by about 2 billion years ago. Several individual features, most notably the steep-sided Gruithuised Domes, have unusual spectral characteristics and might represent lunar granites, whose origins are still debated.

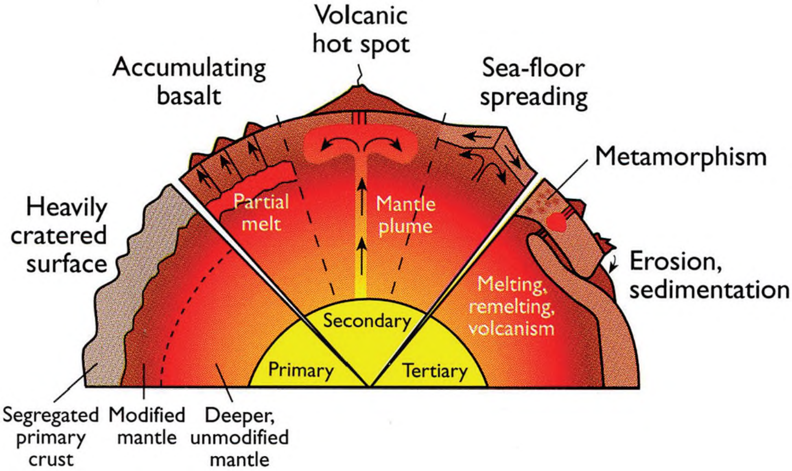

Fig. 5: The major types of heat loss and planetary lithospheres. The Earth loses its heat primarily by active plate tectonics, while the innermost of the Galilean satellites, Io, loses its heat by advection, the direct transfer of heat from the interior by volcanism. The smaller terrestrial planetary bodies, the Moon, Mercury and Mars, lost heat efficiently and have globally continuous lithospheres (one-plate planets) that lose heat primarily by conduction. Venus currently is a one-plate planet losing heat by conduction but experienced different modes of heat loss in the recent geologic past

The global tectonic patterns that characterize global plate tectonics on Earth (divergent and convergent plate boundaries and transform faults) were not found on the Moon. Circular and polygonal impact craters are excellent strain indicators, but few have been deformed and virtually none have been shortened or offset significantly. Instead of being subdivided into laterally moving and interacting lithospheric plates, as on Earth, the lunar lithosphere appears to have stabilized in early history such that the Moon is a "one-plate planet", a single global lithospheric plate that thickened with time (Fig. 5). The major lunar tectonic features are two-fold: 1) Linear and arcuate graben, extensional features formed primarily around lunar impact basins due to faulting associated with loading of the basin interiors by emplacement of several kilometers of basaltic mare fill and associated flexural deformation; linear graben also form above wide magmatic dikes that approach the surface and create near-surface extensional stress fields. 2) Wrinkle ridges and arches, contractional features also commonly associated with lunar mare deposits, and attributed to near-surface loading and subsidence. Graben tend to form earlier in lunar history than wrinkle ridges, an observation interpreted to mean that the global state of stress in the lithosphere transitioned from net extensional to net contractional at ~3.6 billion years ago, due to overall conductive cooling and contraction, and thickening of the one-plate planet global lithosphere.

Seismometers deployed by the *Apollo* astronauts revealed a crust, mantle and core. The crust, averaging about 60 km thick, was thicker on the lunar farside, and was composed predominantly of anorthosite, in contrast to the Earth's "granitic" continental and thinner basaltic oceanic crust. The lunar core was tiny compared to the mantle, in contrast to the mantle-core configuration of the Earth. In contrast to the lateral differences between the Earth's continental and oceanic crusts, the lunar anorthositic crust was globally continuous, with the basaltic lunar maria perched in depressions within the laterally continuous highlands crust.

How did this unusual crustal configuration come to be? Study of lunar highlands samples in terrestrial laboratories suggested that the early intense impact bombardment had melted the outer several hundred kilometers of the Moon, forming a molten "magma ocean" in which lower density plagioclase crystals floated to the top to form the "plagioclase flotation crust". Residue from this process may have been gravitationally unstable, and residual high titanium and KREEP (potassium, rare-earth elements, and phosphorus) layers may have foundered into the deeper lunar interior to form the source regions for subsequent mare basalts.

The Moon became a paradigm for different phases of crustal formation (Fig. 6): 1) primary crust, derived from the energy-associated accretion and early intense bombardment, 2) secondary crust, derived from partial melting of the mantle, and 3) tertiary crust, derived from reprocessing of primary and secondary crust. Clearly, the anorthosite crust is the primary curst and the lunar maria is the secondary crust; the more felsic Gruithuisen Domes could be a candidate for lunar tertiary crust. These crustal formation phases provided an important framework complementary to the Earth, and a baseline for the interpretation of processes of crustal formation on other planetary bodies.

Seismic studies also revealed that the thermal lithosphere was currently many hundreds of kilometers thick, consistent with a relatively rapidly cooling lithosphere that continued to thicken throughout lunar history. Also revealed was a kilometers-thick fractured and brecciated layer (the "megaregolith") resulting from the intense and continuous impact bombardment.

Remote sensing data, verified in the laboratory with lunar samples, permitted the mapping of the global distribution of key minerals and rock types, and an understanding of the vertical and lateral structure of the lunar crust, as well as the discovery of unusual mineral assemblages.

Spacecraft data revealed that the Moon does not currently have a dipolar magnetic field and that most of the magnetic anomalies exist in the crust. Analysis of magnetized lunar rocks showed that the Moon possessed a much stronger magnetic field in its earlier history, but the origin of the crustal anomalies is still debated, with candidate sources being an internal field, impact generated fields, or magnetized projectile material.

But how did the Moon form? Where did it come from? Co-accretion, fission, capture? Study of the *Apollo* samples, and a new appreciation for the role of impact processes in the Solar system, led researchers to hypothesize that the Moon formed following the impact of a Mars-sized object into the proto-Earth, and the accretion of the ejecta formed by this impact. The recent discovery of lunar water in lunar pyroclastic beads has resulted in the refinement of this theory to account for the preservation of volatiles in the lunar interior, but the basic scenario of one or more large impacts into Earth forming the Moon is still the dominant interpretation.

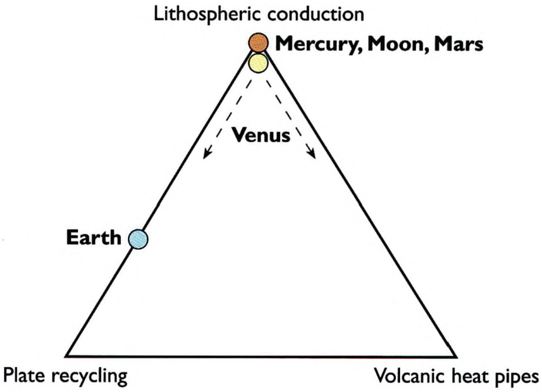

Fig. 6: The major types of planetary crusts, the chemically segregated outer layer (primary, secondary, and tertiary)

Deep craters in the lunar polar regions have long been known to be cold-traps and to be capable of collecting and preserving water ice. Spacecraft observations have revealed evidence for water at and near these lunar cold traps and debate centers on its origin (magmatic, solar wind, cometary impact, etc.) and abundance.

Exploration of the Moon in the Space Age has indeed provided a perspective on the Earth's formative years, missing in the terrestrial geologic record (compare Fig. 3b and d). The Moon is a record of the first half of Solar system history, providing insight into significant global melting, ancient primary plagioclase flotation crusts, the linkage between geological observations and accretionary theory, and a one-plate planet lithosphere and thermal evolution. The lunar record provided insight into wholesale differentiation, segregation, instability and overturn, impact cratering as a fundamental geological process, the possibility of magmatic or cometary volatiles accumulating in polar regions, and the idea that the Moon formed from the impact of a Mars-sized object into early Earth.

4. MERCURY

Due to its distance from the Earth and its proximity to the Sun (see Fig. 1, 2), Mercury has always been difficult to study telescopically, and knowledge before *Mariner 10* included size (about 1/3 that of Earth, slightly larger than the Moon), anomalously high density (~5.43 g/cm^3) implying an iron core the size of the Moon, and its position as the innermost planet. These factors were largely attributed to the temperature and pressure gradient as a function of distance from the proto-Sun and collapsing solar nebula during planetary formation. Mercury was predicted to be small, volatile-poor, and dense due to lighter elements being driven toward the outer Solar system. Radar reflective materials had been detected inside polar craters. But what would the geology be like on a small planet with a huge iron core?

The *Mariner 10* flybys showed that Mercury possessed a dipole magnetic field that was about 1 % of the strength of the Earth's field. This raised the question of whether the core was currently liquid and convecting. *Mariner 10* imaged ~45 % of the surface of Mercury and the surface was seen to be like the Moon, dominated by craters and basins, and a heavily cratered surface with interspersed and sometimes regional smooth plains. No evidence of plate tectonic activity was seen on Mercury (divergent and convergent boundaries, transform faults) and Mercury was also interpreted to be a single lithospheric plate (see Fig. 6), a one-plate planet whose lithosphere stabilized very early in its history. Interestingly, however, there were few to no indications of extensional tectonics (graben); wrinkle ridges and arches, evidence of contractional deformation, dominated the surface, and the large regional scarps were much more prominent and regionally distinctive on Mercury, rising several kilometers above the surface, than on the Moon. This style of tectonics was interpreted to indicate that the radius of Mercury had decreased by several kilometers, perhaps due to core formation or general planetary cooling. But how globally widespread were these scarps? And could the 55 % of the surface of Mercury un-imaged by *Mariner 10* host evidence of extensional deformation?

Even more enigmatically, what was the origin of the regional smooth plains and the intercrater plains. Unlike the low-albedo lunar maria of basaltic extrusive volcanic origin, the plains on Mercury had the same higher albedo as the surrounding uplands, basins and cratered terrain. No volcanic edifices or source vents were definitely identified in the plains imaged by *Mariner 10*. Although the *Mariner 10* team confidently interpreted the regional smooth plains as of extrusive volcanic origin, others, having recently participated in *Apollo* lunar exploration and its results, were not convinced. The reasons for their caution and uncertainty were the results of the *Apollo 16* mission. Targeted to land in the central nearside lunar highlands on the Cayley Formation, *Apollo 16* was designed to explore and sample a geologic unit comprised of smooth, high-albedo plains, plains that stratigraphically pre-dated the low-albedo lunar maria, but filled ancient upland craters. Most geologists had interpreted these high-albedo smooth plains to be of volcanic origin, but perhaps less iron-rich, and thus close to the albedo of the surrounding uplands. When Astronauts John Young and Charlie Duke began their surface exploration, they quickly realized that the Cayley Formation was not volcanic, but rather was composed of impact breccias. Post *Apollo 16* analyses strongly suggested that the Cayley Formation was emplaced by mobilized impact ejecta from the nearby Imbrium basin, mobilized as the curtain of ejecta expanded outward, and emplaced in a fluidized manner into low regions to mimic volcanic processes. Thus, they concluded, smooth plains with albedo similar to the surrounding cratered terrain could be emplaced by impact ejecta fluidization rather than by extrusive volcanic processes. And indeed, a significant percentage of the regional smooth plains documented by *Mariner 10* resided in the region surrounding the huge Caloris impact basin, adding a further note of caution in the interpretation of Mercury smooth plains as volcanic in origin. Without volcanic edifices or source vents, was there any evidence for extrusive volcanism on Mercury?

Mariner 10 raised as many questions as it answered. Mercury appeared to be like the Moon on the outside and the Earth on the inside, with a huge core. But are there extensional tectonic features in the un-imaged majority of Mercury? Are the smooth plains of volcanic or impact origin? What is the origin of Mercury's huge core? Does Mercury have crustal magnetic anomalies? What is the cause of global-scale contraction early in its history? Does significant global contraction inhibit extrusive volcanism? Are radar reflective materials in polar crater interiors composed of water ice? These fundamental questions were of the type used to propose the MESSENGER and *BepiColombo* missions and to explore the 55 % of Mercury unobserved by spacecraft.

The MESSENGER mission involved three flybys of Mercury before orbit insertion, and several important questions were answered during these flybys.

Evidence for the presence of extrusive volcanic activity was found during the flybys on the basis of the occurrence of volcanic vents and flow fronts, impact crater embayment and flooding relationships, impact basin filling histories and relationships, ages from impact crater size-frequency distributions, candidate intrusive structures and features and abundant evidence for pyroclastic deposits.

Following MESSENGER orbit insertion, additional evidence for extrusive and explosive volcanism was found. The northern volcanic plains, comprising 6 % of the surface of Mercury, were seen to be of volcanic origin (associated vents and lava flow features), but unlike the lunar maria, no differences in age could be detected in impact crater size-frequency distribution measurements over the entire northern volcanic plains surface. This implied very rapid, flood-basalt type emplacement of the plains covering 6% of the surface, a mantle that could produce and retain significant volumes of partial melts, and a lithosphere that could fail with wide cracks in order to enable the extensive mantle melts to reach the surface in a short time period.

What was the nature of the heavily cratered primary crust on which these smooth plains were emplaced? Was this a plagioclase flotation crust, like the Moon, or something else? No evidence was found in MESSENGER remote sensing data for the presence of a low-density plagioclase flotation crust. The lack of a low density crust meant that any impediment to the buoyant rise of magma on Mercury, relative to the Moon, had been removed, providing an even higher likelihood of rapid effusive volcanism. Furthermore, the distinction between a primary and secondary crust, although clear conceptually, became difficult to recognize if both might be basaltic in nature.

MESSENGER orbital data revealed additional evidence for over 100 pyroclastic vents and deposits, confirming that the earlier view of a volatile-depleted Mercury was invalid. Uncertain was the nature of the magmatic volatile or volatiles that propelled the pyroclasts to significant radial ranges from the vent, but certain were the high abundances implied by the distances.

Despite the confirmation of the importance of extrusive and explosive volcanism in the early history of Mercury, what was not observed was equally important and informative. No evidence was seen for large Hawaii-like shield volcanoes, Beta-like rift zones and rises as seen on Venus, shallow magma reservoirs, widespread sinuous rilles, vents or volcanic complexes. This suggested that mantle plumes of the type seen on the Earth, Mars, and Venus, have not been part of the volcanic record on Mercury. An explanation for this, consistent with other observations, may be that the scale length of mantle convection on Mercury in a mantle less than several hundred kilometers thick, may be insufficient to cause robust plumes. Mantle melting may instead be more widespread and lateral, favoring production of large melt bodies, mantle expansion, stressing and cracking of the global lithosphere, causing extrusion of large volumes of mantle melts over short time periods.

Documentation of the 55 % of the surface un-imaged by *Mariner 10* revealed no major graben, rift zones or other evidence of significant extensional deformation. Instead, even more examples of global contraction scarps were documented, confirming that the latter half of Mercury's history was dominated by significant global contractional deformation. Such a global state and magnitude of stress in the lithosphere signal cooling of the crust, mantle and interior, a decrease in production of mantle melts, and increased difficulty in propagating magma-filled cracks (dikes) to the surface. This is consistent with the sparse record of volcanism in the last half of Solar system history on Mercury.

MESSENGER confirmed that the radar-reflective deposits in permanently shadowed polar and circumpolar craters were water ice deposits, and were substantial compared to any interpreted to be on the Moon. Recent cometary impacts, such as the one that formed the prominently rayed Hokusai crater, may be the source of these deposits.

Geophysical modeling of the interior of Mercury shows that silicate shell densities can be consistent with the low Fe, Ti, and Al abundances of surface volcanic units and that the internal structure is consistent with strongly reducing conditions in the mantle. Current modeling is exploring these conditions and their implications for the formation of a magma ocean, its stability and aftermath, the role of sulfur, the formation and speciation of volatiles, and the generation ascent and eruption of magma. Further analyses are helping to formulate questions for the upcoming ESA *BepiColombo* mission to Mercury.

5. MARS

The exploration of Mars (see Fig. 1, 2) has revealed a very different planet than initially anticipated. At one-half the diameter of Earth, and possessing an atmosphere and polar caps, and seasonally changing surface features, Mars was thought to be the perhaps the most Earth-like of planets, possibly harboring life. Early flybys of Mars predominantly imaged the ancient cratered terrain in the southern hemisphere, revealing a drab and heavily cratered terrain, and dampening the enthusiasm for life and an Earth-like Mars. The global images obtained by *Mariner 9* and the following *Viking* Orbiters, however, revealed a diverse and geologically very interesting planet (Fig. 7), with an early period of dendritic fluvial valley network formation, a medial period of huge aqueous outflow channels perhaps forming oceans in the northern lowlands, and a later recent period of very dry, cold, and icy conditions, with most of the water sequestered at huge polar caps.

More detailed exploration by orbiters, landers and rovers provided an excellent globally comprehensive picture of the geological nature and evolution of Mars. A glance at the global topography and geological map reveals that Mars is indeed similar to the Moon and Mercury in many ways. Mars is a one-plate planet, showing no signs of plate tectonics (see Fig. 6).

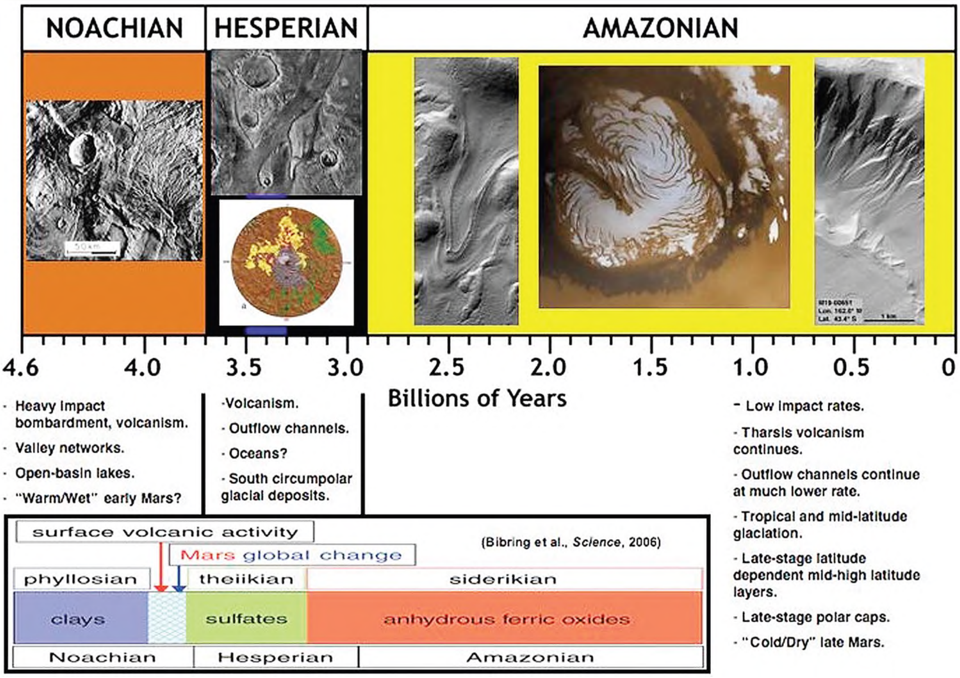

Fig. 7: The geological and mineralogic history of Mars, portraying major events as a function of time. The Noachian period preserves evidence for abundant streams and lakes, the Hesperian period for widespread volcanism and massive water outflows from the subsurface, possibly forming northern lowland oceans, and the Amazonian period signals continued volcanism at Tharsis and a generally cold and dry climate

Yet low altitude magnetic measurements revealed linear seafloor-like bands in some parts of the highlands. Mars displays a significant record of early impact history with large impact basins (Hellas, Isidis, Argyre) and significant areas of heavily cratered terrain. Mars shows an extended record of volcanic activity with volcanism more voluminous earlier in its history than later. Indeed, some consider Mars to be the Moon and Mercury with water and climate. But Mars also differs from the Moon and Mercury in a number of fundamental ways.

1) *Global crustal dichotomy*: The global topography of Mars is characterized by a fundamental global dichotomy; sparsely cratered northern lowlands and heavily cratered southern uplands. This fundamental topographic dichotomy has also been interpreted to be reflected in crustal thickness, with thin crust in the lowlands and thicker crust in the uplands. Debate centered on whether this dichotomy was caused by internal processes (e.g., plate tectonics or other mantle convection patterns), or an external influence, such as a huge bolide impact. Current thinking favors a huge oblique impact event very early in the history of Mars. Clearly, such an impact event had a profound influence on Mars and its subsequent history.

2) *Tharsis and Elysium topographic rises*: Also unseen on the Moon and Mercury are huge, broadly circular, topographic rises that are characterized by abundant volcanic resurfacing and some of the largest volcanoes in the Solar system. The Tharsis rise, about five thousand kilometers across, comprises ~25 % of the surface of Mars and rises ~7 kilometers above the mean planetary radius. Huge shield volcanoes, hundreds of kilometers across, rise up to ~15 kilometers above the surface of Tharsis. Thought to be the surface manifestation of a mantle plume, the Tharsis region defies explanation by conventional terrestrial plume standards, not only due to its immense scale, but also because it appears to have persisted for at least 3.5 billion years, compared to a lifetime of a few hundred million years for Earth hot spots.

3) *Volcanic activity extends up to the geological present*: While volcanic activity on Mars was concentrated in the first half of Solar system history (~30 % of Mars was resurfaced in the Hesperian), unlike the Moon and Mercury, superposed impact crater density indicates that volcanic activity on Mars extends to the last several millions of years (see Fig. 4), and it would be unsurprising if a volcanic eruption occurred today. Uncertain is the nature and origin of the mantle melting, and indeed the source of heat that powered the Tharsis and Elysium rises for so long in such concentrated areas.

4) *Huge crustal magnetic anomalies*: Currently, Mars does not possess an internally generated magnetic field, but when the *Mars Global Surveyor* spacecraft dipped to low altitudes in the Mars atmosphere to undertake aerobraking maneuvers, it detected linear crustal magnetic anomalies reminiscent of magnetic stripes on the Earth's seafloor. Debate has centered on their origin; if they represent crustal spreading, they must date from the very earliest part of the history of Mars, as they are covered with impact craters that have not been deformed. Could they represent huge dikes emplaced early in the history of Mars when it possessed a magnetic field?

5) *True polar wander may have occurred*: Several investigators have found layered deposits, similar to those formed at the poles today, at equatorial and mid-latitudes, leading them to suggest that true polar wander had occurred in the past history of Mars. Others have noted that the distribution of Late Noachian valley networks, currently in a band oblique to latitudes, would parallel latitude if Mars had undergone true polar wander. Central to these discussions is the timing of the huge Tharsis rise, whose formation anywhere on the planet would cause true polar wander to bring it to its current position at the equator. Less clear is the role of true polar wander on the Moon and Mercury, where the redistribution of mass related to large impact basin formation may have caused true polar wander in the distant past, but the paucity of clear markers (such as polar like deposits in non-polar areas on Mars) make such claims difficult to assess.

6) *Mineralogical diversity*: Crustal rocks and minerals on the Moon and Mercury have different composition and mineralogy, but have been altered

largely by impact micrometeorite physical and chemical (agglutinate and glass formation) and solar wind processes. Orbital spectroscopy data have revealed, however, that the mineralogy of the surface of Mars is not only diverse, but appears to reflect a temporal sequence related to its climate and geological history (see Fig. 7). Noachian terrains are characterized by phyllosilicates, clay minerals that have been interpreted to represent the alteration of a basaltic crust to clays in the presence of abundant warm water. Hesperian terrains are dominated by sulfates, interpreted to be related to the eruption of significant volumes of lava during this period. Amazonian terrains are dominated by anhydrous ferric oxides, consistent with a very cold and dry climate and very limited alteration. While these trends may serve to obscure the primary mineralogy in many cases, they do offer fundamental clues to the nature of the climate and its changes with time.

