 

*CONFERENCES AND SYMPOSIA* PACS numbers: **01.10.–m**, 01.10.Fv

# 75th anniversary of the N V Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN)
## (Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 25 February 2015)

DOI: 10.3367/UFNe.0185.201506f.0631

A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) celebrating the 75th anniversary of the N V Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation of the RAS (IZMIRAN) was held in the IZMIRAN conference hall on 25 February 2015.

The agenda of the session announced on the website www.gpad.ac.ru of the RAS Physical Sciences Division contained the following reports:

(1) **Kuznetsov V D** (IZMIRAN, Moscow) "N V Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN) yesterday, today, and tomorrow";

(2) **Gvishiani A D** (Geophysical Center, Moscow) "Studies of the terrestrial magnetic field and the network of Russian magnetic laboratories";

(3) **Sokoloff D D** (Faculty of Physics, Lomonosov Moscow State University, Moscow) "Magnetic dynamo questions";

(4) **Petrukovich A A** (Space Research Institute, RAS, Moscow) "Some aspects of magnetosphere–ionosphere relations";

(5) **Lukin D S** (Moscow Institute of Physics and Technology (State University), Dolgoprudnyi, Moscow region) "Current problems of ionospheric radio wave propagation";

(6) **Safargaleev V V** (Polar Geophysical Institute, Kola Scientific Center, RAS, Murmansk), **Sergienko T I** (Swedish Institute of Space Physics (IRF), Sweden), **Kozlovskii A E** (Sodankylä Geophysical Observatory, Finland), **Safargaleev A V** (St. Petersburg State University, St. Petersburg), **Kotikov A L** (St. Petersburg Branch of IZMIRAN, St. Petersburg) "Magnetic and optical measurements and signatures of reconnection in the cusp and vicinity";

(7) **Kuznetsov V D** (IZMIRAN, Moscow) "Space solar research: achievements and prospects".

Papers written on the basis of oral reports 1, 3, 4, 6, and 7 are given below.

One of the two towers of the main IZMIRAN building, from which observations of the Sun and atmosphere–ionosphere measurements are made

*Uspekhi Fizicheskikh Nauk* **185** (6) 631 (2015)
DOI: 10.3367/UFNr.0185.201506f.0631
Translated by E N Ragozin; edited by A Radzig

*CONFERENCES AND SYMPOSIA*

PACS numbers: 01.10.Fv, **01.65.+g**, **91.25.–r**, 94.05.Sd, **94.20.–y**

*75th ANNIVERSARY OF IZMIRAN*

# N V Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN) yesterday, today, tomorrow

V D Kuznetsov

DOI: 10.3367/UFNe.0185.201506g.0632

## Contents



**Abstract.** **This paper describes the basic and applied research rationale for the organization of IZMIRAN and provides insight into the 75 years of the Institute's activities and development. Historically, early magnetic measurements in Russia were developed largely to meet the Navy's navigation needs and were, more generally, stimulated by the Peter the Great decrees and by the foundation of the St. Petersburg Academy of Sciences in 1724. The paper examines the roles of the early Academicians in developing geomagnetism and making magnetic measurements a common practice in Russia. The need for stable radio communications prompted ionospheric and radio wave propagation research. The advent of the space era and the 1957–1958 International Geophysical Year Project greatly impacted the development of IZMIRAN and spurred the creation of a number of geophysical research institutes throughout the country. Currently, the research topics at IZMIRAN range widely from geomagnetism to solar-terrestrial physics to the ionosphere and radio wave propagation, and its primary application areas are the study and forecast of space weather, an increasingly important determining factor in ever-expanding ground- and space-based technologies (space navigation and communications, space activities, etc.).**

**Keywords:** geomagnetism, ionosphere, radio wave propagation, solar-terrestrial physics

**V D Kuznetsov** N V Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Kaluzhskoe shosse 4, 142190 Troitsk, Moscow, Russian Federation
Tel. +7 (495) 851 01 20. Fax +7 (495) 851 01 24
E-mail: kvd@izmiran.ru

Received 19 March 2015
*Uspekhi Fizicheskikh Nauk* **185** (6) 632 – 642 (2015)
DOI: 10.3367/UFNr.0185.201506g.0632
Translated by E N Ragozin; edited by A Radzig

## 1. Introduction

The 75-year history of the N V Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN in *Russ. abbr.*) has witnessed significant changes in science, the Institute has also changed, as have the scientific priorities. However, the main result of the past years is that the scientific field for which IZMIRAN was established persists and develops, producing new knowledge and being increasingly in demand.