7) *Mars is a "water" planet — rivers, lakes and oceans*: The presence of an atmosphere, tenuous as it is today (6 mbar, CO_2), is sufficient and cold enough (current mean annual temperature ~218 K) to retain huge water ice polar caps and a stable global cryosphere, thought to be ice-cemented to depths of several kilometers, dependent on latitude. Although liquid water is metastable on the surface of Mars today, evidence for flowing liquid water abounds in the earlier history of Mars, suggesting a much denser atmosphere and warm and wet climate conditions (see Fig. 7). Huge outflow channels, largely focused in the circum-Tharsis region, formed in the Late Hesperian and debouched vast quantities of liquid water from the subsurface to the surface, carving wide, often deep valleys that emptied into the northern lowlands. Linear contacts along upper portions of the northern lowlands have been interpreted as potential shorelines, leading to the hypothesis that the northern lowlands were occupied by an ocean in the Late Hesperian. Scientific debate surrounds this hypothesis, centering on the nature of the features interpreted as shorelines, the amount of water delivered by each outflow channel, the difficulty of retaining large bodies of liquid water in the cold climate required by the outflow channel cryospheric cracking mechanism, the fate of this water (freezing, subliming and returning to cold traps), and where that water is today (sequestered in the subsurface, lost to space?).

A different type of evidence exists for fluvial activity and flowing water on the surface of Mars in the earlier Noachian period (see Fig. 7). Noachian impact craters are highly degraded, relative to those formed in the Hesperian, interpreted by many to mean that rainfall-related erosion and infiltration dominated the surface, but was insufficient to cause large fluvial channels. Toward the end of the Noachian, however, a "climate optimum" is envisioned in which rainfall was sufficient to cause significant fluvial activity and runoff. Evidence for this activity is in the form of many hundreds of dendritic fluvial network systems (the valley networks), and several hundred open-basin lakes (water flows in, fills the depression, often an impact crater, and flows out) and closed basin lakes (water flows in but no exit channel is observed). This configuration of fluvial and lacustrine features and systems, together with the phyllosilicate alteration observed in Noachian terrains (see Fig. 7) interpreted as significant warm water-rock interactions to produce clays, led to the interpretation that the climate of Late Noachian Mars was warm and wet, with a mean annual temperature (MAT) >273 K, producing significant rainfall and runoff, and perhaps even a northern ocean.

While the warm and wet Noachian Mars climate scenario is a very plausible interpretation of the geological evidence, global climate models (GCMs) have had great difficulty in achieving sustained temperatures about 273 K, primarily because of the "faint young Sun" thought to have been characterized by about 75 % of its current luminosity. Robust GCMs predict a MAT of ~225 K, at least 48 K below the MAT of a warm and wet early Mars. Furthermore, if the atmospheric pressure exceeds a few tens of mbar, as virtually all envision for early Mars, atmospheric-surface thermal coupling occurs and an adiabatic cooling effect creates an altitude dependent cold trap. Water vapor migrates to the southern upland cold traps, snows out, and accumulates as glacial snow and ice above the equilibrium line altitude of ~1 km. Water remains there as glacial snow and ice until some specific event raises the temperature to >273 K to cause melting of the snow and ice that has accumulated, and causes sufficient runoff to carve the valley networks and form the open and closed basin lakes. This scenario, the "Late Noachian Icy Highlands" model, is in stark contrast to the "Warm and Wet" scenario, in which MAT is consistently >273 K. Distinguishing between these two models is a critical area of current Mars research. The Late Noachian Icy Highlands model predictions are undergoing critical tests (particularly in reference to mechanisms for heating and melting), and sources of sustained greenhouse gases are being explored to validate the Warm and Wet model.

8) *Extreme oscillations in spin-axis obliquity characterize Mars*: In contrast to the Moon and Mercury, Mars undergoes significant periodic changes in its obliquity, eccentricity, and precession. These parameters influence the distribution and magnitude of incident solar radiation and can have profound effects on the distribution and state of water and ice. Analysis of the latitudinal distribution of non-polar ice and glacial features has resulted in the recognition of residual glacial landforms at all latitudes, even the equator. Combination of the recognition and interpretation of these landforms with global climate models and glacial flow models has revealed that when mean spin-axis obliquity increases from its current value of ~25 degrees to ~35 degrees, polar ice is mobilized and transported to the mid-latitudes to form regional glacial deposits, manifested today as lobate debris aprons, lineated valley fill and concentric crater fill. Indeed, an orbiting radar experiment has revealed the presence of hundreds of meters of buried ice preserved below a sublimation till (debris) layer in the northern mid-latitudes, ice that is several hundred million years old. Similar approaches have shown that when mean spin-axis obliquity increases to ~45 degrees, polar ice is mobilized and transported to equatorial regions to produce huge tropical mountain glaciers along the northwest slope of the Tharsis shield volcanoes. Thus, the spin axis and

climate history of Mars may be deconvolved from the documentation and interpretation of these non-polar ice deposits, and preserved ancient ice may provide access to climate records from hundreds of millions to billions of years in the past.

9) *An early "warm and wet" Mars is a likely habitat for formation and evolution of life*: Unlike the Moon and Mercury, past environmental conditions on Mars definitely involved the presence and flow of liquid water, and thus the possibility of environments that might have led to the formation and evolution of life. The diverse aqueous and climate environments that have characterized the surface of Mars offer a very wide range of productive exploration destinations and *Viking*, *Pathfinder*, *Mars Exploration Rover* and *Mars Science Laboratory* landers and rovers have accumulated data on this critical quest.

10) *Mars and early Earth history*: Indeed, these fundamental contrasts with the Moon and Mercury may mean that Mars is the true Rosetta stone of early Earth history, filling in the missing transition between processes associated with the Moon and Mercury (cratering, volcanism, tectonism) and those associated with the presence of a hydrosphere, atmosphere, possible oceans, and the origin of life.

6. VENUS

The smaller terrestrial planetary bodies, the Moon, Mercury and Mars (see Fig. 1, 2), share many characteristics that make then distinctive from Earth: rapid conductive cooling due to their small size and high surface-area to volume ratio globally, consequent development of continuous lithospheres (one-plate planets) (see Fig. 6), and preservation of the early Solar system geologic record of impact bombardment and volcanism. Is size a critical factor in the evolution of the terrestrial planets (see Fig. 4a), or is the Earth unique in terms of its ongoing global plate tectonic regime, its oceans and the evolution of life?

Despite its very dense CO_2 atmosphere and extremely high surface temperatures, Venus is most similar to Earth in its size, density, and position in the Solar system (and thus presumed starting conditions and constituents) (see Fig. 1, 2). Does this mean that the geology and geophysics of Venus are most similar to Earth, in contrast to the smaller terrestrial planetary bodies? Is Venus characterized by a young surface and present-day Earth-like plate tectonics? Is Venus characterized by an ancient surface and a globally unsegmented crust and lithosphere like the smaller terrestrial planets? Does Venus represent something in between Earth and the smaller terrestrial bodies (see Fig. 4a)? Or, does Venus represent *none of the above,* something completely different than we anticipate?

There are a great number of fundamental reasons to study Venus, and these can be formulated into outstanding questions. 1) What can Venus tell us about the early history of the Earth, the Archean? 2) How does Venus lose its primordial and radiogenic heat? 3) Does Venus have continents and ocean basins? 4) Does Venus have plate tectonics? 5) When was the onset of plate tectonics on the Earth and what was its cause? 6) Does the current Venus high-temperature, high-pressure atmospheric environment represent the Earth's past or future? 7) How do the mantle dynamics and history of Venus provide insight into that of the Earth, particularly in Earth's now-missing earlier history? 8) Did Venus ever have oceans and a more clement environment? If so, what caused the transition to the atmosphere of today? 9) Has Venus preserved the record from the first half of Solar system history? 10) What is the average age of the surface of Venus? (see Fig. 4a).

The Soviet Union was extremely successful in exploring Venus with the *Venera* atmospheric probes and landers, revealing much about the atmospheric structure and the surface geology and composition. Landers revealed a rocky, platy surface and basaltic compositions. Earth-based radar observatories documented the presence of circular features, lava flows, and linear tectonic features (Maxwell Montes), and tectonically rifted rises (Beta Regio). The United States contributed flybys, probes and orbiters, and produced a *Pioneer-Venus* topographic map of Venus with a horizontal resolution of ~75 km, revealing the broad nature of the global topography. The global topography altitude-frequency distribution was unimodel and skewed to higher elevation, unlike the bimodal distribution of Earth topography, which consists of the high-standing thick, buoyant continental crust, and the low-lying thin, denser oceanic crust. Regional topography revealed a topography unlike the Moon, Mercury, and Mars, with broad, linear lowlands, circular lowlands, narrow linear mountain belts surround upland plateaus, rifted rises, globally interconnected linear depressions, and a broad symmetric rise reminiscent of Iceland and the mid-Atlantic ridge. These enticing results provided the impetus for the Soviet Union to fly orbital radar missions (*Venera 15*, *16*; 1983–1984) and the United State to launch the orbital *Magellan* mission (1989–1994).

Venera-15, -16 obtained radar images and altimetry of the northern mid- to high latitudes, about 25 % of Venus, and revealed a surface unlike that of the Moon, Mercury, and Mars. Impact craters were rare, tectonic activity was very common (folded mountain belts, rift zones, fracture belts), volcanic features were abundant (lava flows, volcanic edifices, calderas), and large circular deformation features (coronae) dotted the surface. A part of the elevated topography, called tessera, was characterized by densely intersecting tectonic features, reminiscent of continental cores on Earth. No major impact basins were observed. Did these observations represent a view of part of a planet characterized by active plate tectonics? The *Venera-15, -16* results set the stage for the global *Magellan* mission, which obtained planet-wide maps of the morphology, topography, radar properties and gravity structure of Venus.

As Venus rotated under the spaceraft, *Magellan* revealed a long list of surprises, and a global picture emerged. Over 80 % of the planet was covered by a stunning array of lava flows and volcanic edifices. Huge interconnected tectonic rift zones laced the surface, meeting at broad, volcano studded rifted topographic rises. Earth-like linear mountain belts surrounded continent-like upland plateaus. The huge circular deformation features (coronae) discovered by *Venera-15, -16* were common and globally distributed.

No evidence for lunar-like densely cratered terrain was seen, but geologic units could be mapped and their sequence established on the basis of superposition, and cross-cutting relationships. Ancient highly deformed and high-standing tessera terrain was embayed by vast occurrences of volcanic plains deformed by wrinkle ridges; these in turn were cut by global rift zones, and long narrow lava flows emerged from the rifts, flowing down into the lowlands resurfaced earlier by regional plains. The geologic history appeared to involve intense regional to global deformation to produce the tessera terrain, followed by a phase of near-global volcanism, and then rifting and associated localized volcanism. Clearly, Venus was unlike the Moon, Mercury, and Mars in dozens of ways. But what percentage of the history of Venus was documented by the global coverage of *Magellan*, and how much was Venus like the Earth?

The total number of impact craters on Venus was about 1000, and their size-frequency distribution (CSFD) indicated that the mean global surface age was about 500 million years (see Fig. 4b). Thus, the mean global surface age was similar to that of Earth (average of ancient continents and young ocean basins)! Did Venus have active global plate tectonics? What is the areal distribution of ages? Where are youngest units (divergent plane boundaries?)? Where are the oldest units (convergent plate boundaries and continents?)? Very surprisingly, the areal distribution of the crater population could not easily be distinguished from a completely spatially random population. This meant that despite the huge range of geologic features and units mapped by *Venera-15, -16* and *Magellan*, no major differences in age could be determined on the basis of CSFD for the majority of the mapped geologic units. Furthermore, most impact craters appeared to be pristine and unmodified, and relatively unembayed. No evidence for active plate tectonics, ancient continents and younger spreading centers, could be found. To many investigators, this suggested *rapid global resurfacing* (obliterating the previous geologic record), followed by relative quiescence during which time craters could accumulate, but not be heavily modified or flooded by subsequent activity, as on the Moon, Mercury, and Mars. Could the entire history of Venus documented by *Magellan* (tessera, global plains volcanism, rift zones, and related flows) have happened in the last ~5 % of its history? (see Fig. 4b).

On the basis of the Magellan results, many researchers believe that Venus must have undergone *global-scale resurfacing* in its recent history, and that this resurfacing must have been *geologically rapid*! What could have caused such a configuration and event? Among the hypotheses are: 1) transition from mobile lid to stagnant lid lithospheric regime, 2) episodic plate tectonics, and 3) catastrophic overturn of a depleted-mantle layer and rapid volcanic resurfacing.

This of course raises the critical question: Could similar processes lie in Earth's past or future?

In summary, Venus exploration revealed a planetary surface that, like that of the Earth (see Fig. 4b), has little to no remaining morphological record of the first two-thirds of Solar system history! But Earth-like tectonics and aqueous erosion do not seem to be responsible for the loss of the earlier geologic record. Volcanism and tectonism represent the most abundant geological processes operating on the observed surface and the distribution and state of preservation of existing impact craters may be consistent with a range of catastrophic resurfacing models. Venus-Earth Comparative Planetology is clearly a compelling way to understand Earth and the paths that it might have taken in the past or might take in the future.

7. COMPARATIVE PLANETOLOGY THEMES

In the 60 years since the launch of Sputnik 1, we have explored the Earth-like, or terrestrial planetary bodies in detail, and the results of this exploration reveal some fundamental comparative planetology themes (see Fig. 4b). 1) The impact flux in early Solar system history was very high, creating global magma oceans, primary crust, huge impact basins, global breccia layers, large topographic depressions, and crustal dichotomies. 2) The high surface area to volume ratio for small terrestrial planetary bodies means that they lose heat effectively by conduction, creating a thick global lithosphere (one-plate planets) that acts as a preservational template for other processes such as impact cratering and volcanism (see Fig. 5). 3) Volcanism, mantle melting associated with secondary crustal formation (see Fig. 6), was a dominant process for small terrestrial planets early in their history, but waned or ceased in the last half of Solar system history. 4) Large planetary bodies, such as the Earth and Venus, adopted different modes of planetary heat loss (currently plate tectonics for the Earth; conduction for Venus) and may have changed these styles one or more times in their history (see Fig. 6).

We now view the terrestrial planets as laboratories for the study of a wide array of geological and geodynamic processes, and are designing future missions and experiments to usher in the second 60 years of the Space Age.

- *The Earth*: A dynamic planet with the record of its formative years erased by this dynamism. The other terrestrial planetary bodies provide complementary records of the earlier missing history of our own Home Planet.
- *Venus*: A laboratory for the study of crustal accretion, planetary scale geodynamics, and atmospheric evolution on an Earth-like planet;
- *Mars*: A laboratory for the analysis of the history of water, radical climate change, and conditions that might have led to life;
- *Mercury*: The end-member planet for testing models of core formation and mantle and crustal evolution in the first half of Solar system history;

- *The Moon*: The foundation for understanding fundamental planetary processes and chronology in the first half of Solar system history.

8. RETURNING TO HOME PLANET EARTH

Where have we been in the past? Where are we going in the future? No longer do we view the Earth in isolation. Earth is now a member of a family of terrestrial planets that have shared similar events and phases in their histories. We look to the geological record of one-plate planets to understand the role of impact cratering with time. We look to Venus to understand how tectonism and volcanism might appear during the Earth's Archean period, billions of years ago. We observe the thermal evolution of different terrestrial planets and wonder what the distant future holds for Earth. Will plate tectonics cease on our planet, and if so, what will it look like then? Will the Earth's lithosphere undergo catastrophic overturn in the future, and if so, what will be the aftermath and the effect on life?

We now have perspective on the missing chapters in the first half of Earth history. We have insights into multiple ways of crustal formation (primary, secondary, and tertiary crust) (see Fig. 5) and how planetary environment modulate these. We know that impact cratering is a fundamental planetary geological process (early Earth was hit by a Mars-sized projectile; huge impact basins formed in early Earth history; throughout history, impacts had a negative influence on biota, often causing mass extinctions). We now appreciate density inversions of internal layers and the effects that they may have on global resurfacing: Could such events have initiated plate tectonics on Earth? Are they in Earth's future? We have gained insight into atmospheric evolution and potential outcomes, but we do not know how Venus got to the current greenhouse state. Lessons from the origin and evolution of the atmosphere of Mars may well provide insight into radical climate change on other planets, such as Snowball Earth. And finally, we have new laboratories for gaining perspectives on hospitable environments and the most compelling questions of all: What is the origin of life, where did it initially occur, and how abundant is it in the Cosmos?

9. THE FUTURE

Evolution is stochastic and non-linear, and it is thus very hard to predict the nature of the second sixty years of the Space Age. What is clear, however, is that the perspective provided about the Earth from an analysis of similar bodies in its immediate neighborhood, the inner Solar system, is critical to its full understanding, providing examples of similar and related evolutionary paths and indeed, some paths not travelled. Do not the same principles apply to the study of planetary systems as they do to comparative planetology? The immediate future of the next 60 years of the Space Age will surely see us continuing the search for planets and planetary systems around other stars, and as the census of exoplanets continues to grow, we will inevitably be further propelled on an intellectual study of Comparative Planetary Systems. Considering the events and new perspectives gained since Sputnik 1, it is not unreasonable to think that humans will have sent probes to Alpha Centauri before the 120th anniversary of the launch of Sputnik 1 in 2077.

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NEW RADIOASTRON RESULTS

The *RadioAstron* space VLBI Mission utilizes the 10-m radio telescope aboard the dedicated *Spektr-R* spacecraft to observe cosmic radio sources with an unprecedented angular resolution at 92, 18, 6, and 1.3 cm. The longest baseline of the space-ground interferometer is about 350 000 **k**m. Succeeding the tradition of interferometric observations with ground-based and space-ground facilities, it possesses the longest baseline of the space-ground interferometer of about 350,000 km. It successfully operates since 2011 together with up to 40 largest ground radio telescopes. Proposals for its observations are invited annually with deadlines at the end of January. Formal resolution as high as 8 and 11 microarcsec has been achieved for mega-masers and quasars observed at 22 GHz, respectively. Successful results have been obtained in all areas of its science program including active galactic nuclei, pulsars and scattering, galactic and extragalactic masers. In particular, the survey of active galactic nuclei has found that cores of quasars are at least one order of magnitude brighter than what was known previously. This has critical physical implications for physics of jet emission in active galaxies. A new scattering effect was discovered from observations of both pulsars and quasars. It allows scientists to estimate parameters of scattering screens as well as provides a new window of opportunity to reconstruct true images of background sources distorted by scattering. We will discuss in the presented paper the current status of the mission as well as selected recent science results.

1. GROUND-SPACE RADIO INTERFEROMETER RADIOASTRON: PROJECT DESCRIPTION

RadioAstron is a space VLBI Mission aimed at achieving the highest angular resolution of radio observations at centimeter wavelengths through ground-space interferometric measurements on baselines of up to ~360,000 km. The Mission consists of a 10-metre space-borne radio telescope (SRT), *Spektr-R*, operating at wavelengths of 92, 18, 6.2, and 1.2–1.6 cm and supported by a range of ground-based facilities (Kardashev et al., 2013).

The basic parameters of the SRT and *RadioAstron* observations are summarized in Table 1. *RadioAstron* provides observations of radio sources at ultra-high angular resolution, with ground-space baselines of up to 360,000 km reaching a resolution of about 7 microarcseconds at the wavelength of 1.3 cm. These observations enable accurate measurements of structural properties and evolution on sub-milliarcsecond scales in galactic and extragalactic radio sources. At intermediate baselines, high quality imaging of radio sources with moderate resolution can be obtained for objects located near the orbital plane or observed near perigee passages of the spacecraft.

Table 1: Parameters of the space radio telescope and the interferometer, for details see (Kovalev et al., 2014)

Observing bands (cm)	**Frequency range (MHz)**	**Smallest spacing (uas)**	**SEFD (kJy) LCP RCP**		**Baseline sensitivity (mJy)**
92 (P)	316–332	530	13.3	13.5	14
18 (L)	1636–1692	100	2.76	2.93	3
6.2 (C)	4804–4860	35	11.6	–	5
1.2–1.6 (K)	18372–25132	7	46.7	36.8	16

Note: K-band observing can be done at one of the eight central frequencies: 18392, 19352, 20312, 21272, 22232, 23192, 24152, 25112 MHz. The fringe spacing is calculated for the longest possible baseline. The one-sigma baseline sensitivity is estimated for the RadioAstron-GBT pair for a 300 s integration time and 16 MHz bandwidth of a single polarization, single frequency channel (IF).

The *RadioAstron* project is led by the Astro Space Center of the Lebedev Physical Institute of the Russian Academy of Sciences and the Lavochkin Scientific and Production Association under a contract with the State Space Corporation ROSCOSMOS, in collaboration with partner organizations in Russia and other countries. Orbit determination measurements and analysis are performed by the Ballistics Group at the Keldysh Institute of Applied Mathematics (KIAM) in Moscow. Data from the SRT are received at the Pushchino Tracking Station operated by the ASC or the Green Bank Tracking Station operated by National Radio Astronomy Observatory (NRAO), the USA. The data from the SRT are recorded in the RadioAstron Data Format (RDF) specially developed for the Mission operations. Data correlation from *RadioAstron* observations is conducted primarily at the RadioAstron Correlator Facility designed and operated at the Data Processing Department of the ASC. The MPIfR-DiFX software correlator and the EVN software correlator at JIVE (SFXC) are also being used to correlate *RadioAstron* experiments. Block time commitments to *RadioAstron* observations are being organized or considered at many ground radio telescope (GRT) facilities.

Scientific operations of the *RadioAstron* Mission are conducted by the ASC and the radio interferometric networks. The RadioAstron International Science Council (RISC), which is comprised of representatives from the ASC, major GRT facilities, and the radio astronomical community, provides overall policy definitions for the Mission, and discusses scientific issues and priorities.

There are a number of different ground facilities participating in operation, tracking, data transfer and observations with the radio antenna aboard *Spektr-R*. These include the Flight Control Center (FCC) at the Lavochkin Association; the Deep Space Network Communication (DSNC) antennas in Ussurijsk and Bear Lakes employed for the uplink and telemetry communications with the satellite; the Satellite Tracking Station (STS) in Pushchino, Russia, and Green Bank, USA, used for telemetry and data acquisition from the *Spektr-R* spacecraft; the laser ranging stations (LRS) used for orbit determination measurements; and more than 40 most sensitive ground radio telescopes (GRTs) taking part in Very Long Baseline Interferometry (VLBI) observations with the *Spektr-R* antenna (hereafter, *RadioAstron* observations). VLBI methods are being also utilized to determine the spacecraft state vector for orbit reconstruction.

The scientific program of *RadioAstron* consists of three major parts: the Early Science Program (ESP), Key Science Program (KSP), and General Observing Time (GOT) projects. The Early Science Program, which ended in June 2013, explored the main scientific capabilities of *RadioAstron* observations and paved the way for the subsequent open access KSP and GOT programs. Scientists from about twenty countries take part in *RadioAstron* observations within the KSP and GOT programs. The observing projects are being selected annually by the RadioAstron Program Evaluation Committee. They cover the following science areas: quasars and nearby active galaxies, super-massive black holes in galactic centers, pulsars and interstellar medium, galactic and extragalactic masers, gravitational redshift experiment — checking the General Relativity theory. Below we present selected recent scientific results of *RadioAstron* observations achieved in 2016–2017. The full list of *RadioAstron* publications can be found at http://www.asc.rssi.ru/radioastron/publications/publ.html

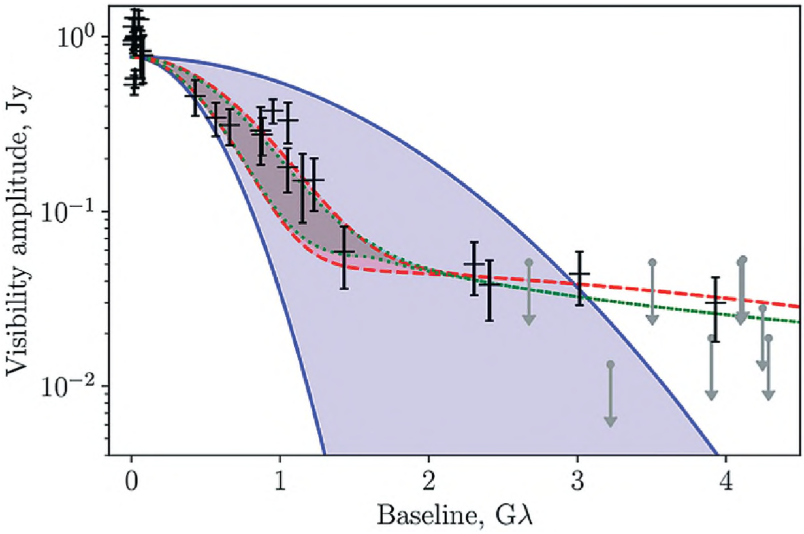


Fig. 1: The visibility amplitude as a function of baseline length at 4.8 GHz. Error bars represent *RadioAstron* data, blue shaded region between solid lines — single elliptical Gaussian model, red region between dashed lines — double Gaussian model, green region between dotted lines — model with refractive substructure. Borders of the shaded regions correspond to minor and major axes of the model, the regions itself cover visibility amplitude values for various position angles

2. THE HIGH BRIGHTNESS TEMPERATURE OF B0529+483 REVEALED BY RADIOASTRON AND IMPLICATIONS FOR INTERSTELLAR SCATTERING

The high brightness temperatures, $T_b > 10^{13}$ K, detected in several active galactic nuclei by *RadioAstron* space VLBI observations challenge theoretical limits. Refractive scattering by the interstellar medium may affect such measurements. We quantify the scattering properties and the sub-mas scale source parameters for the quasar B0529+483. Using *RadioAstron* correlated flux density measurements at 1.7, 4.8, and 22 GHz on projected baselines up to 240 000 km we find two characteristic angular scales in the quasar core, about 100 and 10 μas. Some indications of scattering substructure are found. Very high brightness temperatures, $T_b > 10^{13}$ K, are estimated at 4.8 and 22 GHz even taking into account the refractive scattering. Our findings suggest a clear dominance of the particle energy density over the magnetic field energy density in the core of this quasar. See for details Pilipenko et al. (2018).