The terrestrial magnetic field is of fundamental importance to our civilization, being part and parcel of the human environment and a kind of magnetic shield which protects all life on Earth from cosmic radiation. It forms the magnetosphere of Earth (Fig. 1) and affects the properties of ionospheric plasma, making it magnetoactive and changing the conditions of radio wave propagation. During magnetic storms, the near-Earth space (NES) is disturbed, which produces problems for satellites, radio communication, and ground-based power systems. Nowadays, NES perturbations also affect the signals of the modern navigation systems GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System), as well as everything related to them. The interrelation of effects on the Sun and in the terrestrial magnetosphere and ionosphere, as well as their influence on the milieu of human habitation and activity, impart a complex nature to the study of the terrestrial magnetic field, which includes all factors responsible for changes, both from above — from the Sun, and from below — from Earth's interior.

## 2. From the history of geomagnetism

It is not precisely known in the history of terrestrial magnetism when the magnetic compass was invented; however, there is documentary evidence of its use for orientation in the north–south direction even in the first

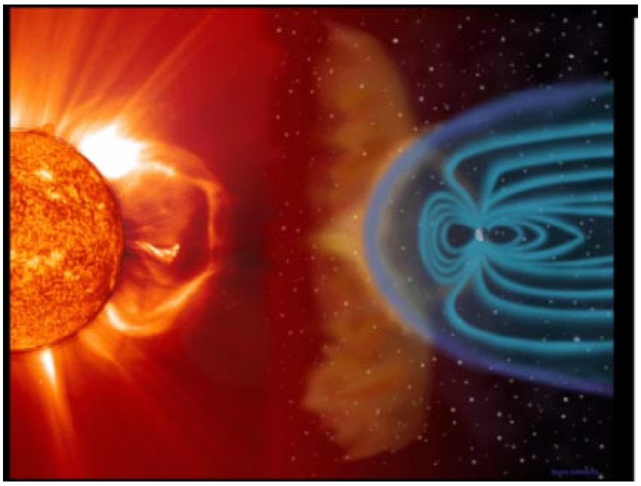

Figure 1. Magnetosphere of Earth formed in the flow of the solar wind past the dipole terrestrial magnetic field.

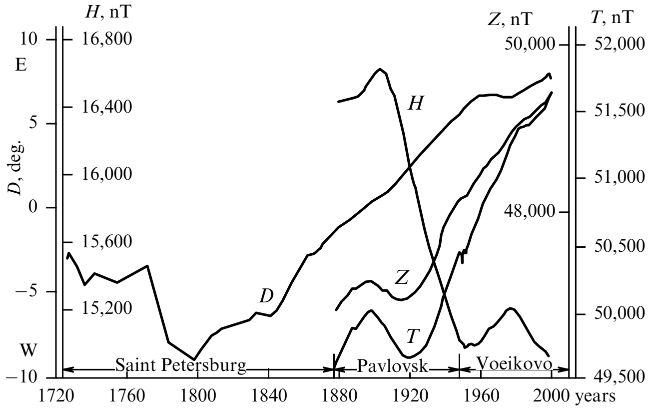


**Figure 2.** Plots of the secular run of the elements of the geomagnetic field in the cities of Saint Petersburg (1724–1878), Pavlovsk (1878–1941), and Voeikovo (1948–2000) constructed in the Saint Petersburg's Branch of IZMIRAN. Arrows indicate the times of observation transfers to new sites [1]. *D* — magnetic declination, *H*, *Z*, respectively, the horizontal and vertical components of the magnetic field *T*.

centuries of the Common Era. The beginning of geomagnetism studies dates back to the 15th century, and it was related to the development of seafaring and navigation [1]. The first measurements of terrestrial magnetic field intensity with the simplest compass were made in Italy in 1436.

A major impetus to the development of geomagnetic science was made by the discovery of magnetic declination (the angle between the directions to the geographic and magnetic poles) during Columbus's four expeditions from Europe to America (1492–1504). The magnetic declination was found to depend on the ship's geographical position, and today we know that it also varies with time at each point due to the secular drift of the geomagnetic field itself. Interestingly, when residing in a line connecting the magnetic and geographic poles, the direction to the geographic pole is strictly opposite to the magnetic arrow direction.

The first determination of magnetic declination on Russia's territory was made in 1556 by the English traveler Steven Borough in Pechora; more recently, the magnetic declination was determined by English researchers. Coast-dwelling navigators were some of the first to notice that the 'matka' (the word they used in reference to a compass) played pranks during auroras. We now know why. The idea that the operation of a compass is related to the terrestrial magnetic field was presumably expressed by the English scientist William Gilbert in his book, *De Magnete* (*About the Magnet*), published in London in 1600. This work originated our notions of the existence of a common geomagnetic field.

In Russia, a start in studies of the geomagnetic field was made at the time of Peter the Great (1672–1725), which was related to the development of Russia's fleet and sea navigation needs. According to a decree enacted by Peter I, the duty of measuring the magnetic declination when sailing was imposed on all ship captains and commanders. Peter I also wrote the first instructions for the navy "On the practical application and handling of compasses." The establishment of the Petersburg Academy of Sciences at Peter's behest by a 1724 Decree of the Governing Senate became an important step in the development of geomagnetic research in Russia. Even at the first grand public Academy meeting on 27 December 1725, the Academy placed the science of terrestrial magnetism into the category of those with the highest importance.