3. RADIOASTRON IMAGE OF NGC 1275 REVEALS A WIDE AND COLLIMATED JET STRUCTURE ON THE SCALE OF A FEW HUNDRED GRAVITATIONAL RADII

The *RadioAstron* Nearby AGN Key Science Program has published its first results in *Nature Astronomy* Giovannini et al. (2018). A 22 GHz space-VLBI image of the recently restarted parsec scale jet in 3C 84, a radio source located in the giant elliptical galaxy NGC 1275 in the Perseus Cluster, transversely resolves the strongly edge-brightened young jet just 30 microarcseconds from the core — ten times closer to the central engine that in the previous ground-based studies. This corresponds to a de-projected linear distance of just a few hundred gravitational radii. The ability to resolve the jet and measure its collimation profile inside the acceleration region is important for testing the current jet formation models.

It was found that the jet in 3C 84 is surprisingly wide (Fig. 2), with a transverse radius greater than 250 gravitational radii. This implies that either the bright outer layer rapidly expands closer to the black hole or that this “sheath” is launched from the accretion disk.

Another major result of the paper is that the previously found, almost cylindrical collimation profile on the scales larger a few thousand gravitational radii extends down to a scale of a few hundred gravitational radii. It indicates a flat density profile of the external confining medium. The authors propose that the recently restarted jet in 3C 84 is shaped by shocked material of a cocoon forming around the jet — just like the kiloparsec scale jets are recollimated in a cylindrical shape before they enter the leading hot spot.

The observations were made during a perigee passage in September 2013. In addition to SRT, more than two dozen ground radio telescopes, including the European VLBI Network together with the Russian *Kvazar* network, the Korean VLBI Network, Kalyazin, and the NRAO telescopes of Very Long Baseline Array, the Green Bank Telescope, and the phased Very Large Array, participated in the experiment.

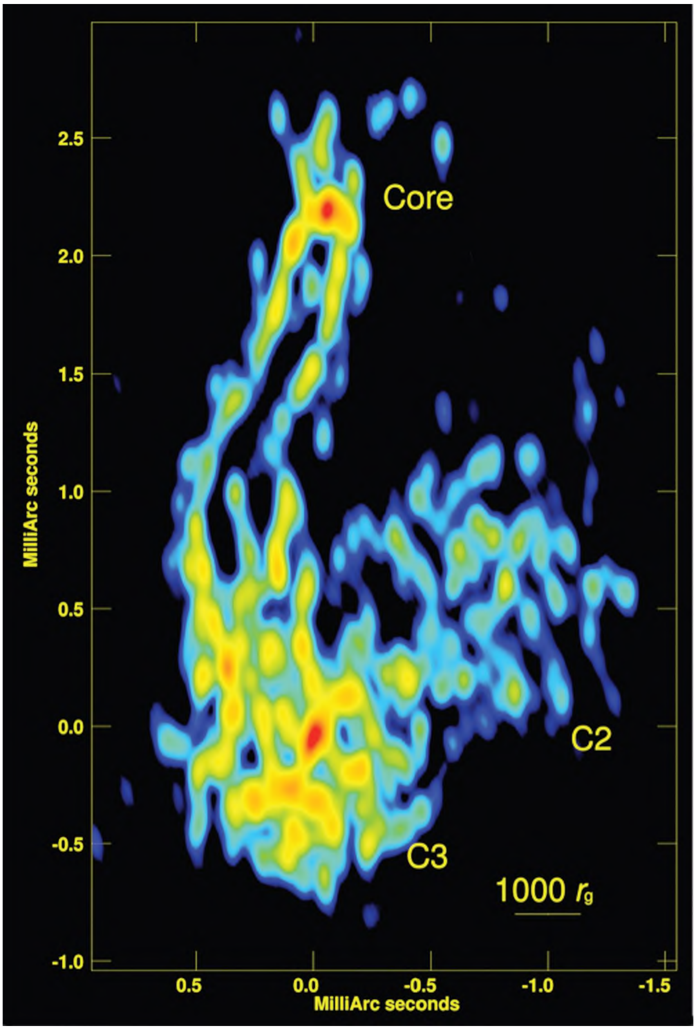


Fig. 2: Radio image of the central parsec in 3C84 obtained with *RadioAstron* at 1.3 cm

4. WATER VAPOUR MEGAMASER IN NGC4258

The H_2O MegaMaser emission regions in NGC 4258 are confined to a nearly edge-on disk of 0.5 pc surrounding the nuclear AGN (Herrnstein et al., 1998), also qualified as a compact symmetric object (CSO). The orbiting molecular regions within the disk drift in front of the southern part of the CSO radio continuum and amplify this continuum. Because of the orbital motion in the disk, the maser components drift across the spectrum from low velocity to high, at approximately 8.1 km/s/yr across the velocity range 440–550 km/s (Haschick et al., 1994; Humphreys et al., 2008). The systemic velocity of NGC 4258 is 472 km/s at a distance of (approximately) 7 Mpc.

At the time of this writing, the H_2O mega-maser emission in NGC 4258 has been detected with 11 *RadioAstron* experiments, the first dating back to 2014. While fringes were initially found in observational data at a baseline of 1.9 Earth diameters (ED), the updated orbital model of the SRT at the ASC correlator resulted in subsequent detection of fringes up to baselines of 26.7 ED (corresponding to 340,000 km). The detection of fringes of the H_2O mega-maser emission on this long SRT-GBT baseline constitutes an absolute record of 8 μas in angular resolution.

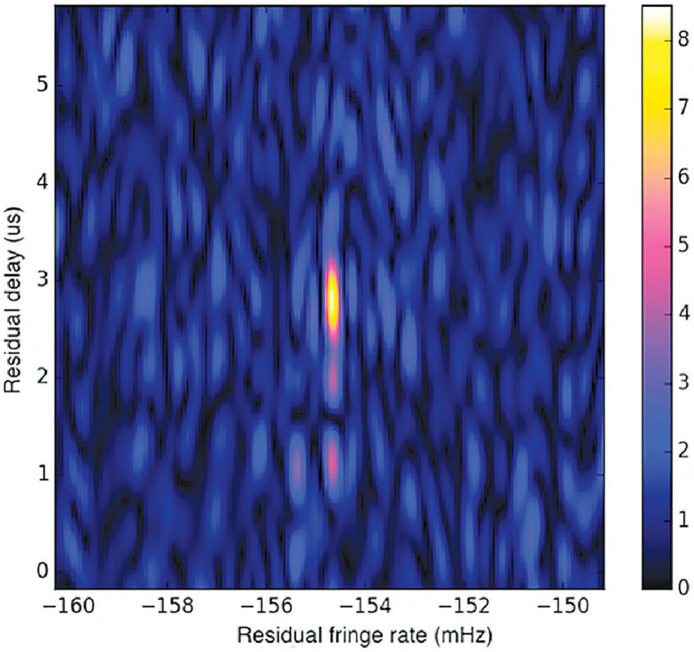


Fig. 3: The fringe amplitude plot of the SRT-Medicina detection of NGC 4258 at 26.7 Earth diameters. The ratio of the interferometer fringe amplitude to the average noise amplitude is plotted against residual delay and fringe rate

At higher resolution an increasing part of the diffuse maser components in NGC 4258 will be resolved, and only more compact components will remain unresolved. This is evident in the fringe amplitude plot of the detection with the 26.7 Earth diameter SRT-Medicina baseline displayed in Fig. 3. Several individual components may be identified with a spatial resolution of ~56 a. u. at the distance of NGC 4258. The mere detection of such compact maser components in NGC 4258 provides stringent limits on the degree of saturation and the excitation process. In addition, these more compact masering regions are likely to have less tangled magnetic fields and may allow detection of the magnetic field strength by its polarization properties.

5. SUN-SIZED WATER VAPOR MASERS IN CEPHEUS A

VLBI observations of a Galactic water maser (in Cepheus A) made with a very long baseline interferometric array involving the RadioAstron Earth-orbiting satellite station as one of its elements. Two distinct components at −16.9 and 0.6 km/s were detected with a fringe spacing of 66 µas. In total power, the 0.6 km/s component appears to be a single Gaussian component of strength 580 Jy and width of 0.7 km/s.

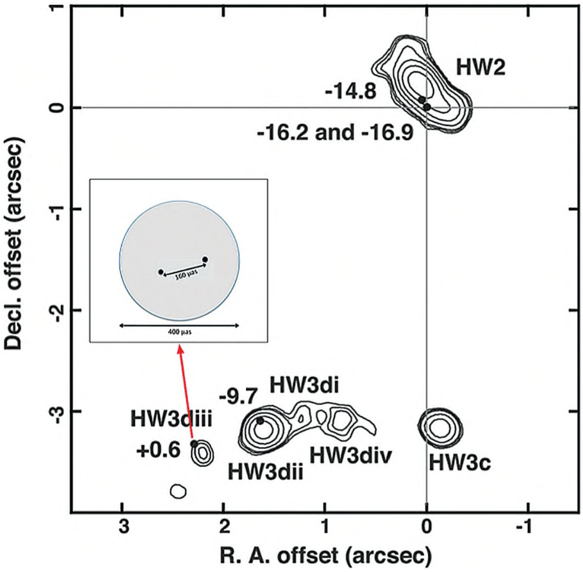


Fig. 4: The central part of the star-forming region Cepheus A. The contours show the extent of the continuum components taken from the 1.3 cm VLA image (adapted from (Torrelles et al., 1998)). The dots mark the positions of masers labeled by their velocities. Inset: a cartoon of the maser emission from the 0.6 km/s feature, which shows two sub-components separated by 160 µas. They are aligned with the axis of the outflow from Hd3ii

Single-telescope monitoring showed that its lifetime was only eight months. The absence of a Zeeman pattern implies the longitudinal magnetic field component is weaker than 120 mG. The space–Earth cross power spectrum shows two unresolved components smaller than 15 μas, corresponding to a linear scale of $1.6 \cdot 10^{11}$ cm, about the diameter of the Sun, for a distance of 700 pc, separated by 0.54 km/s in velocity and by 160±35 μas in angle.

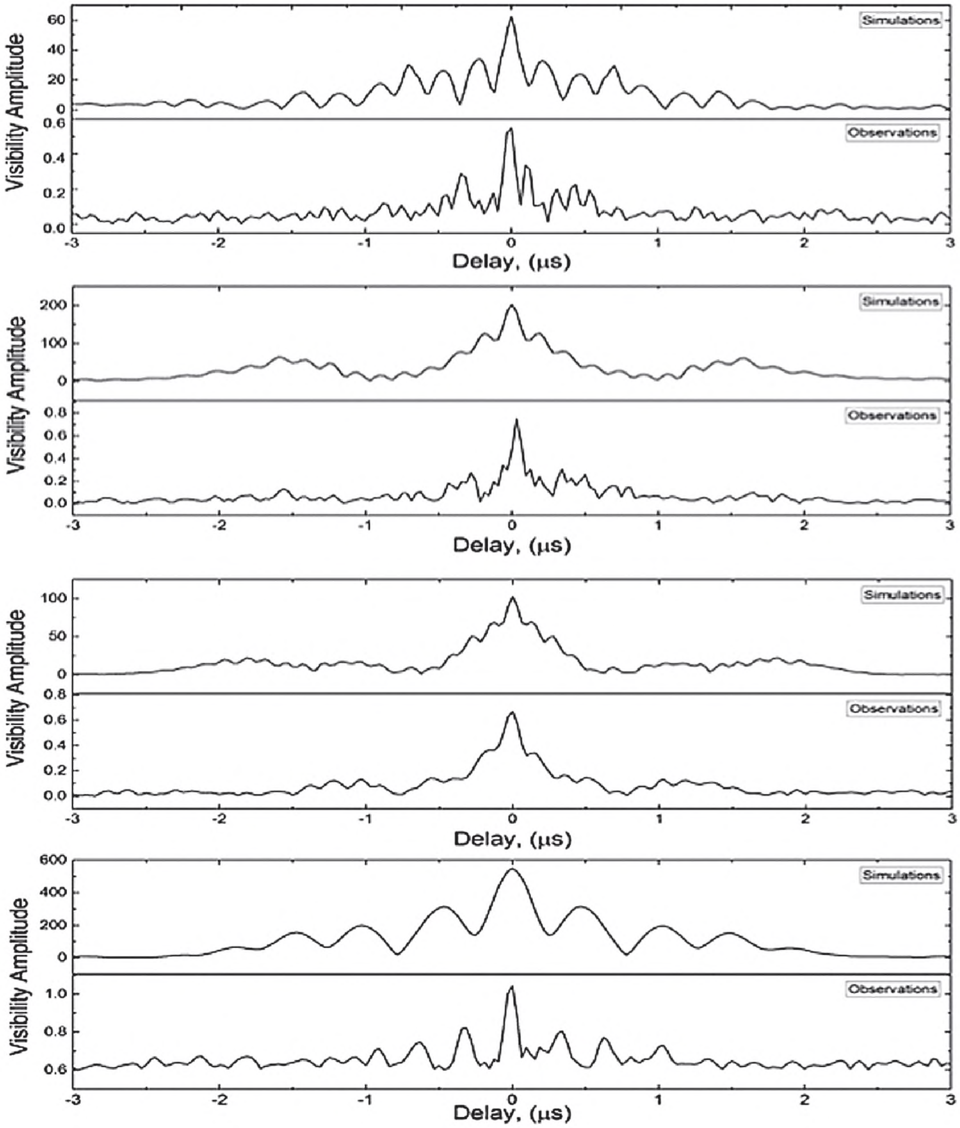


Fig. 5: Examples of visibility functions obtained in observations (lower part of every figure), and in our simulation (upper part). They prove that giant pulses contain super compact components

This is the smallest structure ever observed in a Galactic maser. The brightness temperatures are greater than $2{\cdot}10^{14}$ K, and the line widths are 0.5 km/s. Most of the flux (about 87 %) is contained in a halo of angular size of 400 ± 150 μas. This structure is associated with the compact H II region HW3diii. We have probably picked up the most prominent peaks in the angular size range of our interferometer. We discuss three dynamical models: (1) Keplerian motion around a central object, (2) two chance overlapping clouds, and (3) vortices caused by flow around an obstacle (i.e., von Kármán vortex street) with a Strouhal number of about 0.3. The observed structure most likely can be explained in the model of turbulent vortices shed by an obstacle in a flow. See for details Sobolev et al. (2018).

6. GIANT PULSES OF THE CRAB NEBULA PULSAR AS AN INDICATOR OF A STRONG ELECTROMAGNETIC WAVE

The observed quasi-regular visibility functions of individual giant pulses indicate the presence of strong, unresolved components in the structure of these pulses at 1668 MHz (Popov et al., 2017). Similar components were observed earlier only at frequencies above 5 GHz, in the frequency range, where they are not blurred by scattering. Thus, VLBI observations of giant pulses from the Crab Nebula pulsar indicate the presence of fine structure in the pulses at 1668 MHz — unresolved peaks with duration $\tau \leq 30$ ns and brightness temperature $T_b \geq 10^{39}$ K. Thus, we concluded that unresolved components with such high brightness temperatures shall propagate as strong electromagnetic waves that accelerate particles in the ambient plasma. This gives rise to new components in the pulsar pulse profile (HFC1, HFC2) at frequencies above 4 GHz.

7. REVEALING COMPACT STRUCTURES OF INTERSTELLAR PLASMA IN THE GALAXY WITH RADIOASTRON

We have observed five pulsars with *RadioAstron* ground-space radio interferometer and measured angular sizes of scattering disks. In order to determine the location of the scattering region we used thin screen model. That model was proposed right after the discovery of pulsars (Scheuer, 1968; Rickett, 1977, 1990) and, despite its simplicity, it sufficiently describes the results of our observations. The uniform model of scattering medium distribution along the line of sight cannot be reconciled with the experimental data of the observed pulsars. Therefore the observational evidence favours the conclusion that the scattering is mainly produced by relatively compact plasma layers. See for details Popov et al. (2016).

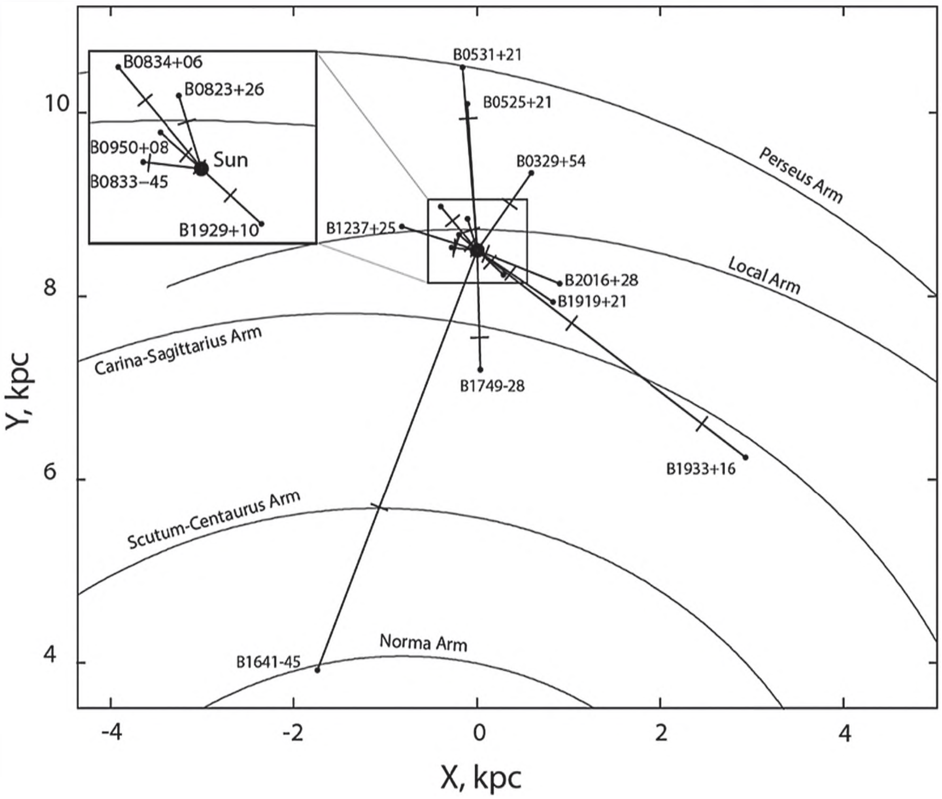
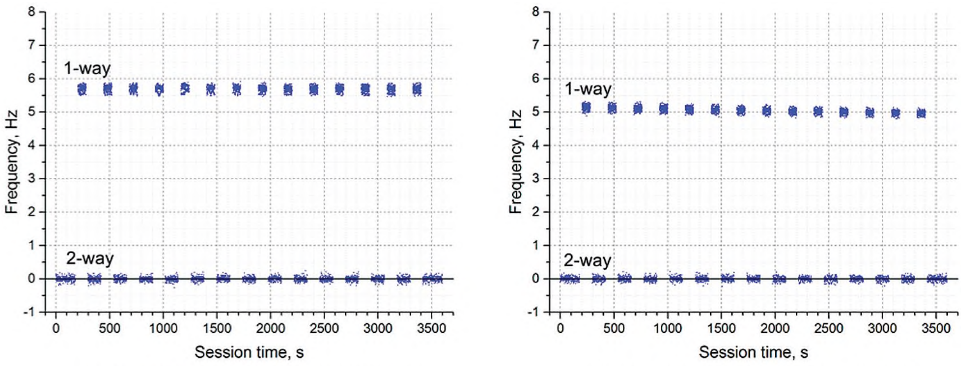


Fig. 6: Location of pulsars and detected scattering screens relative to the spiral arms of the Galaxy. The position of screens are indicated by the short bars along the line connected every pulsar

8. TESTING EINSTEIN'S GENERAL RELATIVITY

The *RadioAstron* Key Science Program on the gravitational redshift experiment has completed its data collection stage. The observations for the experiment were supported by EVN, NRAO, and several geodetic radio telescopes (Badary, Russia; Effelsberg, Germany; GBT, USA; Hartebeesthoek, South Africa; Onsala, Sweden; Svetloe, Russia; VLBA, USA; Wettzell, Germany; Yarragadee, Australia; Yebes, Spain; Zelenchukskaya, Russia). The goal of the project is to test Einstein's Equivalence Principle — the basis of general relativity. Specifically, the team aims to verify Einstein's formula for the gravitational redshift effect or, equivalently, the gravitational time dilation due to a nearby massive body. For the *RadioAstron* spacecraft the effect due to the Earth is about 58 microseconds per day relative to an observer at the Earth's surface — time actually flows faster aboard the spacecraft hence the minus sign. The most accurate test of this kind to date was performed in 1976 by the

NASA-SAO *Gravity Probe A* mission. That experiment proved the validity of Einstein's formula with an accuracy of about 0.01 % using a suborbital probe equipped with a hydrogen maser frequency standard. The experiment with *RadioAstron* is based on a similar approach, but benefitted from a better performing hydrogen maser and a favorable highly eccentric orbit, which allowed the team to perform their measurements multiple times. All this, coupled with an evaluation of the quality of the collected data, make the team believe they'll be able to supersede the result of their renowned predecessor by an order of magnitude. This anticipated result will mark an important milestone in our challenge to find the level, at which general relativity breaks down and a more general theory, such as string theory, is beginning to reveal its subtle features. The team have recently published a paper, presenting their techniques and giving a status update of the experiment. Fig. 7 illustrates the results of preliminary data processing of one of the experiments. While the data processing is far from finished, the currently achieved accuracy is already at the level of that of *Gravity Probe A*. See for details Litvinov et al. (2018).



raks17an (28/05/2016, distance: 246,904 – 243,580 km)

raks17ap (29/05/2016, distance: 54,414 – 42,171 km)

Fig. 7: Results of the data processing of an experiment performed in May 2016. The experiment consisted of three observations at greatly varying distances, each ~1 hour long, supported by the Effelsberg, Onsala, Svetloe, Wettzel (Wz and Wn) telescopes. The two panes of the figure depict the residual frequencies of the 1- and 2-way 8.4 GHz downlink signals from the RadioAstron spacecraft measured with the Onsala 20-m telescope, for the two outermost observations. The 1-way signal contains the useful gravitational redshift, while the 2-way signal is used to suppress the contribution of the nonrelativistic Doppler shift. The observations were performed using the interleaved measurements approach, with a switching cycle of 4 min. The 1-way frequency residuals are not corrected for the gravitational redshift. This makes the variation of the gravitational redshift between the two outermost observations clearly visible (varying from 5.69 to 4.96 Hz)

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X-RAY ASTRONOMY: YESTERDAY, TODAY, AND TOMORROW

A brief overview of the history of X-ray astronomy since its first steps in the 1960s is presented. The emphasis is on how technological achievements in the development of X-ray detectors and optics have led to major discoveries in high energy astrophysics and cosmology. This paper is based on a review written by Dr. Mikhail Revnivtsev, who passed away in 2016. Part of his outstanding contribution to X-ray astrophysics is covered here.