Systematic observations of magnetic declination, which commenced in 1726 according to Peter's decree, have not been interrupted and are now one of the longest European series of observations (Fig. 2). Curve *D* in Fig. 2 is the secular run of terrestrial magnetic declination in St. Petersburg for almost 300 years. The change of field direction over this period amounts to about 16°, which is quite substantial, and therefore the field variations are to be continually measured and taken into consideration. Nowadays, observations of magnetic declination continue at the Voeikovo Observatory, which is a part of the St. Petersburg Branch of IZMIRAN.

In the Petersburg Academy of Sciences, interest in geomagnetism was so keen that many outstanding Russian academicians worked, to one extent or other, in this area. Academician Leonard Euler (1707–1783) was one of the first to derive formulas which permitted determining the locations of magnetic poles and later on calculating the strengths of the magnetic field at any point on the globe, although the accuracy of calculations by these formulas turned out not to be high enough for practical applications. Euler disputed Halley's hypothesis of the existence of two magnets inside Earth. Inside the globe, he believed, there was a single magnet displaced relative to Earth's center, and the "amount of magnetic matter residing in Earth's interior was subject to appreciable changes, resulting in temporal variations of declination." In 1741, Academician Daniel Bernoulli was awarded a prize from the French Academy of Sciences for developing the theory of an inclinator — an instrument for measuring the terrestrial magnetic declination, which was a topical problem at that time. In 1759, Academician Franz Aepinus wrote a treatise, *Tentamen Theoriae Electricitatis et Magnetismi* (*An Attempt at a Theory of Electricity and Magnetism*), which had a profound impact on the subsequent development of the science of magnetism, at least in Russia. He supported Euler's idea of a single magnet. Aepinus wrote: "...the core itself is subject to slow variations as regards its shape and the distribution of magnetic matter over it."

A significant contribution to the development of the doctrine of geomagnetism was made by Mikhail Vasil'evich Lomonosov in his work, *Rassuzhdenie o Bol'shei Tochnosti*

*Morskogo Puti* (*Reasoning about the Higher Accuracy of Shipping Routes*). He made quite a modern assumption that the globe consisted of variously magnetized tiny particles. In the aggregate, they make up a nonuniformly magnetized globe, which accounts for the difference in magnetic declination in different parts of the globe. This was a step forward relative to W Gilbert's notions, which considered the terrestrial magnetic field to be the field of one magnet with two poles, and thereby forestalled C F Gauss's idea of an arbitrary magnetization of Earth globe. M V Lomonosov also promoted the solution of practical problems of measuring the elements of terrestrial magnetism. An expedition was dispatched in accordance with his project; one of the tasks set before the expedition was making measurements of the magnetic field.

In 1835, a Corresponding Member of the Petersburg Academy of Sciences Ivan Mikhailovich Simonov elaborated a new theory of geomagnetism in his work, *Opyt Matematicheskoi Teorii Zemnogo Magnetizma* (*Experience on Mathematical Theory of Terrestrial Magnetism*) [2, 3]. He showed that Earth's magnetic field due to the combined effect of magnetic particles residing inside the globe would coincide with the field of a dipole, assuming a uniform distribution of the particles. I M Simonov's work came out even before the publication of C F Gauss's fundamental work [4] (translated into Russian as *Obshchaya Teoriya Zemnogo Magnetizma — General Theory of Geomagnetism*), and the dipole potential as a function of latitude and longitude given by Simonov turned out to be identical to the first expansion term of the potential introduced by Gauss.

A thorough and comprehensive study of terrestrial magnetism at a qualitatively new scientific level is associated with two classical studies by the great mathematician, Academician Carl Friedrich Gauss (Fig. 3). In the first of them, dated 1832, he proposed a new method of measuring the horizontal component of magnetic field induction, which immediately permitted an improvement in measurement accuracy, and proposed a design of the instrument for these purposes. In 1837, Gauss invented a unipolar magnetometer, and in 1838 a bifilar one. In the second study [4], dated 1838, Gauss developed the mathematical theory of the potential, which represented the terrestrial magnetic field **B** in the form of an expansion of terrestrial magnetic potential $V$ in an infinite series of spherical functions:

$$V(r,\theta,\varphi) = R\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{n+1} \times \left(g_n^m \cos m\varphi + h_n^m \sin m\varphi\right) P_n^m(\cos\theta)\,, \quad \mathbf{B} = -\nabla V\,,$$

where $R$ is the standard radius of Earth (6371.2 km), $r$ is the distance from Earth's center, $g_n^m$ are the Gauss coefficients, and $P_n^m$ are spherical functions (associated Legendre polynomials).