1. THE DISCOVERY OF COSMIC X-RAY RADIATION

X-ray astronomy is a very rich field of science. There are plenty of classes of object that emit X-rays (i.e. photons with energies between ~0.1 and ~100 keV): the heliosphere, normal stars, white dwarfs, neutron stars, black holes, supernova remnants, interstellar medium; supermassive black holes in galactic nuclei, hot plasma in clusters of galaxies, etc.

The atmosphere of Earth is completely opaque to X-rays. Although measurements at photon energies above 20 keV are possible from high-altitude balloons, it is necessary to rise above 100 km to detect radiation at energies near 1 keV. That is why early steps in this direction closely followed progress in rocket technologies.

Astronomical X-ray measurements began in the late 1940s – early 1950s with observations of the Sun from V-2 rockets (Friedman et al., 1951). A modified Geiger counter was used as the detector. A simple scaling of the measured solar X-ray flux to stellar distances indicated that detection of X-ray emission from stars other than the Sun would hardly be possible. Estimates of the X-ray luminosities of other astrophysical objects (such as supernova remnants, flaring stars, etc.) had large uncertainties, and it is the Moon that was expected to be the next object in the sky to be detected in X-rays (due to reflection/fluorescence of X-rays from the Sun).

In the early 1960s, there were attempts to improve X-ray detection systems using proportional gas counters. Higher sensitivity was achieved thanks to the advent of anti-coincidence shields (which suppress charged particle contamination of the signal). The flight of the *Aerobee 18* rocket on June 18, 1962 with an X-ray detector developed by Riccardo Giacconi's group (AS&E) aboard, at altitudes up to 220 km (with the 350 seconds total time at altitudes higher than 80 km), ushered in the era of X-ray astronomy.

No X-ray emission from the Moon was detected, but two great discoveries were made: an isotropic X-ray radiation — the cosmic X-ray background (CXB), and a point-like X-ray source, Scorpio X-1 — the brightest X-ray source in the sky (Giacconi et al., 1962).

Over the next 10 years, a large number of experiments were carried out using X-ray detectors mounted on rockets and balloons. Balloon experiments were intended to detect harder X-rays, at energies above 20 keV. Since proportional gas counters are virtually transparent at such energies, scintillation NaI (Tl) crystals surrounded by plastic or Cs (Tl) scintillators were usually used, with the latter playing a role of an anticoincidence shield. As a photon passes through the scintillator, a flash of light arises, which is then registered by the photomultiplier. The brightness of the flash depends on the photon energy, enabling spectroscopic measurements.

During these observations, a number of X-ray sources including the Crab Nebula were found. Balloon-borne experiments enabled observations lasting for many hours. Some sources were found to be variable on minute timescales, which was later demonstrated to result from rotation of a neutron star.

2. FIRST X-RAY MEASUREMENTS AND SKY SURVEYS FROM SATELLITES

A breakthrough in X-ray astronomy came with the advent of specialized orbital observatories. This led to an increase in exposures from a few minutes, achievable in rocket measurements, to months and even years. The first specialized X-ray observatory was developed in the framework of NASA's program of small astronomical satellites and was named *Uhuru* (operated in 1970–1973), which means "freedom" in Swahili. The satellite was launched on December 12, 1970 from a sea platform near the coast of Kenia and was intended to survey the whole sky with a record sensitivity.

Uhuru systematically scanned the sky using two collimated proportional gas counters with a collective area of 840 cm^2 each. The scanning speed could be changed on request. In the standard regime of observations, the optical axes of the spectrometers (with fields of view of 0.5×5 and 5×5 degrees) scanned the sky in big circles, moving by 1 degree per day. The *Uhuru* all-sky survey resulted in a catalog of 399 sources of various origins, from white dwarfs and neutron stars in our Galaxy to galaxies and clusters of galaxies (Forman et al., 1978).

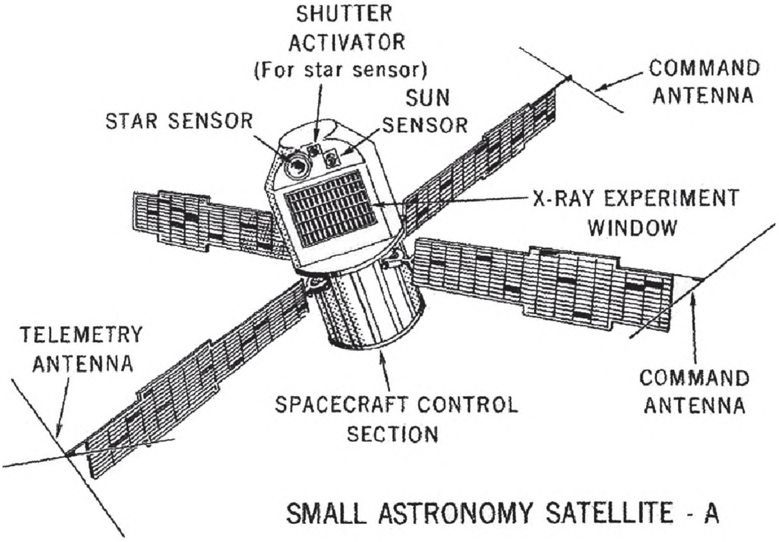

Fig. 1: Schematic view of the *Uhuru* X-ray observatory

Before *Uhuru*, despite the discovery of a substantial number of X-ray sources and the optical identification of the brightest of them, Scorpio X-1 (Sandage et al., 1966), the mechanism of generation of such a high luminosity (X-ray luminosity of Sco X-1 is 100 thousand times the bolometric luminosity of the Sun) was unclear. Although ideas that the energy might be tapped from the gravitational energy of matter falling onto a compact stellar remnant were put forward early on (Zeldovich, 1964; Salpeter, 1964), convincing observational evidence was missing.

The situation changed when *Uhuru* revealed that at least some X-ray sources were binary stellar systems (Schreier et al., 1972). One of the brightest X-ray sources (Cen X-3) was found to be pulsating, with the pulsation frequency changing systematically due to the motion of the pulsating object around the center of mass of the binary. In addition, a systematic increase of the pulsation frequency (i.e. acceleration of the rotation of the pulsating object) was discovered, suggesting that some interaction between the companion star and the pulsating object was going on. This, together with the discovery of radio pulsars by Hewish and Bell in 1967, implied that the pulsating source was a neutron star. Some of the X-ray sources were associated with known radio sources. This is how the first X-ray binary with a black hole, Cygnus X-1, was identified.

Uhuru has also detected X-ray radiation from clusters of galaxies, which turned out to originate in a hot intracluster medium (Gursky et al., 1971). Afterwards, the *Ariel-V* (see below) observatory confirmed this by discovering an emission line of highly ionized iron in the X-ray emission of clusters of galaxies (Mitchell et al., 1976).

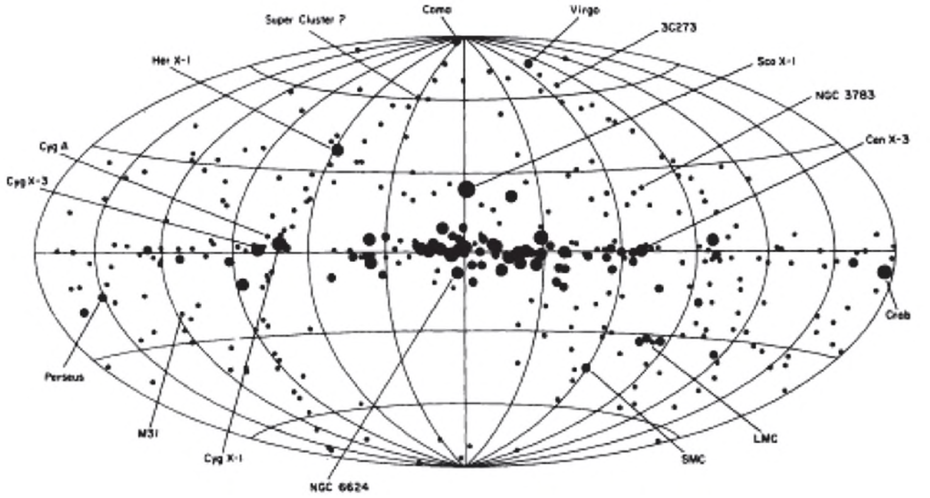

Fig. 2: Positions of the X-ray sources discovered by *Uhuru* on the sky. Image courtesy Forman, W. et al., The Astrophysical Journal Suppl. Series 38, 357 (1978)

In order to determine the nature of an X-ray source, it must be identified in optical, infrared or radio bands. This was difficult to do for many of the sources discovered by the first X-ray observatories, since only a rough X-ray localization was usually available. The problem was especially acute in the Galactic plane and Galactic bulge regions, where the surface density of stars is very high.

A fruitful approach toward determination of the angular sizes and accurate positions of X-ray sources turned out to be using so-called modulation collimators (the flux from a source is modulated in time by a system of open and closed parts of the collimator). Initial measurements of this type were done already in rocket experiments (Gursky et al., 1966; Schnopper et al., 1970). The method was further developed and realized on the successors of the *Uhuru* X-ray observatory, SAS-3 (USA, 1975–1979), HEAO1 (USA, 1977–1979) and *Ariel-V* (UK/USA, 1974–1980). Positions of several tens of objects were measured to within 30 arcsec (Doxsey et al., 1979).

3. FURTHER X-RAY STUDIES OF ACCRETING BLACK HOLES AND NEUTRON STARS

From the late 1970s to the 2010s, several generations of X-ray observatories have changed. Modernization of X-ray instruments has been proceeding via enhancement of their effective area and improvement of their spatial, spectral, and temporal resolution.

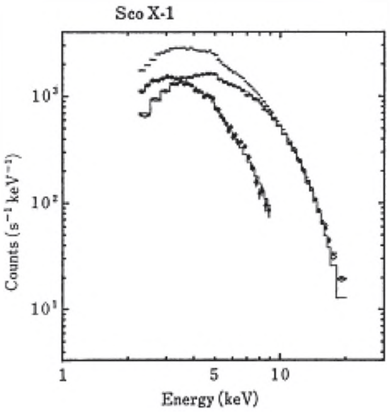

Fig. 3: Spectrum of the brightest X-ray source in the sky, Scorpio X-1, measured by the *Tenma* observatory and approximated by models of emission from an accretion disk and blackbody emission from a neutron star. Image courtesy Mitsuda et al. (1984)

Observations carried out with the Japanese observatory *Tenma* (1983–1985) enabled a testing of the theory of radiation of accretion disks around compact objects (Shakura, Sunyaev, 1973) and demonstrated good agreement with its predictions (Mitsuda et al., 1984). As a result, it became possible to estimate the inner size of the accretion disk and thus the size of the central compact object (a neutron star or black hole) for a number of sources.

In the hard X-ray band (above 10–20 keV), the count rate of charged particles on the detector turns out to be crucial. In order to subtract the background contribution reliably, a “rocking collimator” method was put forward: measurements of the source flux are alternated with those of the flux from nearby empty fields. Balloon-borne experiments based on this principle, carried out in the late 1970s, made important measurements of the spectra of sources of various classes and discovered a number of features shedding light on the physical parameters of matter near neutron stars and black holes.

In 1976, emission features in the spectrum of a neutron star in the binary system Hercules X-1 were discovered with a balloon-borne hard X-ray spectrometer (Truemper et al., 1978). These were shortly interpreted as cyclotron absorption features — arising due to absorption of X-ray radiation by electrons transiting between Landau levels in a strong magnetic field (this effect had been predicted by Gnedin, Sunyaev (1974)). This made it possible to measure the intensity of the magnetic field near the neutron star’s surface, which turned out to be of order 10^{12} Gauss.

Balloon-borne experiments also revealed power-law-like spectra at energies of 10–50 keV for a number of black hole systems. It was proposed that this hard X-ray radiation could originate in a hot, rarefied plasma in the close vicinity of the compact object, as a result of multiple scatterings of seed photons off hot electrons (Shapiro et al., 1976).

The key prediction of this model was an exponential cutoff in the spectrum at the energy corresponding to the temperature of the hot electrons. It is only in the late 1970s that this feature was reliably detected in the spectrum of Cyg X-1 (Sunyaev, Truemper, 1979; Sunyaev, Titarchuk, 1980). This provided reliable diagnostics of physical parameters of the plasma near black holes.

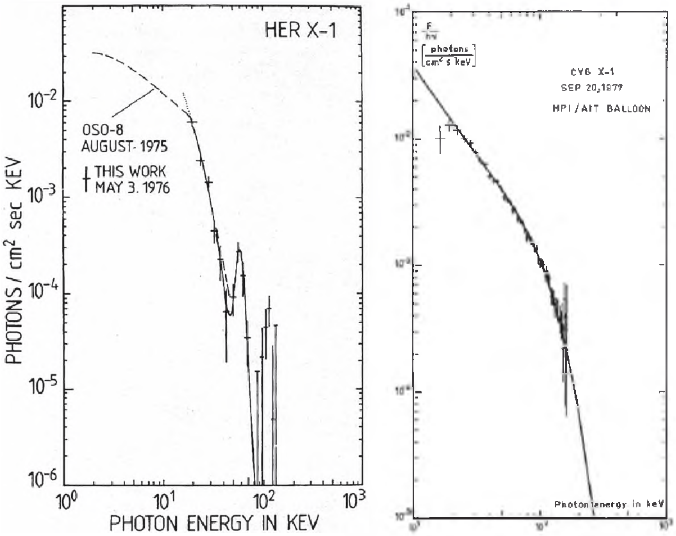

Fig. 4: *Left*: Spectrum of the neutron-star X-ray binary Her X-1. The drop at 40 keV results from cyclotron absorption in the strong magnetic field of the neutron star . Image courtesy Truemper et al., (1978). *Right*: Spectrum of the black-hole X-ray binary Cyg X-1, approximated by a model of Comptonization of photons in hot plasma. Image courtesy Sunyaev, Truemper (1980)

During observations of the source 4U 1820-30 in the globular cluster NGC 6624 in September 1975, the ANS satellite (Netherlands, 1974–1976) detected two bursts with a characteristic rise time of less than 1 s and an exponential decay on a timescale of about 10 seconds (Grindlay et al., 1976).

It turned out that a similar event had been observed from the source Cen XR-4 already in 1969 by the surveying US satellite *Vela-5B* (Belian et al., 1972). Further studies of such events led to the conclusion that they result from explosive thermonuclear burning on the surface of a neutron star (Lewin, 1981). The radiation is formed in the optically thick atmosphere of the neutron star when a large amount of energy is released in a short time. Such thermonuclear bursts are very interesting because they provide constraints on the masses and radii of neutron stars.

Long observations of X-ray sources in our Galaxy have also led to the discovery of so-called X-ray novae. These are objects whose radiation in the quiescent state is orders of magnitude weaker than during their outbursts. The latter are most likely related to non-stationary accretion in a binary system (Lasota, 2001). In the "turn-off" state, the accretion rate is very low. Gradual accumulation of matter in the accretion disk leads to its transition to an "active" state, when the accretion rate reaches as high as 10^{-8} solar masses per year and a powerful burst of radiation is produced. After a large fraction of the mass accumulated in the disk is dumped onto the compact object, it switches back to the turn-off state and the source practically disappears from the sky.

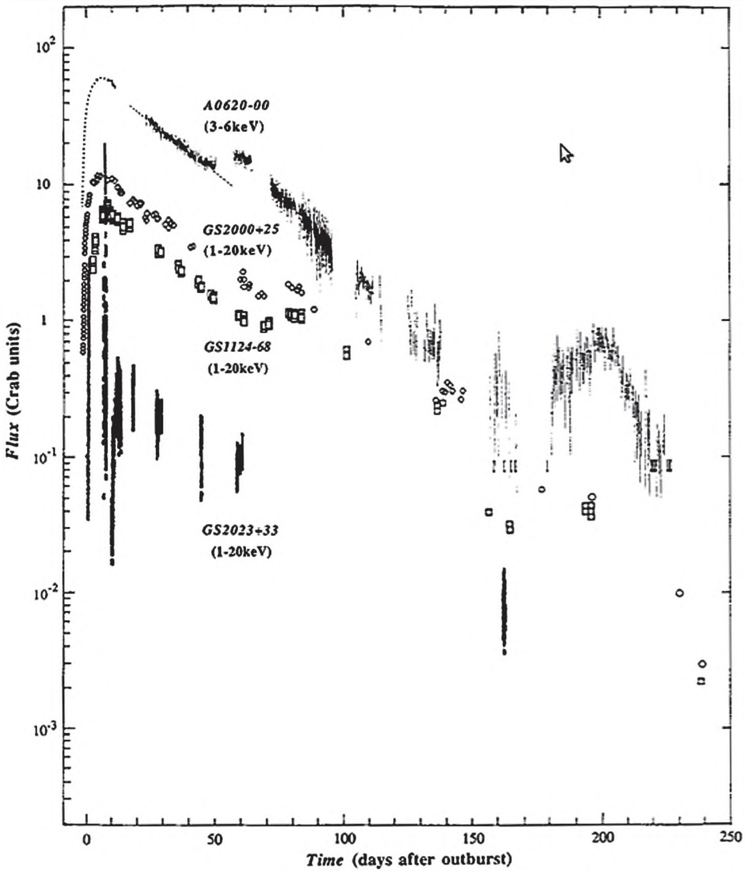

Fig. 5: Light curves of black-hole X-ray novae.
Image courtesy Tanaka, Shibasaki (1996)

It turned out that a large fraction of X-ray novae are binary systems with a black hole. Such objects are mainly interesting because of their brightness, which allows studying X-ray emission properties of black holes in detail. One of the brightest outbursts of X-ray novae ever observed happened in the Monoceros constellation in 1975. This nova received a name A0620-00 (the letter "A" means that the object was discovered by the *Ariel-V* observatory). It was several tens times brighter than the Crab Nebula.

4. GAMMA-RAY BURSTS

The X-ray sky is not stationary. Sources change their brightness on various timescales from milliseconds to (at least) tens of years. The exception is large extended objects such as supernova remnants, which have sizes of parsecs and tens of parsecs, and clusters of galaxies, with sizes of hundreds of kiloparsecs and megaparsecs.

As X-ray astronomy has been developing, transient events of various types have been discovered: bursts associated with unstationary thermonuclear burning on the surface of neutron stars and white dwarfs, outbursts associated with unstable accretion in disks around compact objects, outbursts resulting from tidal disruptions of stars by supermassive black holes, etc.

Among the first discoveries of "fast" transient phenomena was that of "gamma-ray bursts" (GRBs). These were found by US military satellites *Vela 5A*, *5B*, *6A*, *6B*, whose main goal was to monitor bursts of gamma-rays caused by atmospheric nuclear explosions. Although GRBs were discovered in 1969, this information was first announced in 1973 (Klebesadel et al., 1973). An independent confirmation of the GRB phenomenon was provided by the Soviet *Cosmos-461* satellite in 1971 (Mazets et al., 1974).

A GRB appears on the gamma-ray (and hard X-ray) sky for a very short time, when it suddenly becomes the brightest object. Early studies showed that there are two peaks in the distribution of GRB durations, one at durations shorter than 1 second and another at several tens of seconds. The first observations of GRBs also demonstrated that their distribution over the sky was fairly uniform. However, the nature of these events remained unknown for a long time.

In the 1970s – 1980s, a lot of satellites carried hard X-ray and gamma-ray detectors aimed at studying the GRB phenomenon: American *Apollos* and *Pioneers*, Soviet satellites *Meteor*, *Cosmos*, and *Prognoz* and interplanetary stations of the *Venera* and *Phobos* series, etc. In exceptional cases, when a GRB was registered by three or more satellites separated by large distances, its accurate position in the sky could be determined via triangulation. One of the first successful realizations of this approach was the registration of a spectacular event that occurred on March 5, 1979. The burst of hard X-ray and gamma ray radiation was detected by the *Konus* instruments aboard the Soviet interplanetary stations *Venera-11* and *Venera-12* (Mazets et al., 1979). Pulsations detected during the decaying part of the burst unambiguously pointed out that the source was a spinning neutron star in the Large Magellanic Cloud (a satellite of our Galaxy).

It turned out that the March 5, 1979 event was not a GRB, but rather a powerful burst of a so-called "soft gamma-ray repeater" (SGR), or a "magnetar" — a neutron star with very strong magnetic field (10^{14}–10^{15} G), which produces strong bursts of hard X-ray and gamma-ray radiation as a result of a reconstruction of the magnetic field (Duncan, Tomson, 1992). Since then, several more such sources have been discovered in our Galaxy. A burst from one of them, SGR 1806-20, in December 2004 has become the brightest X-ray flash in the sky ever observed: the peak flux reached several million photons per second per cm^2.

The largest number of GRBs, more than 3,000, were registered by the BATSE instrument aboard the *Compton* GRO observatory (NASA, 1991–2000). It was found that the spatial distribution of GRBs is highly uniform, which excluded their Galactic origin.

In 1997, the X-ray telescopes aboard the Italian-Dutch *BeppoSAX* observatory (1996–2003) discovered an “afterglow” of a GRB (GRB 970228) and accurately measured its position (Costa et al., 1997). This made it possible to determine the distance to the source of the burst (van Paradijs et al., 1997) and to finally prove that GRBs occur at cosmological distances.

It is now widely accepted that GRBs appear due to either collapse of a massive star or merger of two neutron stars, with the ejection of a collimated flow of ultrarelativistic matter that produces a hard X-ray and gamma-ray burst. Energies released in these processes can reach as high as 10^{52} erg and are thus comparable to the rest energy of a low-mass star.

More recent progress in the study of GRBs is associated with the *Swift* observatory (NASA, launched in 2004). Its BAT (Burst Alert Telescope) coded-mask telescope observes at any given moment about 8 % of the sky. Once a GRB is detected by this telescope, the satellite quickly points toward the object and a more accurate position of the GRB source is determined using the grazing incidence X-ray telescope XRT. *Swift* has discovered more than 1000 GRBs, and for more than 300 of them the redshifts have been measured.

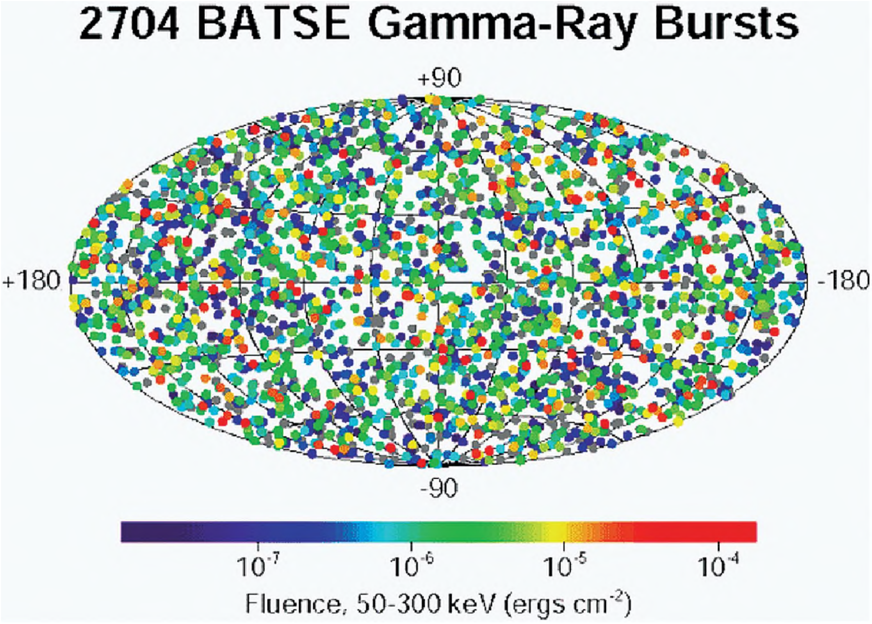

Fig. 6: Distribution of GRBs detected by the BATSE instrument aboard the *Compton* GRO observatory over the sky . Image courtesy G. Fishman et al., BATSE, CGRO, NASA

5. GRAZING INCIDENCE TELESCOPES: REVOLUTION IN X-RAY SENSITIVITY

The sensitivity limit of most X-ray instruments is determined by detector noise, which mainly arises due to propagation of charged particles: cosmic rays or secondary particles emerging due to interaction of high-energy cosmic rays with the spacecraft. X-ray counters equipped with collimators record both the useful signal (X-ray photons) and charged particles from the same area of the detector. If it were possible to focus X-ray photons onto a small spot in the focal plane of an instrument, one would obtain a huge gain in sensitivity.

An idea to build such an X-ray telescope was put forward already in 1960 (Giacconi, Rossi, 1960). However, its realization took a long time, since focusing of X-ray photons required new technologies. X-rays cannot be reflected in a usual way (by large angles), but reflection becomes possible if the angle of incidence on a well-polished surface is very small, less than one degree. In such case, a plane-parallel beam of X-rays can be concentrated in the focal plane. An X-ray telescope is thus a system of nested cones or paraboloids and hyperboloids, the internal surfaces of which must be polished to an accuracy of several angstroms, while the shape of the mirrors must be kept to within a few microns.

This technology was first tested aboard the *Skylab* space station with its S-054 solar telescope (energy range 0.2–5 keV) in 1973–1974 (Vaiana et al., 1977). The first astrophysical observatory equipped with a grazing incidence telescope was HEAO 2 (*Einstein*), which operated from 1978 to 1980.

Scientific results of the *Einstein* observatory greatly expanded the boundaries of X-ray astronomy. Despite the relatively small effective area of the telescope, about 10 cm^2, the use of focusing optics led to a thousand-fold increase in sensitivity compared to *Uhuru*.

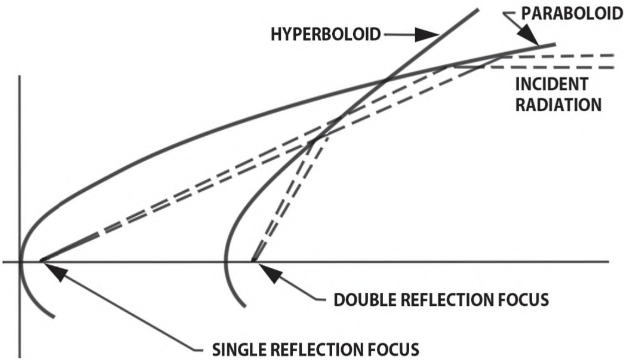

Fig. 7: Principal scheme of a grazing incidence X-ray telescope. X-rays from a distant souce are focused as a result of double scattering from the mirror system

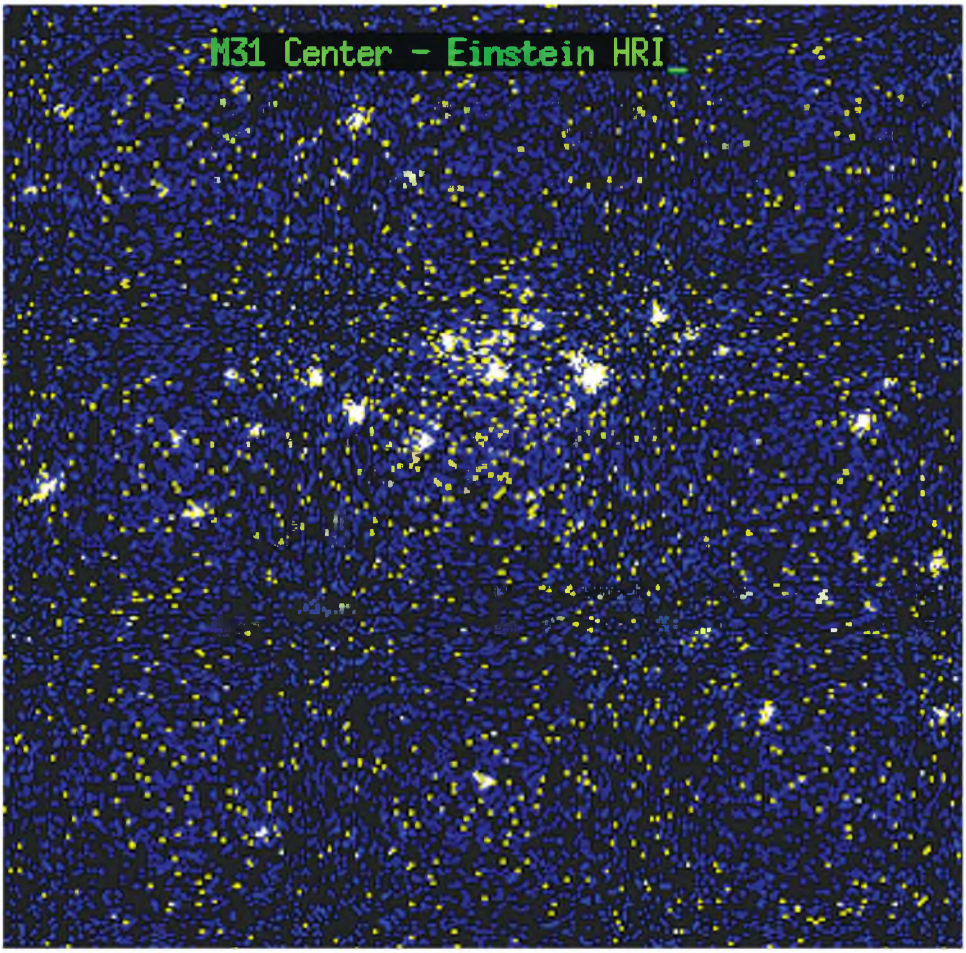

Fig. 8: Image of the central region of the M31 galaxy (Andromeda) obtained by the X-ray telescope aboard the *Einstein* observatory Image courtesy NASA

X-rays were detected from a great variety of sources: the polar regions of Jupiter, normal stars of all types, supernova remnants, white dwarfs, hot gas in elliptical galaxies, etc. Investigation of neutron stars and black holes became possible throughout the Galaxy and even in other galaxies. Amazingly high-quality images of the central region of the Andromeda galaxy were obtained.

A breakthrough occurred in our understanding of the cosmic X-ray background. Observations made in 1977–1979 by the HEAO 1 observatory had demonstrated that CXB energy spectrum could be described by a model of bremsstrahlung emission from plasma with temperature of $\sim 5 \cdot 10^8$ K. Does it mean that the whole Universe is filled by hot rarefied plasma? The answer was given by deep observations performed by the *Einstein* observatory. It turned out (Giacconi et al., 1979) that as the sensitivity of observations increases, the number of detected sources increases dramatically. The summed X-ray flux of sources detected by *Einstein* accounted for 40 % of the total CXB brightness at energies of 1–2 keV. It was clear that, improving the sensitivity further, one could find even more sources and resolve a yet larger fraction of the CXB.

The *Chandra* observatory has now resolved about 80 % of the CXB into individual sources. The large majority of sources making up the CXB are active nuclei of remote galaxies — accreting supermassive black holes. The discovery of numerous sources of this type has opened a new area of research — cosmological evolution of black holes.

The capabilities of the *Einstein* X-ray mirror system exceeded those of its focal instruments. The size of the spot into which the mirror system could focus photons was 80–100 micron (corresponding to 5–6 arcsec in the sky), while the proportional gas counters (IPC), which had the best sensitivity among the *Einstein* instruments, provided an angular resolution of just about 1 arcmin. Significantly better angular resolution was provided by the microchannel-plate detectors, HRI, which however had an order of magnitude lower sensitivity than IPC. Subsequent development of detector technologies in the 1980s and 1990s led to a convergence of the characteristics of focusing optics and detectors.

A giant leap forward was achieved thanks to the development of a grazing incidence telescope with large field of view and effective area (240 cm^2) for the observatory ROSAT (Germany, USA, UK, 1990–1999). ROSAT carried out a sensitive survey of the whole sky in soft X-rays (0.2–2.5 keV) and discovered some 150 thousand sources of various classes. The ROSAT mission was extremely successful. It provided detailed information about supernova remnants, found isolated neutron stars and X-ray emission from comets, etc.

The cosmic X-ray background is very isotropic at energies above ~1 keV. However, already in the late 1960s, measurements at softer X-rays (~0.25 keV) had shown that the background brightness in this energy band was inconsistent with an extrapolation of the CXB spectrum measured at 1–10 keV and that it was significantly anisotropic. Detailed exploration of the soft X-ray background and its correlation with the distribution of interstellar medium in the Galaxy with ROSAT demonstrated that this radiation is of Galactic origin and arises in the hot plasma component of the ISM. ROSAT also discovered a variable radiation arising in the heliosphere due to charge exchange of highly ionized ions of heavy elements (e.g., oxygen) with neutral interplanetary matter.

In studying compact stellar remnants, such as black holes, neutron stars, and white dwarfs, spatial information is not available: such sources have too small angular sizes (for example, a neutron star has a size of just 10–15 km and is located at a distance of hundreds or thousands of parsecs from us). There is thus only spectral and timing information.

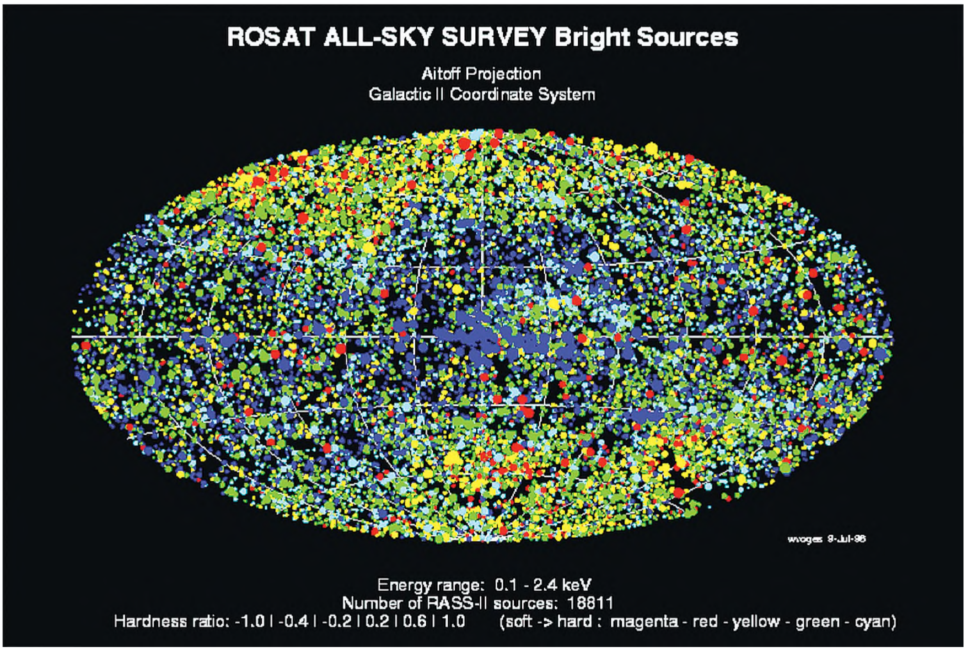

Fig. 9: Positions of bright X-ray sources detected during the ROSAT all-sky survey. Image courtesy Voges et al., Astronomy & Astrophysics 349, 389 (1999)

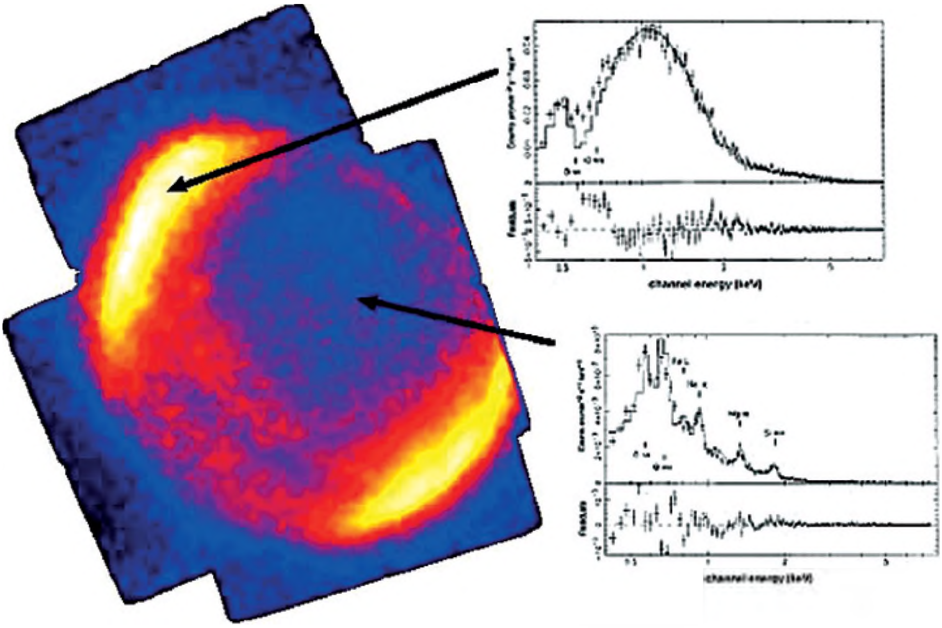

Fig. 10: Image of the supernova remnant SN1006 obtained by ASCA. The emission at the remnant's rim is generated by non-thermal processes, in contrast to the emission in its interior . Image courtesy Koyama et al., Nature 378, 255 (1995)

In 1978, high energy resolution solid-state detectors were used for the first time in X-ray astronomy. The Solid State Spectrometer (SSS) of the *Einstein* observatory was based on a cryogenically cooled silicon detector and provided a resolution of 160 eV. But energies only up to 4 keV were accessible due to the properties of the mirrors.

The Japanese ASCA observatory (1993–2000) for the first time combined moderate spatial resolution with good energy resolution. The payload consisted of four grazing incidence telescopes, with two positionally sensitive gas scintillation proportional counters and two solid-state/CCD detectors in the focal planes.

ASCA has made a lot of important discoveries, including non-thermal radiation from supernova remnants, inhomogeneities of hot gas in clusters of galaxies, and structure in the fluorescent emission lines of compact objects.

6. BROADBAND X-RAY IMAGING AND SPECTROSCOPY WITH CODED-MASK INSTRUMENTS

Early on there were indications that emission from accreting black holes contains separate components with characteristic temperatures of 1–2 keV and 30–50 keV. Since it is hardly possible to study X-ray emission properties over this broad energy range with a single instrument, it was necessary to use combinations of them. The hard X-ray band (energies above 5–10 keV) is interesting also because the interstellar medium practically does not absorb photons of such energies. In softer X-rays, interstellar absorption obscures the Galactic plane and especially the Galactic Center from our view.

One of the first attempts to map the Galactic Center region at energies above 3 keV was undertaken with the X-ray Telescope (XRT) of the *Spacelab 2* observatory, which operated on the *Challenger* space shuttle in July – August 1985. The total duration of these observations was just 6 hours, which limited the depth of the resulting map. XRT used a novel principle of imaging, namely a method of "coded aperture": the incident X-ray flux is spatially modulated by a mask located above the detector and consisting of a large number of randomly located transparent and opaque segments. The flux from a distant source is thus "coded" by the mask and registered by a positionally sensitive detector. Depending on the source position, a specific pattern is formed on the detector (a shadowgram). If there are several sources in the field of view, the detector records a superposition of shadowgrams, with the contribution of each source being proportional to its intensity. Since the instrumental background is not modulated by the mask, it is possible to reconstruct a two-dimensional image of the observed field, which was demonstrated in the *Spacelab 2*/XRT experiment.

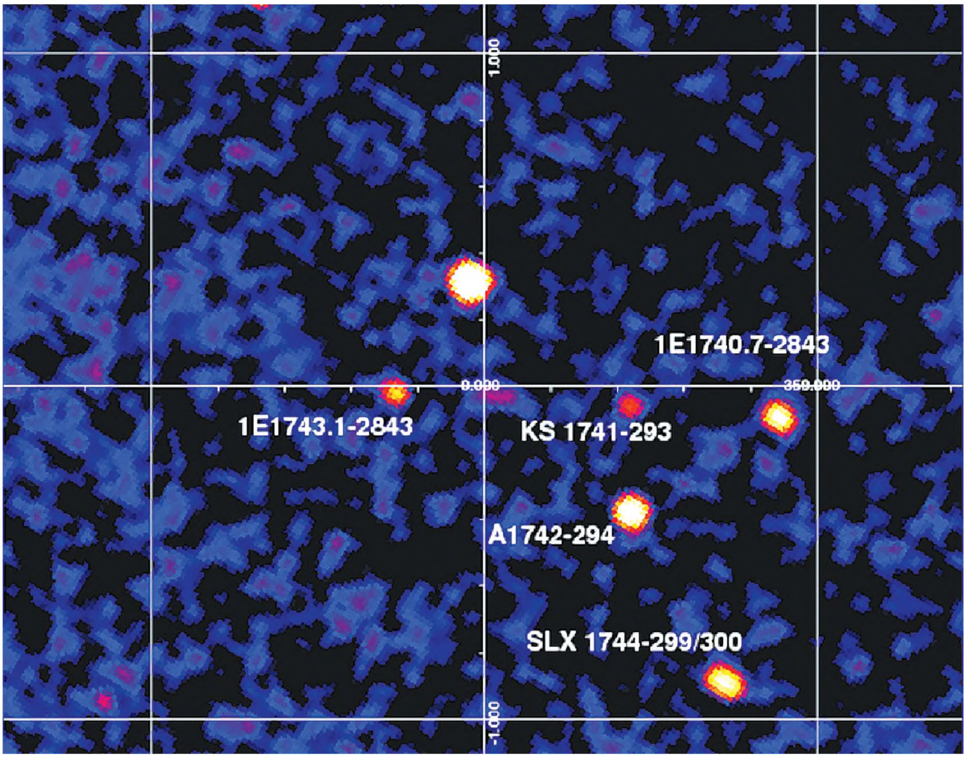

Fig. 11: Image of the Galactic Center region obtained by TTM coded-mask instrument aboard the *Mir*/*Kvant* module. The size of the image is 2×2 deg

The concept of a coded-mask telescope found further application in the international *Rentgen* observatory aboard the *Kvant* module of the Soviet *Mir* orbital station (1987–1996). Its payload covered a very broad energy range from 2 to 800 keV; it had been developed by specialists from the USSR (telescope-spectrometer *Pulsar X-1*), the Netherlands and the UK (the coded-mask telescope TTM), Germany (the HEXE spectrometer) and the European Space Agency (the *Sirene 2* spectrometer). Using TTM, maps of large fields at energies up to 30 keV were obtained for the first time and new sources in the Galactic Center region were discovered.

An outstanding result of the *Rentgen* observatory was the discovery of hard X-ray radiation from Supernova 1987A. This supernova went off in February 1987 in the Large Magellanic Cloud and is the nearest known supernova of the last 400 years. The shell that formed as a result of the explosion of a star with a total mass of more than 15 solar masses was initially so dense that X-rays could not leak out. However, as the shell was rapidly expanding, it was gradually becoming transparent to X- and gamma-rays. The gamma-ray radiation arising from the decay of radioactive cobalt (^{56}Co) was expected to start escaping through the expanding shell approximately half a year after the explosion (Grebenev, Sunyaev, 1987).

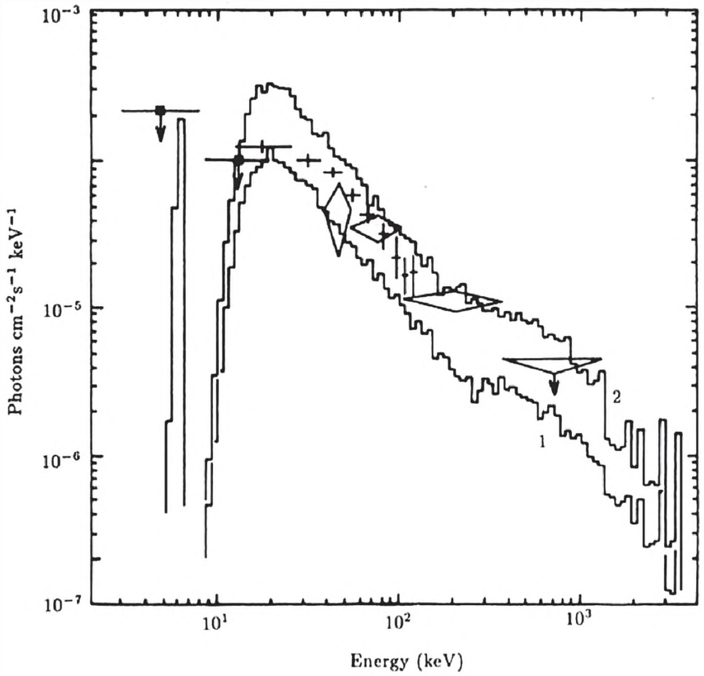

Fig. 12: Energy spectrum of Supernova 1987A measured the *Roentgen* observatory. The histograms show the results of spectral modeling. Image courtesy Sunyaev et al. (1987)

On August 10, 1987, the instruments of the *Rentgen* observatory did detect hard X-ray radiation from the supernova. To verify the source of this emission, it was proposed to "swing" the whole *Mir* orbital station so that other X-ray sources would fall in and out of the field of view of the instruments. The control system brilliantly performed the task. It was demonstrated that the radiation was indeed coming from Supernova 1987A and its measured spectrum confirmed theoretical predictions (Sunyaev et al., 1987).

At about the same time, another observatory, GRANAT (1989–1998), was implemented together by Soviet, French, Dutch, and Bulgarian scientists. It was designed for detailed astrophysical studies at energies from 2 keV to 100 MeV. The main instruments aboard the GRANAT spacecraft were the French-Soviet telescope SIGMA and the ART-P telescope developed at the Space Research Institute of the Academy of Sciences of the USSR. Both telescopes were based on the coded-mask principle and had overlapping energy ranges: 2–60 keV (ART-P) and 40 keV – 2 MeV (SIGMA). ART-P consisted of 4 identical modules, each containing a positionally sensitive gas counter and a coded mask. Each module had an effective area of about 600 deg^2 and a field of view of 1.8×1.8 deg. The angular resolution of ART-P was 5 arcmin. SIGMA was the first telescope capable of building images in the hard X-ray/soft gamma-ray band (40–1300 keV).

GRANAT payload also included a number of survey-type detectors, WATCH, PHEBUS, and *Konus*. They covered a very broad energy range from 5 keV to 100 MeV and were designed mainly to find and study GRBs, although the WATCH all-sky monitor was also successfully used to detect and localize transient X-ray sources. In particular, it discovered the Galactic microquasar GRS 1915+105 ("GRS" is for GRanat Source), in which superluminal motion of relativistic jets was later discovered.

Among the most important results of GRANAT are: (i) detailed maps of the Galactic Center region in the hard (40–150 keV) and soft (4–20 keV) X-ray bands (Sunyaev et al., 1991; Pavlinsky et al., 1994; Revnivtsev et al., 2004), in which a number of black holes and neutron stars were discovered, (ii) high-quality broadband spectra of black hole and neutron star candidates, (iii) discovery of extended hard X-ray (8–22 keV) diffuse emission around the Galactic Center and in the direction of the giant molecular cloud Sgr B2 — an "echo" of activity of the central supermassive black hole in the past (Sunyaev et al., 1993).

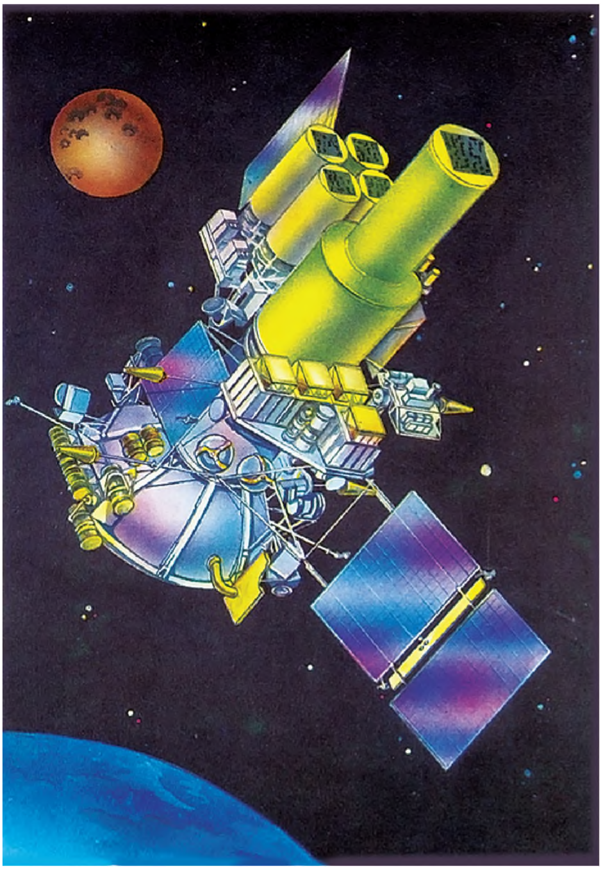

Fig. 13: GRANAT observatory

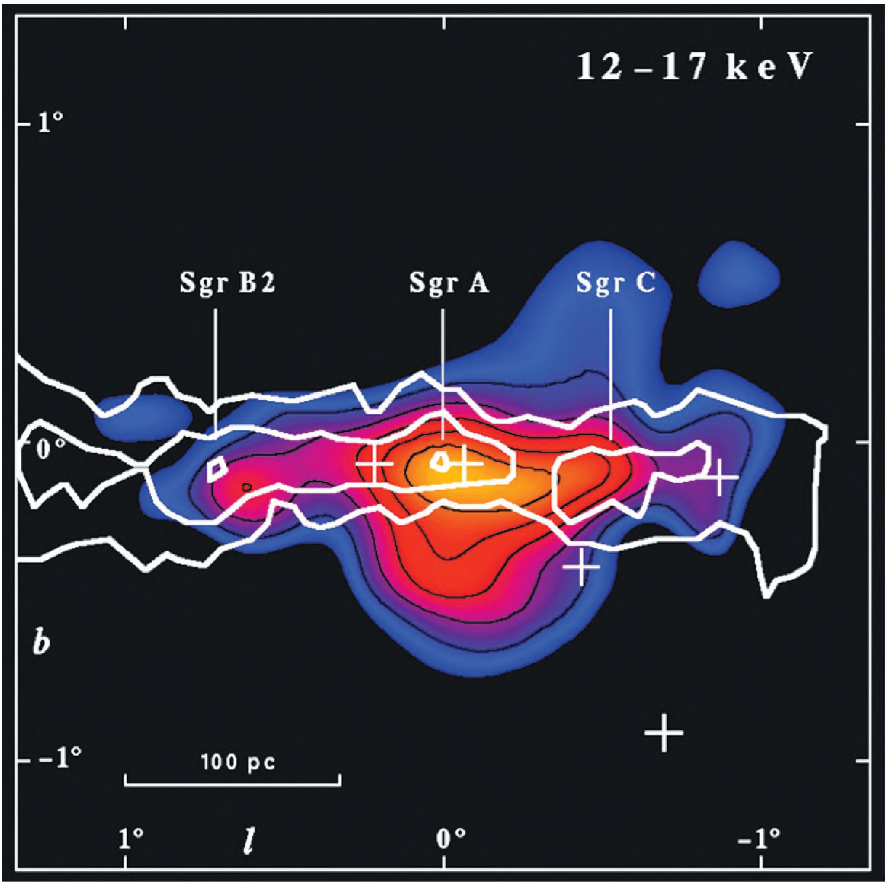

Fig. 14: Image of the Galactic Center region in the 12–17 keV energy band obtained by the ART-P telescope of the GRANAT observatory. The white contours show the distribution of the molecular gas. The X-ray signal from the direction of the giant molecular cloud Sgr B2 is reflected radiation from the supermassive black hole (Sgr A) emitted about 300 years ago

The success of *Rentgen* and GRANAT led scientists to think about an orbital gamma-ray laboratory, which would combine capabilities of imaging, high-resolution spectroscopy and timing analysis in hard X-rays and gamma-rays. So, the INTErnational Gamma Ray Astrophysical Laboratory (INTEGRAL, in orbit since 2002) was born.

The main instruments of INTEGRAL are the IBIS gamma-ray telescope and the SPI spectrometer. As it was for GRANAT, imaging with INTEGRAL is based on the coded-mask principle. The SPI spectrometer has much better sensitivity to nuclear lines than previous instruments. It operates in the 20 keV – 8 MeV energy range and has a spectral resolution of E/dE ~ 500. The gamma-telescope IBIS (energy range 15 keV – 10 MeV) enables imaging in the hard X-ray and gamma-ray bands with good angular resolution.

The very precise insertion of INTEGRAL into a high-apogee orbit by a *Proton*/DM rocket/booster made it possible to save fuel and prolong the mission's lifetime. The observatory remains active today, 16 years after launch. Over the course of the mission, many important results have been obtained. Among them is a precise measurement of the energy of the positron-electron annihilation line (Churazov et al., 2005). The spatial distribution of this emission implies that of order 10^{43} positrons are annihilating each second in the central region of the Galaxy. The width of the 511 keV line and the relative brightness of the three-photon continuum (below 511 keV) imply that annihilation takes place in a warm (~10,000 K) and partially ionized interstellar medium.

INTEGRAL has provided a detailed map of our Galaxy (Krivonos et al., 2012), helped to solve the problem of diffuse hard X-ray emission along the Galactic plane (Galactic Ridge X-ray Emission, Revnivtsev et al., 2006; Krivonos et al., 2007), which turned to be the cumulative emission of numerous accreting white dwarfs, and discovered gamma-ray lines of radioactive titanium and scandium at energies of 67.9 and 78.4 keV from Supernova 1987A (Grebenev et al., 2012).

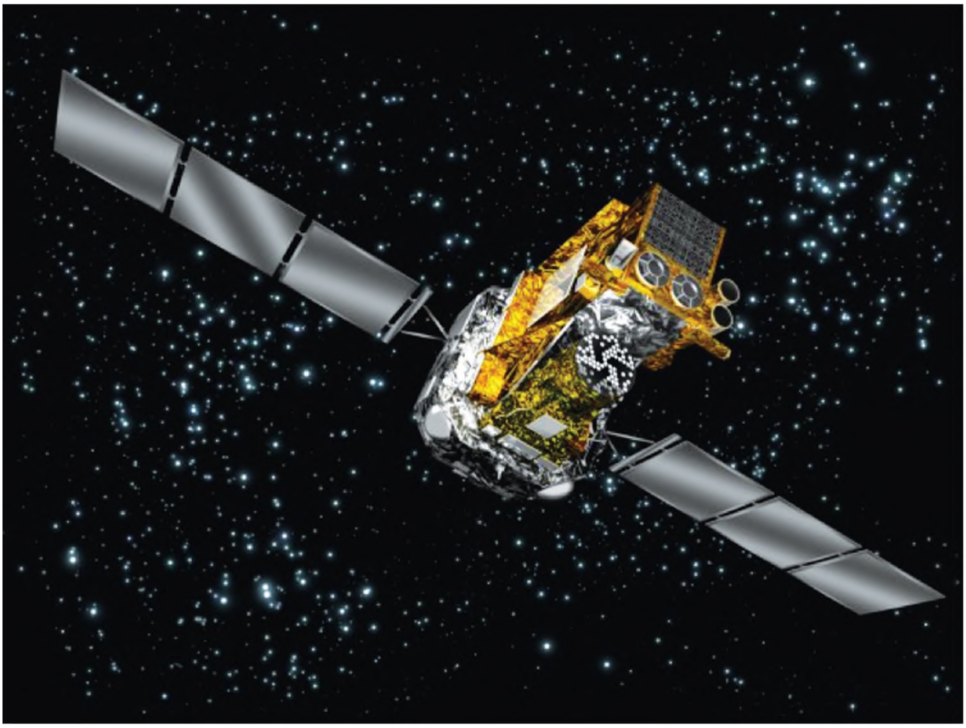

Fig. 15: INTEGRAL observatory. Image courtesy ESA

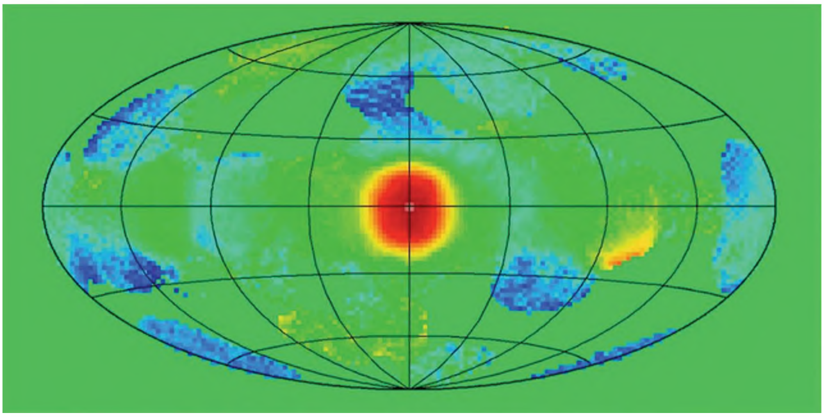

Fig. 16: Sky map of positron-electron annihilation radiation (511 keV), obtained by INTEGRAL/SPI. Concentration of the signal around the Galactic Center is clearly seen

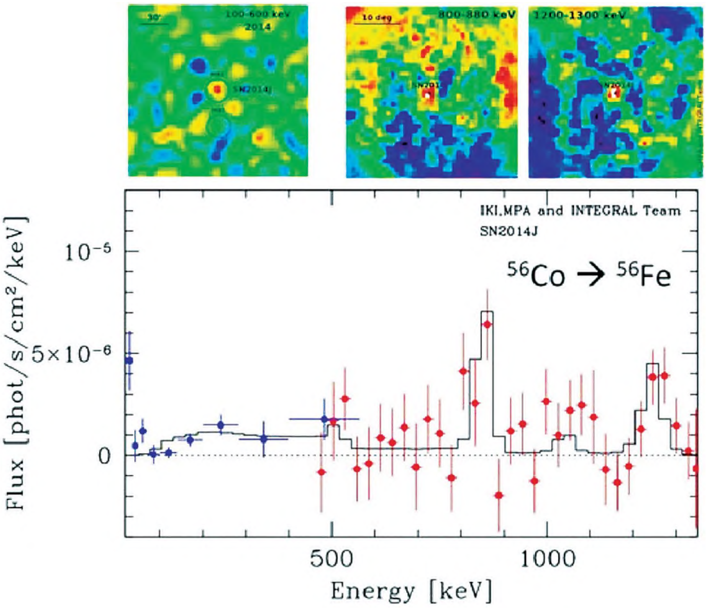

Fig. 17: Spectrum of the type Ia supernova SN2014J observed by INTEGRAL 50 to 100 days after the explosion. The top row shows images in the three high-energy spectral bands of INTEGRAL. In all images, it is possible to clearly see a gamma-ray source at the position of SN2014J. Image courtesy Nature

One the brightest results of INTEGRAL is the detection of gamma-ray lines associated with the decay of radioactive cobalt (^{56}Co, which itself is the product of the decay of ^{56}Ni), from the type Ia Supernova 2014J (Churazov et al., 2014), which exploded in 2014 in the nearby galaxy M82. This provided a direct proof of the long-standing hypothesis that a type Ia supernova results from the thermonuclear explosion of a white dwarf as its mass exceeds the fundamental Chandrasekhar limit, which happens through accretion or merger with another white dwarf.

INTEGRAL also played a crucial role in the groundbreaking discovery of an electromagnetic counterpart of gravitational waves detected on August 17, 2017 by the LIGO experiment. This was the first ever detection of the collision of two neutron stars (Savchenko et al., 2017).

7. X-RAY TIMING MISSIONS: FAST VARIABILITY PHENOMENA

Already the first rocket and satellite measurements of the brightest compact objects (e.g., Cygnus X-1) demonstrated that their X-ray flux can change on timescales shorter than one second (Oda et al., 1971). It is on such timescales that rotation of matter around black holes and neutron stars takes place (the size of a stellar-mass black hole or a neutron star is 10–30 km, whereas the speed of rotation of matter around them can reach half the speed of light).

The main difficulty associated with observations of such fast variability is that the objects of interest are located so far from us that the rate of photons detected from them is very low. For example, the X-ray luminosity of Cyg X-1 is hundred thousand times the bolometric luminosity of the Sun, but because of the large distance to the source (2,000 parsecs), its X-ray flux near Earth is just a few photons per second per cm^2. Therefore, to obtain timing information about the physical processes taking place near black holes and neutron stars, large instruments are needed.

One of the first attempts to study fast variability of X-ray sources was made during the *Exosat* mission (1983–1986) of the European Space Agency. Its main instrument was a system of proportional gas counters with a total effective area of 1600 cm^2. *Exosat* discovered different types of quasi-periodic oscillations in the brightness of X-ray sources (Hasinger, van der Klis, 1989), likely related to processes occurring in the accretion flows around compact objects. This provided a new method of diagnostics of accreting black holes and neutron stars.

Further progress in this direction was associated with the observatories GINGA (Japan, 1987–1991, effective area 4,000 cm^2) and RXTE (NASA, 1995–2012).

The RXTE observatory was equipped with X-ray detectors having a record large collective area, about 6,400 cm^2. This led to a breakthrough in the study of fast variability of X-ray sources and in particular to the discovery of quasi-periodic oscillations with frequencies up to 1 kHz, reflecting fast motion of matter near the horizons of black holes and surfaces of neutron stars (van der Klis et al., 1996).

Another discovery made by RXTE is the detection of pulsations in the X-ray flux of neutron stars with frequencies of hundreds of Hz, indicating that some neutron stars are rotating with periods as short as 1–2 milliseconds (Wijnands, van der Klis, 1998). This confirmed the long-standing hypothesis that neutron stars in binary systems can evolve into millisecond radio-pulsars after having accreted a significant mass from the companion star.

Rapidly spinning neutron stars have been discovered not only among pulsars (i.e. neutron stars with magnetic fields sufficiently strong for collimation of matter onto the magnetic poles), but also among neutron stars with weak magnetic fields. In particular, pulsations were found during thermonuclear bursts occurring in the atmospheres of neutron stars. These brightness oscillations arise at the early stage of thermonuclear burning due to rotation of the compact site of burning (Strohmayer et al., 1998).

The discovery of high frequencies of neutron stars' rotation provided a new tool to study their physical parameters. At a spinning frequency of 500 Hz, the speed at the surface of the neutron star is 10–20 % of the speed of light, which should lead to observable effects in the X-ray light curve. Measurement of such distortions can help determine the radii of neutron stars and shed light on the equation of state of matter in the centers of such compact objects. Are neutron stars actually quark ones? Is kaon or boson condensate formed in the core of a compact star?

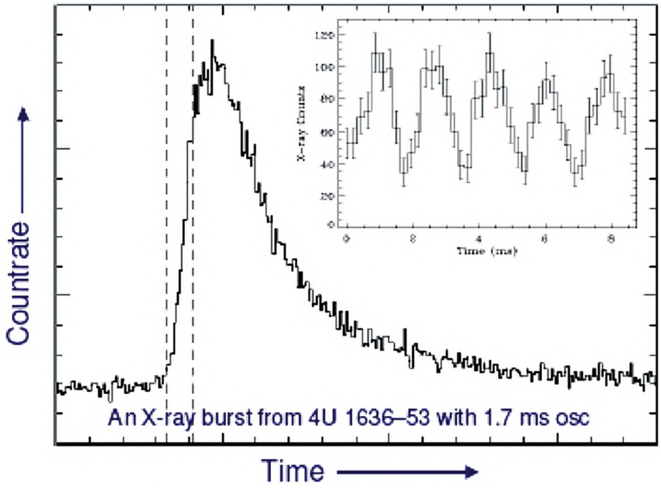

Fig. 18: X-ray light curve of 4U 1636-563 during a thermonuclear explosion on the neutron star. During the rise phase of the burst, before the burning has spread over the whole surface of the star, X-ray brightness oscillations are observed (see inset) due to the fast rotation of the star. Image courtesy Strohmayer et al. (1998)

8. RECENT ACHIEVEMENTS IN X-RAY ASTRONOMY

In 1999, two major X-ray observatories were launched: AXAF/*Chandra* (NASA) and *XMM-Newton* (ESA). Both are still operational in 2018. The *Chandra* observatory uses 4 nested grazing incidence mirrors, which build upon the legacy of the *Einstein* observatory. The effective area has increased to 600–700 cm^2 at energies 1–2 keV and the energy has extended up to 8 keV. The angular resolution is a fantastic 0.5 arcsec. CCD detectors with energy resolution of 150–200 eV at 6 keV are used. The inclusion of diffraction gratings enables spectroscopy of point sources with yet higher energy resolution (E/dE ~ 1000). *XMM-Newton* uses grazing incidence mirrors based on a somewhat different technology. It has three mirror systems, each consisting of 58 nested paraboloid and hyperboloid shells. Difficulties in aligning such a large system have limited the angular resolution to 5–7 arcsec, but *XMM-Newtion* has a significantly larger effective area than *Chandra*.

The combination of high spatial and energy resolution with large effective area of the instruments aboard *Chandra* and *XMM-Newton* has boosted the development of various branches of X-ray astronomy, such as the study of populations of accreting objects in other galaxies, studies of the chemical composition of hot plasmas in galaxies, clusters of galaxies, and supernova remnants, exploration of the impact of supermassive black holes on galaxies and clusters of galaxies, etc.

Chandra observations of the “Bullet cluster”, which formed as a result of the merger of two clusters of galaxies, in combination with optical observations have revealed that the gravitational potential in this system traces the distribution of galaxies rather than that of hot plasma.

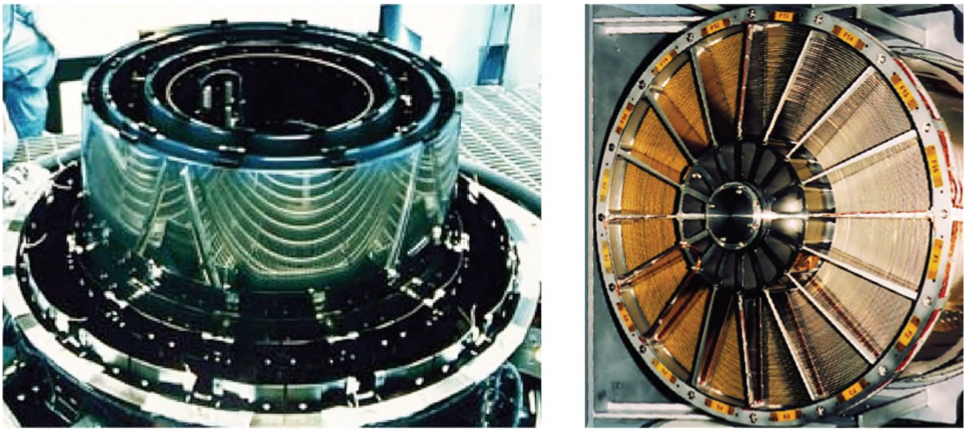

Fig. 19: Mirror systems of the *Chandra* (left) and XMM-*Newton* (right) observatories

Fig. 20: *Chandra*/optical/lensing composite image of the "Bullet" galaxy cluster. During the collision of two clusters of galaxies, the dark matter moved ahead of the gas, producing the separation of the dark and normal matter seen in the image. Image based on Clowe et al. (2006)

This provided strong support in favor of the existence of dark matter in the Universe and against modifications of the gravitaitional force law (Clowe et al., 2006). The intracluster gas is very interesting in its own right. Thanks to the unique capabilities of *Chandra* and *XMM-Newton*, the physical properties of such hot, rarefied, and magnetized plasmas have now been studied in great detail (Markevitch, Vikhlinin, 2007).

The growth of clusters of galaxies, the largest gravitationally bound objects in the Universe, depends on cosmological parameters. In particular, if dark energy significantly contributed to the total density of the Universe, the growth of clusters of galaxies would be suppressed. Based on this idea, using a sample of galaxy clusters selected from the ROSAT sky surveys and explored with *Chandra* and *XMM-Newton*, an independent confirmation of the existence of dark energy in the Universe has been obtained (Vikhlinin et al., 2009).

Further progress has long been expected to be linked with the development of X-ray microcalorimeters, promising energy resolution of 3–5 eV, much better than that of CCDs. However, the advent of such detectors was delayed by technical accidents. The *Astro-E* observatory (Japanese Aerospace Exploration

Agency, JAXA, and NASA), equipped with a cryogenic X-ray calorimeters spectrometer, was lost during a failed launch in 2000. Its replication (with somewhat improved energy resolution) was successfully launched in July 2005 on the *Astro-E2* (*Suzaku*) satellite, but problems in the cooling system led to a complete loss of the fluid helium and a shut-down of the X-ray spectrometer shortly after the launch.

A third attempt was undertaken in February 2016, when the *Astro-H* (*Hitomi*) observatory was launched, again with an X-ray calorimeter spectrometer on board. The fate of this observatory, however, turned out to be tragic too, as about one month after the launch the spacecraft suddenly began to rotate rapidly and ultimately broke into pieces. Nevertheless, the mission was partially successful, as some scientific data were received before the accident. Most importantly, *Hitomi* observed the Perseus cluster of galaxies and for this first time mapped the motions of hot gas (Hitomi Collaboration, 2016). Surprisingly, the gas turned out to be not strongly turbulent despite it being continuously stirred by fast outflows from the supermassive black hole located in the nucleus of the cluster's central galaxy. These observations clearly demonstrated the huge potential of microcalorimeter technology for X-ray astronomy. Currently, a successor of *Hitomi* is under development.

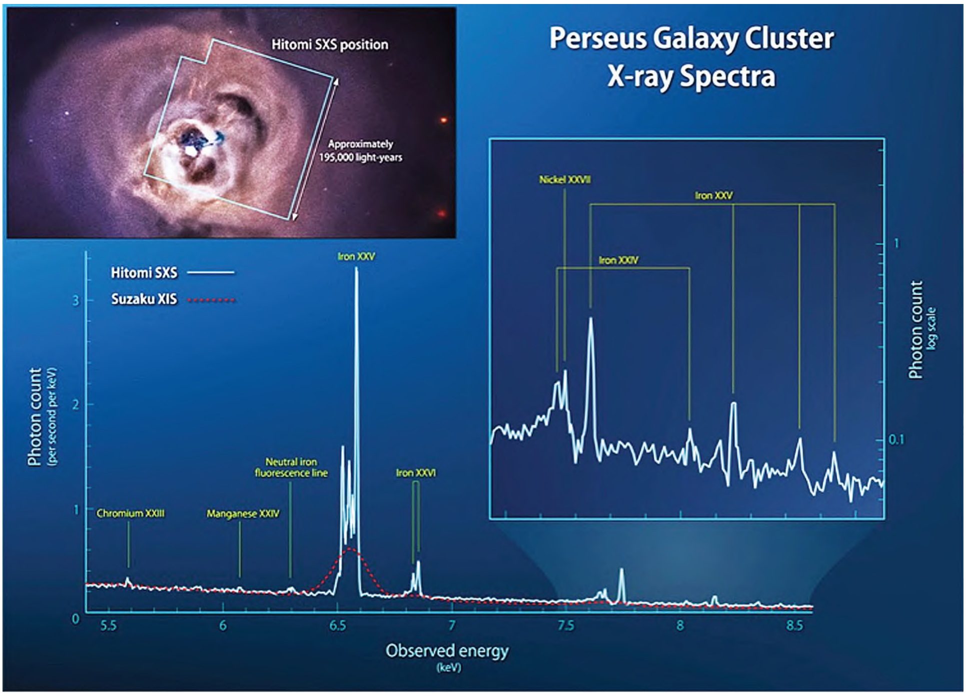

Fig. 21: X-ray spectrum of the Perseus galaxy cluster measured by the Soft X-ray Imaging Spectrometer of the *Hitomi* observatory. Also an X-ray image obtained by *Chandra* is shown, the square indicates the area targeted by *Hitomi*. Image courtesy NASA's Goddard Space Flight Center

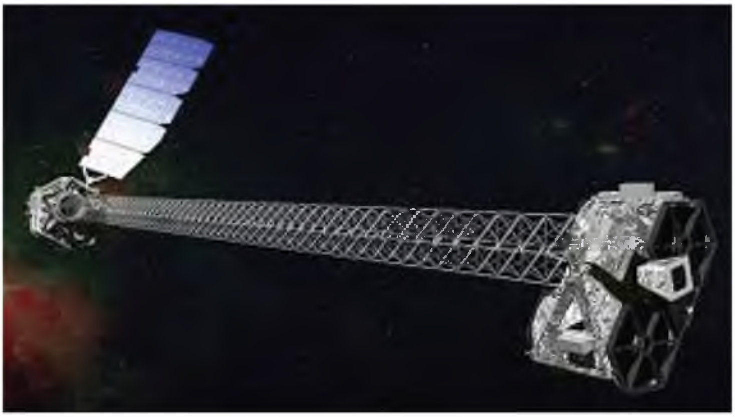

Fig. 22: NuSTAR observatory. Image courtesy NASA

At higher energies, recent progress has been associated with the advent of grazing incidence mirror systems capable of focusing hard X-rays. An orbital observatory with such mirrors, NuSTAR (NASA), was launched in June 2012. The NuSTAR X-ray telescope covers an energy range from 3 to 80 keV and is about 100 times more sensitive than the IBIS imager on INTEGRAL.

Over the first 5 years of the mission, NuSTAR has observed X-ray sources of various classes. In particular, it has provided a map of radioactive material in a supernova remnant, Cassiopeia A, shedding light on how the progenitor of this supernova exploded, and measured (together with *XMM-Newton*) the spin rate of the supermassive black hole in an active galactic nucleus, NGC 1365.

Since 2009, the X-ray all-sky monitor MAXI (JAXA) operates on the Japanese module *Kibo* of the International Space Station. Its task is to monitor the whole sky in the 1–20 keV energy band with a single-day sensitivity similar to the sensitivity of the 3-year survey by *Uhuru*.

9. PROSPECTS OF X-RAY ASTRONOMY

Due to new technological capabilities of X-ray astronomy, its objectives now strongly overlap with those of fundamental physics. Among the main scientific problems being addressed are the equation of state of matter at extra-nuclear densities, existence of quark matter, structure of the Universe, nature of dark matter and dark energy, fundamental problems of plasma physics, etc.

The all-sky soft X-ray survey performed by ROSAT in the early 1990s has proved to be very important for under understanding of the Universe. However, there is now a strong need in an all-sky survey with better sensitivity and broader energy coverage.

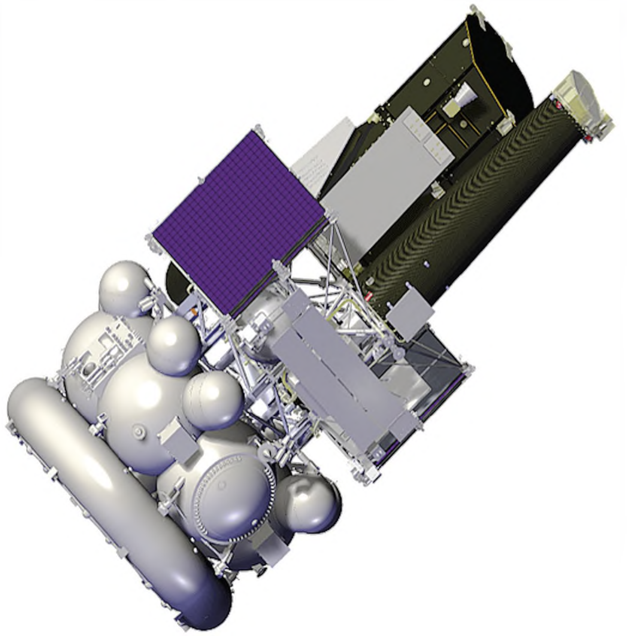

Fig. 23: *Spektr-Rentgen-Gamma* observatory

Such a survey is planned to be conducted by the *Spektr-Rentgen-Gamma* (SRG) observatory. This is a joint project of Germany and Russia, aimed at the solution of fundamental questions of cosmology and astrophysics.

The SRG payload consists of two X-ray telescopes, eROSITA (Germany) and ART-XC (Russia, with USA participation), which together cover an energy range of 0.2–30 keV. The main goal of the observatory is to perform an all-sky survey with sensitivity about a hundred times better compared to previous surveys. SRG is expected to detect all (about 100 thousand) massive clusters of galaxies in the observable Universe, several millions of accreting supermassive black holes, thousands of star-forming galaxies, tens of thousands of accreting white dwarfs, hundreds of thousands of stars with active coronae, etc. The launch is expected in 2019.

There are also bright prospects for the study of fast variability of X-ray sources. Here, the main hopes are linked with the NICER experiment (NASA), which has already (in 2017) begun operating aboard the International Space Station. NICER is the successor to the highly successful RXTE mission, with an order-of-magnitude improvement in sensitivity, energy resolution and time resolution. Due to these unprecedented characteristics, NICER is capable to perform rotation-resolved X-ray spectroscopy of neutron stars with the goal of obtaining stringent constraints on their equation of state. An additional objective is to test X-ray pulsar based navigation technologies, which are expected to become practical in future development of space.

On a longer, 10–20 year, timescale, even more ambitious X-ray astronomy missions are expected to get on line. Building on the success of the *XMM-Newton* observatory, the ATHENA observatory is being currently developed by the European Space Agency, with an expected launch in 2028. Thanks to the novel silicon-pore X-ray optics technology, ATHENA will be about one hundred times more sensitive than *Chanrda* and *XMM-Newton*, whereas its brand new cryogenically cooled transition edge detectors will enable a few electronvolt energy resolution over the 0.2–12 keV energy band. Also, an extremely ambitious successor (the *Lynx X-ray Surveyor*, NASA) to the *Chandra* observatory, is currently under study. This mission, if approved, will combine sub-arcsecond angular resolution with a few square meters collecting area. These future missions are expected to revolutionize our knowledge of the high-energy processes in space and to pierce the Universe to its very early epochs.

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LASER PRECISION COLLISION AVOIDANCE: A NEW CONCEPT IN SPACE DEBRIS MITIGATION

The extraordinary path to discovery made possible by the launch of the Sputnik in 1957 has been done at the expense of an unfathomable number of derelicts of all size and shape cluttering our near-Earth space. If this situation is not handled promptly and deftly, it may prevent any further access to space and its applications.

We are introducing a novel laser-based concept, capable to make an accurate inventory of the debris as far as their position, distance, velocity with centimeter precision. The precision renders possible to predict collision accurately and renders collision avoidance practical with small amount of fuel. The technique we call Laser Precision Collision Avoidance could become our only viable recourse for the near future.

INTRODUCTION

The heralding of the space age over 50 years ago inadvertently began increasing the risk of subsequent low-Earth orbit (LEO) space missions through the introduction of orbital debris. Today we estimate that 28,000 tons have been launched to the LEO corresponding to the mass of four Eiffel towers and the generation of 5,000 tons, or half an Eiffel tower, of debris ranging from millimeter to meter sizes, see Fig. 1. What exists as an innocuous flake of material on Earth can in LEO become a bullet-like projectile with a relative velocity of over 30,000 km/h with the potential to impact great damage on space-based hardware, optics, and even astronauts. There are millions of such unintended “satellites” orbiting between 100–2000 km above the Earth, a fraction of which are tracked and known, see Fig. 2. This space debris extends to larger chunks of material from fully intact instruments to frozen coolant droplets, and has seen increasing growth in its population since the arrival of Sputnik in 1957. With increasing collisions and more frequent deployments, it is of course impossible to alleviate such a problem via natural decay especially for higher orbits. With rates of debris creation exceeding their natural decay, there is growing danger of chain reactions as described by the Kessler syndrome (Kessler, 1991; Kessler, Cour-Palais, 1978; Liou, 2011). Fragmentation debris from 1 to 10 cm are now considered the main threat to breaking up the far less numerous large objects such as derelict rockets [Maier et al., 2013]. With increasing costs and dangers to space missions there is a significant motivation to develop new tools for active removal and cataloguing of space debris.

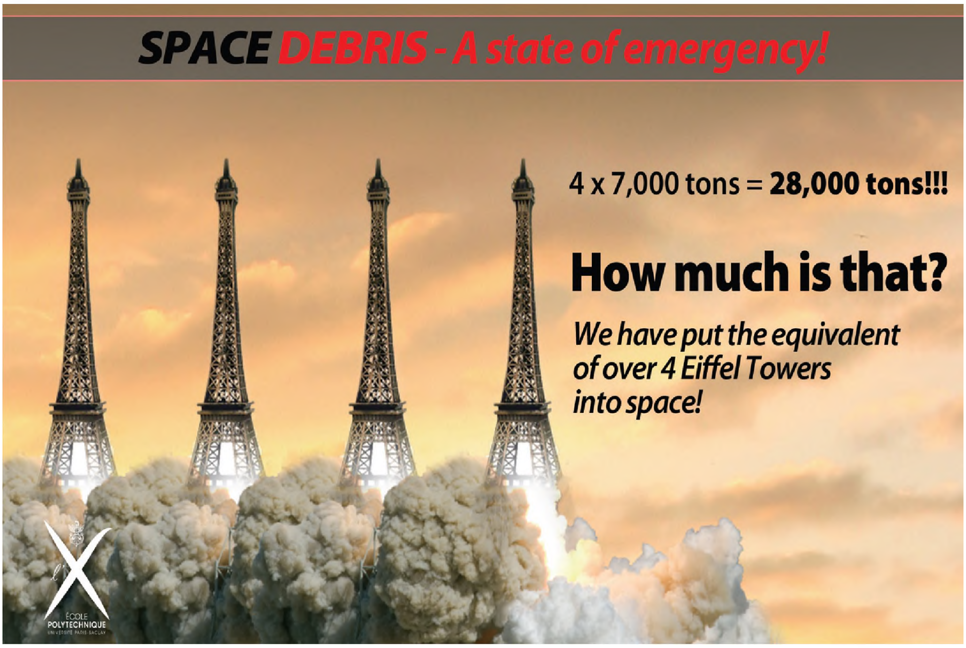

Fig. 1: Illustration of the 30 000 tons equivalent to 4 Eiffel Towers that were sent to space since the first Sputnik launch. The mass of the debris represents half the weight of one Eiffel Tower

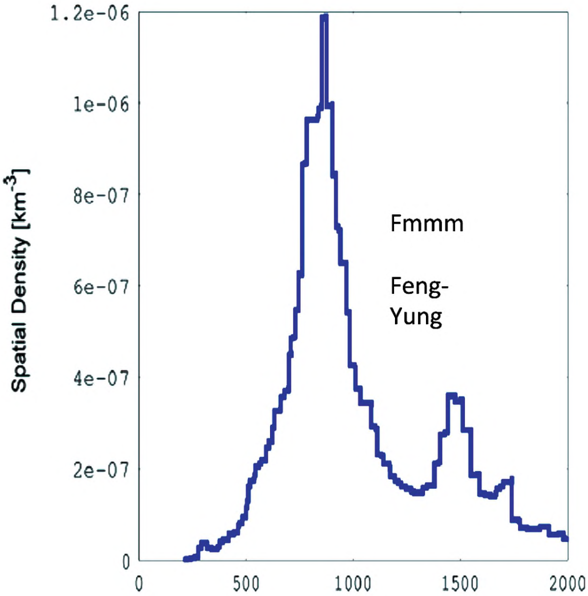

Fig. 2: The distribution of debris in low-Earth orbit for 1–10 cm debris (Tagawa et al., 2013). The peak near 800 km is in large part the debris remaining from the *Iridium*, *Cosmos*, and *Fenhyun-1c* satellites

Contemporaneously to the first satellites, the demonstration of the first lasers, beginning in 1957 with microwaves and then optical amplification in 1960, have enabled an abundance of new disciplines. With rapidly evolving technology, laser science has found applications in a host of terrestrial environments. Together with precise focusability and directionality, lasers have been appraised as a means for removal of space debris (Phipps, 1994; Schall, 1998; Rubenchik et al., 2010).

Rather than total vaporization, it is only necessary to reduce the orbital velocity by a few percent and thus push the debris to a lower orbit after which the drag of the Earth's atmosphere completes the process of re-entry and burn-up. Approaches using ground-based laser systems have been studied using large optics to deliver the energy through the atmosphere onto the debris some hundreds of km overhead (Phipps, 1994). Alternatively, given the inadequate size, average power and efficiency of traditional lasers, designs for localized debris removal by an orbiting system has up to now not been permissible (Schall, 1998).

Recent development of the novel laser-based laser architecture ICAN (Mourou et al., 2013) shows that a new paradigm of diode-pumped laser technology is within grasp, enabling high average power operation with kHz repetition and energy efficiency near 40 %. Here in this article we show that such a system opens a new frontier on debris mitigation. It opens the possibility to produce a plasma recoil (Fig. 3) that could modify the debris trajectory and establish its elemental composition (Fig. 4). Furthermore, it can also be used to establish with precision the debris position, velocities, tumbling motion, that could decrease by many orders of magnitude the number of false collision alerts and minimize fuel consumption in satellite avoidance maneuvers.

Monitoring and tracking of space debris is an ongoing challenge and there is some degree of uncertainty on the populations for different sizes and orbits. For known objects <10 cm, there is the possibility of using collisional avoidance for manned or sensitive spacecraft. For sizes less then 1 cm, there are shielding materials such as Kevlar, which can be utilized. The size range 1 to 10 cm is especially problematic as it is difficult to shield or indeed avoid such debris. Their size also prohibits continuous tracking and as shown in Fig. 2, the peak in debris distribution for 1–10 cm sizes in LEOs occurs near 800 km.

Laser-based efficient techniques have been conceived to neutralize the debris, especially by changing their orbit so they can be burned upon their re-entry in the Earth's atmosphere. However, the small-size debris are more difficult to discard since they are more difficult to locate and be safely disposed. It was Claude Phipps (Phipps, 1994) 30 year ago who offered an elegant solution to neutralize small debris by using the laser recoil produced during laser-plasma interaction (see Fig. 3). The laser recoil could be sufficient to deorbit the debris into the Earth's atmosphere where they burn, as the result of their hyper velocity.

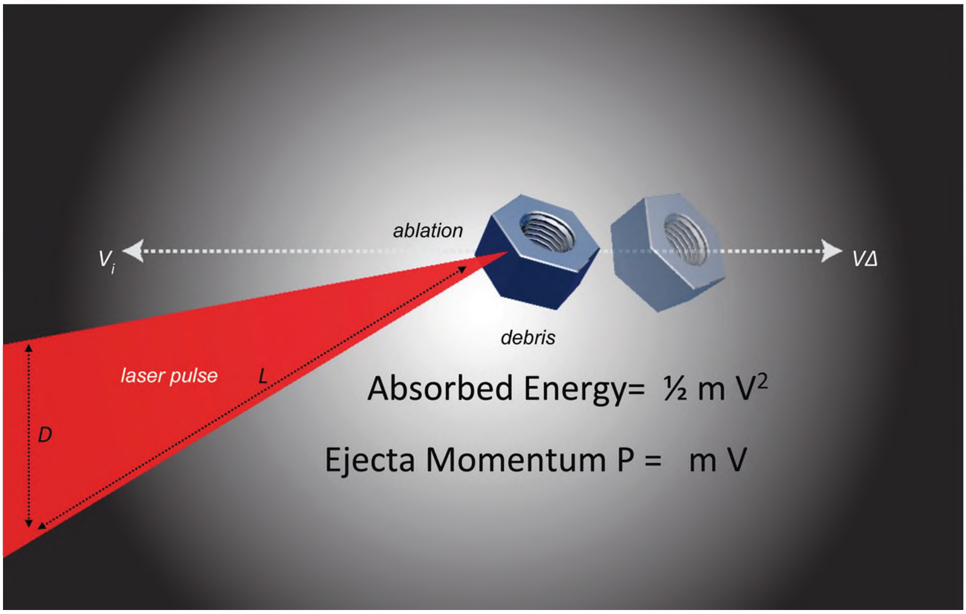

Fig. 3: Illustration of the recoil produced by the short pulse induced-plasma

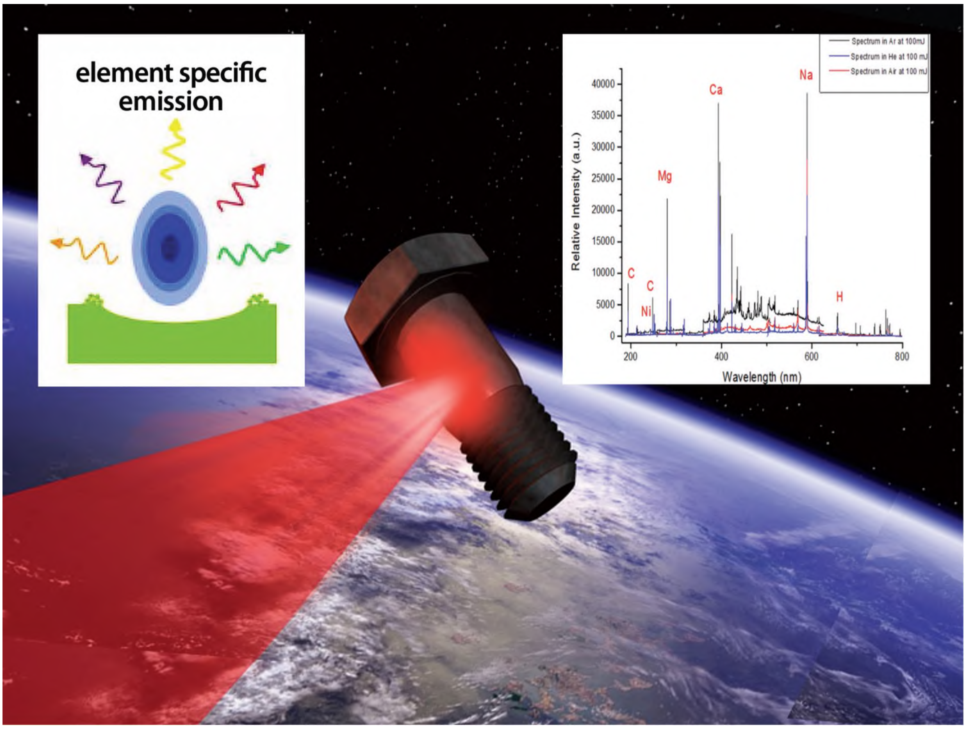

Fig. 4: The plasma emission spectra provides the fingerprint of the elements composing the debris

Collision avoidance to deorbit large debris requires a large amount of the laser energy that is difficult to produce, see Soulard et al. (2015). A preferable strategy would be to avoid their collision by predicting it, point with precision. It is precisely what is attempted today. Unfortunately, as shown in Fig. 5, the positions provided by radars lack precision. It is today of the order of 1.5 km along the trajectory and 100 m across it. The ratio between the debris uncertainty volume over the debris' real volume can easily be of the order 10^6 to one. This translates to an enormous number of false alerts, in the range of 1 million per year. For instance, the CNES, the French National Space Centre, dealt with more than 1 million collision notifications in 2016 to protect 16 satellites in LEO, *in-fine* leading to only 16 Collision Avoidance Maneuvers. The corresponding activity is huge, with teams working 24/7, dealing mostly with false alarms.

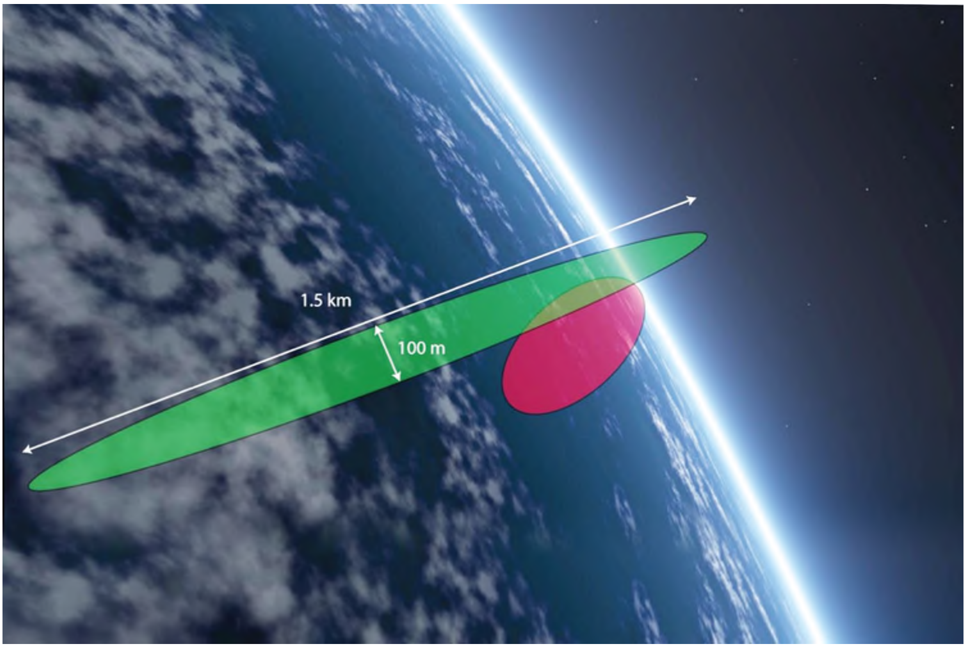

Fig. 5: Illustration of the large uncertainty associated with the detection of a debris. The size of the two ellipsoids corresponds to the radar uncertainty measurement. When these two ellipsoids intersect, it triggers a false alert

Improving the precision on position and velocity of every debris would be of paramount importance and would avoid this 99.998 % ratio of false alarms.

Collisions between a debris larger than 1–5 mm and an operational satellite can disable the spacecraft and induce a significant economic loss. Current estimates show that the probability of losing an operational satellite in the 700–900 km altitude band is higher than 5 % over the lifetime of the satellite. Unfortunately, as mentioned, objects smaller than 10 cm in LEOs are currently not catalogued. Performances of radars and telescopes at worldwide level are increasing with years, but the best projections made today show that an objective of cataloguing objects larger than 5 cm is still very ambitious, on the other hand this precision could be easily reached by an on orbit high repetition rate laser with modest energy (1 joule) and short pulses, i.e. 100 fs pulse

1. INTRODUCING PRECISION AVOIDANCE COLLISION (PAC)

To avoid possible collision, the most efficient recourse is to change the satellite orbit. This can prove to be expensive in combustion fuel. Increasing the precision will dramatically decrease the number of false alerts but also will linearly save fuel consumption. Increasing the accuracy by ten to a hundred times will improve fuel consumption by ten to a hundred folds.

The technique starts with a newly developed laser architecture called CAN for Coherent Amplification Network (Mourou et al., 2013), see Fig. 6, that can provide short pulses with high energy, high repetition rate and high efficiency. Combined with an ultrafast synchronized detector, Fig. 7, extremely high degree of precision in the sub-mm range could be obtained over a thousand kilometers.

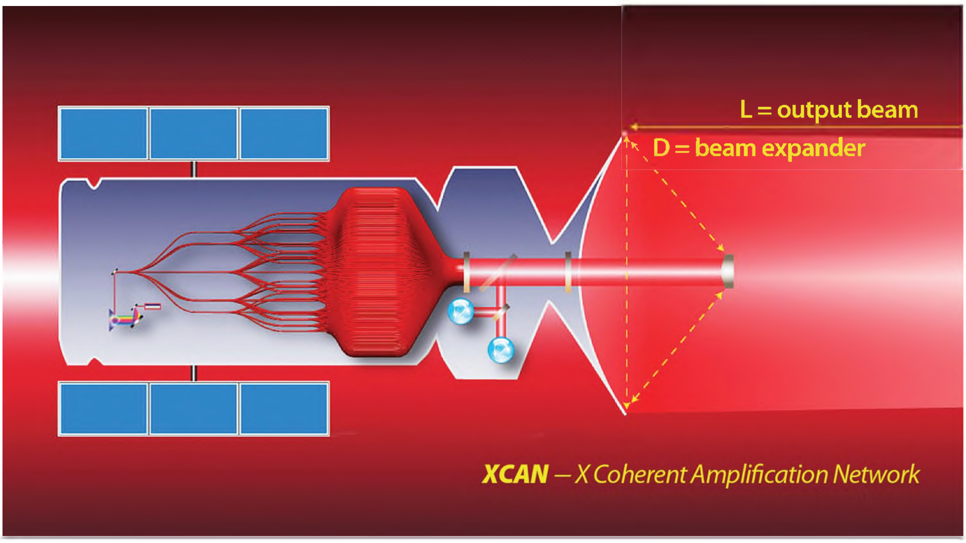

Fig. 6: The concept of the laser CAN, a fiber array composed of a large number of phased fiber amplifiers. The fibers are large core or tapered core

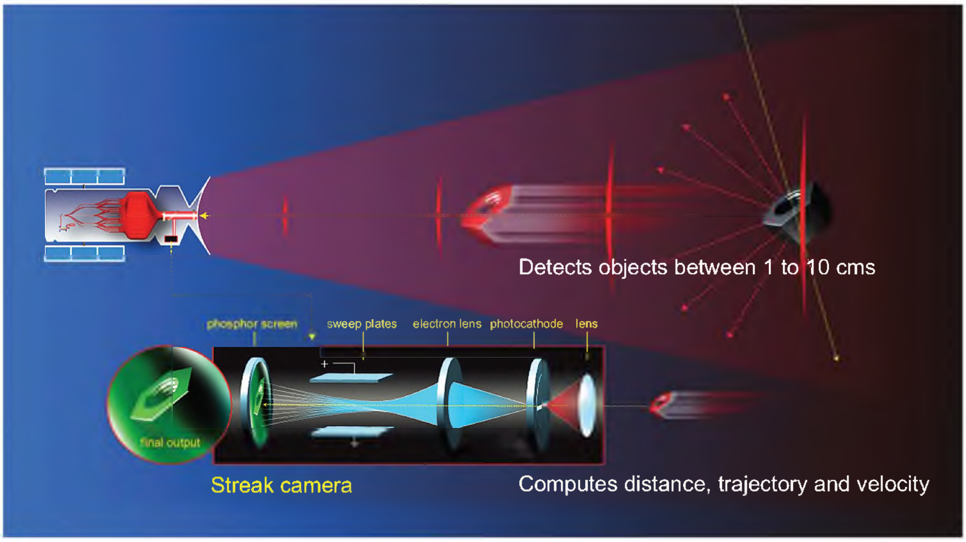

Fig. 7: The detection system showing the CPA: CAN laser, the emitter, receiver, and the streak camera

2. THE ULTRA-INTENSE LASER SYSTEM CAN (Mourou et al., 2013) AND MEASUREMENT CONCEPT (Braun et al., 1994)

As shown in Braun et al. (1994), to reach mm to sub mm accuracy over long distance the laser pulse must simultaneously produce short pulses (< ps) for distance precision and large pulse energy at the joule level for long distance ranging (100–1000 km). It must also have a high repetition rate (kHz) for debris velocity measurements, and high wall-plug efficiency (30 %). This is conveniently produced by a laser CPA (Chirped Pulse Amplification) see Strickland, Mourou (1985). In a CPA laser, the short pulse is first produced by a pulse oscillator (<1 ps). To avoid the nonlinear effects in the amplifier the pulse is first stretched from < ps to > ns, corresponding to a stretching factor of 1,000 to 100,000. This stretching decreases the laser's intensity accordingly, and puts a large quasilinear chirp on the nanosecond pulse. Because the pulse power has been decreased by a factor of ~10^5, the pulse can be amplified safely to 10^5 times in energy. In order to produce high repetition rate, we adopt a CAN architecture (Mourou et al., 2013) composed of a large fiber array of tens to thousands single mode amplifying fibers, in order to increase the laser cooling capability and increase its repetition rate. Alternatively, in this concept, the CAN laser could be replaced by a thin disk laser (Mukhin et al., 2017), or as we will see later by a large core fiber or tapered rods.

The large energy (stretched) pulse is now broadcasted towards the debris under interest by a telescope to minimize the beam divergence. The pulse will be scattered by the debris, sending back to the antenna (telescope) a chirped echo identical to the input pulse, but much less intense. The return pulse contains all the spatial and temporal information of the debris, i.e. distance and profile. It will subsequently be compressed by a compressor, which is the phase conjugate of the stretcher. After compression, the signal is detected by the ultrafast detector, like a streak camera, to recompose the image with sub mm precision in X, Y, and Z (Fig. 7).

Because, the laser kHz repetition rate, this operation can be renewed every ms. Hence it becomes trivial to extract the position and debris velocity component vector ($\mathbf{V}_X$, $\mathbf{V}_Y$, $\mathbf{V}_Z$).

3. THE ULTRAFAST DETECTOR, STREAK CAMERA

A streak camera transforms an optical time dependent signal into a spatially dependent electron signal that will be spread over a CCD array. To work, a streak camera relies on a high temporal and spatial resolution detector, commensurate with the laser pulse duration. A streak camera in synchroscan mode (see for instance Hamamatsu Photonics Products URL: https://www.hamamatsu.com/jp/en/index.html), which is commercially available, can provide all the necessary features for our application:

1. demonstrated temporal resolution, less that a ps;
2. offers a very good quantum efficiency, >50 %;
3. can be synchronized to the laser pulse with ps accuracy, using the Optical Clock (Udem et al., 1999) concept and technology.

To broadcast the signal from the CAN laser with minimum divergence and collect the debris echoes we will use a telescope as described by Ebisuzaki et al. (2015).

4. SPACE-BASED ICAN LASER SYSTEM

Regarding a laser system for debris de-orbiting, there are a number of design factors, which should be considered for space-based operation. For a solar-powered system a high electrical efficiency is required. Likewise, with high relative velocity >10 km/s, interaction times are short, <10 s, and hence good average power and high repetition rates are demanded. Heat dissipation, compactness, and robustness are also key factors for operation in space. All of these factors are absent with traditional gas or crystal-based laser technology, which are limited by poor wall-plug efficiency, 0.1 %, and poor heat dissipation, limiting the repetition to a few Hz and hence providing very low average power of 1 W. However, with the rapid development of laser-based diode-pumped laser science, embodied by the ICAN concept, these design factors can be realized. By their intrinsic geometry, the surface area of optical fibers enables more effective dissipation of heat than traditional media providing access to kHz repetition rates in pulsed-mode. Similarly, the orders of magnitude improvement in electrical efficiency of diode pumping over traditional lasing-media is well known (> 30 %), as is their high average power (>10 kW). Transport within single mode fibers provides increased robustness of the system, which is critical for stability of optical systems in orbit. The ICAN concept comprises an array of thousands of phase-combined lasers enabling a very high degree of beam control providing direction limited focusing and beam shaping with the potential for adapting to target surface interaction conditions heuristically. For the basic ICAN design (Mourou et al., 2013) each channel in the array could provide laser energy with 1 μm wavelength. The output of all the fibers, after amplification means, are then phased-combined (Mourou et al., 2013). An excellent analysis between the different method to produce high average power was conducted by Mukhin et al. (2017). Large core fiber, thin-tapered rod and Thin-Disc, phase-combined produce beam of excellent spatial quality with a total energy of up to 1–10 J.

A conceptual design of an orbiting ICAN system is shown in Fig. 8.

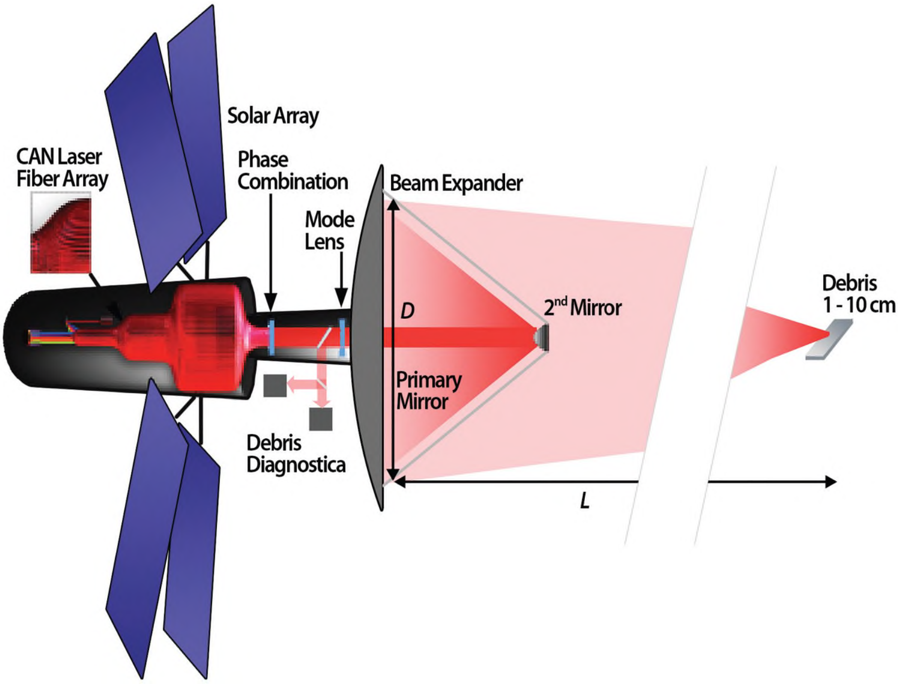

Fig. 8: Full view of the Precision Avoidance Collision system

Here, an array of solar panels provides the kW's power required for the multichannel fiber laser. In order to deliver pulses over 100 km the beam would be expanded to meter scale via multiple optics such as a simple telescope design. Here primary and secondary mirrors provide mechanical motion to steer and focus the beam with coarse precision. Such a system will also function in reverse by collecting their reflected laser light from the high velocity space debris, enabling its tracking and characterization via diagnostics related to debris velocity and orientation. With complete control of the wavefront, intrinsic to the ICAN concept, fine precision of the focal distance, spot size, and steering of the beam can be achieved. Also, since the wave front of the phase array is adjustable at rates of 103 Hz, an ICAN system can evaluate debris surface conditions with kHz pulses and respond quickly with parameters for an optimal interaction. Such a heuristic approach could rapidly scan and optimize the coupling in terms of recoil thrust or reflectivity with debris of distinct orientation, rotation, and surface type.

CONCLUSION

According to the laser and detector state of the art, the concept of Precision Avoidance Collision is possible. It could be put in place over only a few years to test, giving us the elements to move a step further as the number of satellites and its associated debris augment as expected.

ACKNOWLEDGMENTS

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INTERNATIONAL SYMPOSIUM “STUDIES OF THE MOON, PLANETS, AND SMALL BODIES OF THE SOLAR SYSTEM WITH THE HELP OF SPACECRAFT” BOOK OF ABSTRACTS

International Symposium

STUDIES OF THE MOON, PLANETS, AND SMALL BODIES OF THE SOLAR SYSTEM WITH THE HELP OF SPACECRAFT

To the 60th anniversary of the Space Age

04.10.1957–04.10.2017
St. Petersburg, October 5–6, 2017
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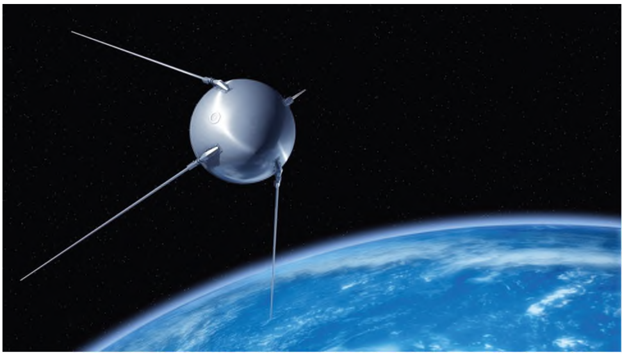

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- Cosmonautics and Rocket Technology Museum (State Museum of History), St. Petersburg
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The Symposium was an associated event to the International Forum
"Space: 60 years along the path of discoveries"

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1. FROM THE WORKS OF K.E. TSIOLKOVSKY TO THE SATELLITES OF THE EARTH

Valery N. Kupriyanov
Section on the history of astronautics and rocket technology, North-West Interregional Public Organization of Russian Federation of Cosmonautics, St. Petersburg, Russia

K.E. Tsiolkovsky laid the foundations of cosmonautics with his work "Exploration of the world spaces by jet devices", first published in the journal "Scientific Review" in 1903. Basing on his work, inspired by his ideas of conquering the Universe, Soviet scientists, engineers, and workers created rockets that allowed mankind to realize the age-old dream of starting flights into space. On October 4, 1957, the world's first artificial Earth satellite — Sputnik — was launched, and this event opened the space era of mankind. A story about creation of this technique, about people who paved the first road into space.

2. NEIL ARMSTRONG AND NASA DELEGATION IN LENINGRAD (COSPAR SESSION, MAY 1970). FROM SURVEYOUR 5 TO LUNOKHOD 1

Sergey V. Victorov
Ioffe Institute, St. Petersburg, Russia

Highlighted events at the 13th session of COSPAR were the exhibition of lunar rock brought by the *Apollo 11* crew and the presentation by the first man on the Moon Neil Armstrong. The author cooperated with members of NASA delegation (Richard Porter, Head of delegation, Leigh Scherer, Director, Department of Lunar Studies, *Apollo* Program) and was Armstrong's interpreter during his presentation on May 25, 1970. By the irony of fate at that period the author was participating in designing of RIFMA device for *Lunokhod 1* at the Astrophysical department of Ioffe Institute (Physical-Technical Institute of the Academy of Sciences of the USSR). Comparison of devices based on principles of nuclear physics which were installed on *Surveyour 5, 6, 7* and *Lunokhod 1, 2* for analysis of lunar soil composition is presented in brief.

3. SOME ACTUAL PROBLEMS OF THE RUSSIAN PROGRAM IN SPACE SCIENCE

Mikhail Ya. Marov
Russian Academy of Sciences, Moscow, Russia

Throughout several decades after launch of the First Soviet Earth's satellite Russia occupied the leading position in space exploration. The great achievements were made in the study of near-Earth space, Sun, some astrophysical objects and specifically, in the pioneering flights to the Moon, Venus, and

Mars. After the tough "perestroika" years when mainly piloted flights have been maintained, the scientific space program in Russia is recovered, as it is summarized in the Federal Space Program (FSP-2025). Its main objects and some blueprint projects are discussed.

4. EXPERIMENTS AND WORKING DAYS ABOARD THE INTERNATIONAL SPACE STATION

Andrey I. Borisenko
Yuri A. Gagarin State Scientific Research-and-Testing
Cosmonaut Training Center, Zvezdnyi, Russia

The report was prepared on the basis of personal observations of the author in the process of performing flight missions on board the ISS during two flights: first flight — start 05.04.2011, landing 16.09.2011; second flight — start on 10.19.2016, landing on 10.04.2017. The total flight time is 337 days 8 hours 57 minutes.

5. REVEALING THE MYSTERY OF LUNAR SWIRLS FOR A POTENTIAL LUNAR BASE AFTER 60 YEARS OF LUNAR EXPLORATION

Carle Pieters
Dept. of Earth, Environmental, and Planetary Sciences,
Brown University, Providence, RI, USA

While glancing through the book "Fifty Years of Space Research" produced by the RAS after the 50th Sputnik anniversary, I was struck by the summary paper by V. V. Shevchenko on Moon research, in which he described some of the magnetic traverses made by *Lunokhod 2*. Shevchenko went on to describe some of the unusual prominent magnetic anomalies observed from orbit that are associated with mysterious albedo features called 'swirls'. Since lunar swirls have been an area of active research for me with the modern lunar data over the last decade and are currently of great interest across the lunar community, I believe several of them would make excellent targets for the next generation '*Lunokhod X*' sent to the Moon.

6. ESA-RUSSIA COOPERATION IN SPACE

Rene Pischel
European Space Agency, Head of the Permanent Mission
in the Russian Federation

For the European Space Agency (ESA) Russia is one of the strategic partners in its international cooperation in space. The cooperation of ESA and Russia comprises various areas and is now focused on the joint *ExoMars* project and the International Space Station.

7. INTRODUCTION TO CONFIGURATION OF CHINA'S MARS ROVER MOBILITY SYSTEM

Gao Haibo
Harbin Institute of Technology, China

The presentation introduces the active suspension of China Mars Rovers. Earlier Mars exploration practice has shown that passive rover suspension lack the capability of travelling through rugged and soft Mars surface. A novel active suspension configuration is proposed based on the standard rocker-bogie suspension to meet this challenge. The rocker in the rocker-bogie mechanism is broken into two parts. The angle between the two parts is driven to control the distance between the rocker wheel and bogie pivot, simulating a "creeping" mechanism in addition to normal wheel-driven mechanism. On condition of deep wheel-sinkage, the rocker wheel is pushed away from and pulled to the bogie pivot by a force much larger than the possible draw bar pull, ploughing grooves on sand and escaping from sand trap.

8. THE DEVELOPMENT OF THE SPACE SEGMENT OF SYSTEM FOR AUTOMATIC IDENTIFICATION OF SHIPS BASED ON NANO-SATELLITES IMPLEMENTED ON THE SYNERGY PLATFORM

Evgeny A. Popov, Denis Malygin
Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

The report considers a technology of design and architecture of the onboard communication system "S-AIS" for a series of experiments on processing signals received from navigational equipment of ships. In order to examine the message collision preventing method, based on Doppler filtering, in space-based AIS system, a series of space experiments is planned to be conducted on *Cubesat 3U* format satellite developed in the laboratory "Space communication technologies" of Peter the Great St. Petersburg Polytechnic University. The equipment, needed for the experiments, contains the following components: spacecraft in *Cubesat 3U* form; onboard AIS receiver; ground station, consisting of rotating antenna system and retransmission point, for controlling spacecraft and receiving AIS information.

9. TECHNOLOGICAL DECISION FOR NEW-GENERATION PLANETARY ROVERS

Mikhail I. Malenkov
JS Co. Scientific and Technical Center "ROCAD", St. Petersburg, Russia

The accessibility of the investigated surfaces of the Moon and Mars directly depends on the properties of the locomotion and navigation systems of planetary rovers. In the presentation, as the best models for a comparative evaluation of these systems, the current American Mars Rovers *Opportunity* and *Curiosity* were selected. They have established an extremely high level for the resource, quality and reliability of onboard systems. However, there are reserves for increasing mobility, the generalized parameter of which is the time spent on redeployment from one research area to another. The speed of the rovers during automatic driving is limited, so one needs to use the shortest routes. This is made possible by increasing the cross-country ability of a self-propelled chassis by implementing automatic wheel-walking propulsion and active suspension functions. The weight of the chassis does not increase, due to the reduction of the number of supports to four and the synthesis of new schemes of walking mechanism and suspension. Simultaneously, the maneuverability of the planetary rovers increases, the equivalence of the forward travel and reverse motion by mobility and navigation is ensured.

10. SPACE MANIPULATORS FOR IN-SITU RESEARCH ON THE SURFACE OF OTHER CELESTIAL BODIES

Tatiana O. Kozlova, Andrey B. Kiselev
Space Research Institute (IKI) of the Russian Academy of Sciences
Moscow, Russia

The report summarizes the work of Space Research Institute in the new century on the development, creation and ground handling of manipulation mechanisms to support the work of scientific payload and equipment on the surface of the Moon, Mars, and its moon Phobos. In the first place, these mechanisms are designed to work with soil, including taking subsurface layers of soil for study with onboard instruments and for returning to Earth.

11. EXPERIENCE IN THE DESIGN, TESTING AND OPERATION OF ROTARY PLATFORMS FOR SPACECRAFT AND STATIONS

Sergey V. Fedoseev
JS Co. VNIITRANSMASH, St. Petersburg, Russia

At the end of the 1980s, VNIITRANMASH won a tender for the development of the tri-axial stabilized platform (TSP) of the «Argus» scientific complex for the IKI Terms of Reference for the *Mars 96* orbital module. The flight sample of the platform provided an error of stabilization of the apparatus with a total mass of 85 kg, no more than 1.5′. However, in November 1996, the expedition was lost during the first stages of carrier flight. The obtained technical reserve was realized in a short time in the design of a two-axis guidance platform (DPN) "Orientator", intended for installation on board the *Mir* orbital station. The flight sample of DPN was delivered to the customer — RSC *Energia*, and in May 1997 was delivered to orbit and loaded into the "Spectrum" module. However, in the same year the module was damaged during the abnormal reconnecting of the *Progress M-34* spacecraft. Installation of DPN on the external surface of the station was impossible. In the same year, 1997, work was begun on the creation of a bi-axial turntable “Monitor” for the International Space Station (ISS) and a new component base. This platform successfully supports the work of Canadian optic-electronic equipment on board the ISS from 2014 to the present.

12. SPACECRAFT POSITION DETERMINATION USING REFERENCE STATIONS

Peter A. Kusotskiy
Science and Technology Center, St. Petersburg, Russia

Functioning spacecraft needs a permanent orbit control and adjustment. Calculation of the compensating effect requires the determination of the spacecraft coordinates with high accuracy. This study proposes a method to determine the spacecraft position using reference stations working in radio frequency range. Triangulation is the method proposed to solve this problem. Benefit of the method is the possibility to determine the spacecraft position regardless of weather conditions.

13. RTC: ROBOTICS EQUIPMENT FOR ORBITAL AND PLANETARY MISSIONS

Igor Yu. Dalyaev, Andrey V. Vasiliev
Russian State Scientific Center for Robotics and Technical Cybernetics
St. Petersburg, Russia

The history of space systems development in RTC begins with the creation of soft landing systems for descent modules in the 1960s and later — onboard manipulators “Aist” for the space shuttle *Buran* in the 1980s. Nowadays, the work carried out in RTC in the field of space robotics is connected with the creation of: space transport and manipulation robotic system for performing process operations on the external surface of the spacecraft and support crew during extra vehicular activity; manipulation system for robotic support of servicing spacecraft; mobile robotic systems for scientific research on the surface of the Moon and other celestial bodies, as well as to support the deployment and maintenance of industrial and scientific objects.

Professor **Mikhail Ya. Marov**, academician, chairman of the Program Committee, opens the first session in V. P. Glushko Museum of Cosmonautics and Missile Technology, State Museum of History of Saint Petersburg. Photo courtesy Design Bureau 'Arsenal' named after M. V. Frunze

The end of the anniversary session in V. P. Glushko Museum of Cosmonautics and Missile Technology, State Museum of History of Saint Petersburg. Photo courtesy Design Bureau 'Arsenal' named after M. V. Frunze

To the great pioneer of Space Age. Konstantin Tsiolkovsky monument in St. Petersburg. From left to right: Professor **Alexander P. Kovalev** (K. E. Tsiolkovsky Russian Academy of Cosmonautics), **Sotnik**, Professor **Mikhail Ya. Marov** (Russian Academy of Sciences). Photo courtesy Design Bureau 'Arsenal' named after M. V. Frunze

In the Peter and Paul Fortress after the Noon Shot ceremony in honour of the 60th anniversary of Space Age. From left to right: **Andrei I. Rudskoi** (Peter the Great St. Petersburg Polytechnic University), **Oleg P. Mukhin** (North-West Interregional Public Organization of Russian Federation of Cosmonautics), **Andrey I. Borisenko** (Yuri A. Gagarin State Scientific Research-and-Testing Cosmonaut Training Center), **Olga B. Dluzhnevskaya** (Institute of Astronomy, Russian Academy of Sciences), **Mikhail Ya. Marov** (Russian Academy of Sciences), Mikhail I. Malenkov (K. E. Tsiolkovsky Russian Academy of Cosmonautics). Photo courtesy Peter the Great St. Petersburg Polytechnic University

Symposium Plenary session at Peter the Great St. Petersburg Polytechnic University. Photo courtesy Peter the Great St. Petersburg Polytechnic University

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СПУТНИК: 60 ЛЕТ ПО ДОРОГЕ ОТКРЫТИЙ

INTERNATIONAL FORUM

SPUTNIK: 60 YEARS ALONG THE PATH OF DISCOVERIES

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**«Спутник: шестьдесят лет
по дороге открытий»**,
3–4 октября 2017 г., Москва
Труды Форума

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