The fitting of Gauss coefficients in his expansion that best describe magnetometric data of the network of magnetic observatories and satellites still underlies modern models of the geomagnetic field — the so-called International Geomagnetic Reference Field, which is updated every five years.

The Magnetic Union scientific society (Göttingen), launched by C F Gauss and W Weber in 1834, set itself the task of studying terrestrial magnetism on the whole planet. Gauss and other scientists succeeded in attracting the attention of the governments of different countries to the study of the terrestrial magnetic field and to the organization of new and development of existing observatories in Germany, France, England, and Russia.

In 1829, the Petersburg Academy of Sciences came to a decision to construct the first magnetic observatories in Russia, the credit going to Alexander von Humboldt and a member of the Petersburg Academy of Sciences, professor at Kazan' University, A Ya Kupffer (Fig. 4). By that time, approximate maps of magnetic fields had already been

**Figure 3.** Great mathematician C F Gauss (1977–1855), who contributed significantly to the theory of geomagnetism.

**Figure 4.** Academician of the Petersburg Academy of Sciences Adolf Yakovlevich Kupffer (1799–1866).

plotted for the entire Russian territory, and a start was made on the development of projects for the systematic magnetic survey of the territory of the Russian Empire. In Petersburg, the first regular magnetic observations were made by A Ya Kupffer in the physics office of the Academy of Sciences in 1829.

## 3. IZMIRAN's prehistory

In 1830, A Ya Kupffer built a magnetic pavilion, which was referred to as a Magnetic Observatory, behind the northern wall of the Petropavlovsk Fortress in St. Petersburg. This first Petersburg magnetic observatory may be said to have become the first step in the setting up of IZMIRAN. The plan of deploying a set of magnetic observatories was approved, and magnetic measurements were further elaborated. Later on, owing to the interference introduced by trams, precision magnetic measurements in the center of St. Petersburg became impossible, and the magnetic observatories were moved, initially to the Vasil'evskii Island to the so-called Normal Observatory of the Main Physical Observatory (MPO), and then to the town of Pavlovsk (Slutsk after the revolution) near St. Petersburg. The Pavlovsk Observatory was the best one in the world: scientists would come there from abroad to train, gain experience, and calibrate instruments, and it played the role of a base observatory in the teaching of personnel and making reference instruments.

In 1892, on Academician F A Bredikhin's suggestion, the first simultaneous observations of magnetic storms and solar phenomena were carried out on the basis of the Pavlovsk Magnetic Observatory and the Central Astronomical Observatory at Pulkovo. Subsequently, such observations, despite the fact that they were interrupted more than once, eventually led to the establishment of the Solar Survey as a necessary element for studying the solar-terrestrial relationship and cause-and-effect relations in the Sun–Earth system.

The year 1896 saw the publication of the first issue of the quarterly international journal *Terrestrial Magnetism*, which was renamed *Terrestrial Magnetism and Atmospheric Electricity* in 1899. In 1938, S Chapman suggested replacing the term 'terrestrial magnetism' with the term 'geomagnetism'.

In 1916, the post of MPO director was filled, for a short period, by Academician A N Krylov, who published the book *O Zemnom Magnetizme* (*On Terrestrial Magnetism*) [5] in 1922. In 1924, the MPO in Pavlovsk was renamed the Main Geophysical Observatory (MGO), and the Geomagnetic Division was organized at Petersburg as a part of it, with its supervision entrusted to N V Roze. The major task of the Geomagnetic Division was preparing for the General Magnetic Survey of the country, interrupted by the World War I.

During the succeeding years, the MGO underwent several reorganizations to become in 1930 an All-Union Research Institute with specialized institutes organized within it, including the Institute of Terrestrial Magnetism and Atmospheric Electricity (ITMAE) (1931). Subsequently, it was several times renamed and reorganized, with the result that the initially united magnetic divisions of the institute — the Geomagnetic Expeditions Group (formerly the General Magnetic Survey Bureau), Atmospheric Electricity Sector, Terrestrial Magnetism Group, Slutsk Magnetic Observatory — all taken separately became centrally subordinate to the MGO. N V Pushkov was appointed supervisor of the Slutsk (Pavlovsk) Magnetic Observatory.

In 1938, a conference, held on a regular basis in the Central Slutsk Observatory, of the supervisors of all magnetic observatories, whose number amounted to 17 by that time, adopted a recommendation to apply, in the name of the Central Administration of the Hydrometeorological Service, to the USSR Council of People's Commissars (Sovnarkom) with a suggestion to organize, on the basis of the Slutsk Observatory and the Geomagnetic Expeditions Group, the Institute of Terrestrial Magnetism as a unified scientific and methodical institution on terrestrial magnetism and solar survey.

## 4. Establishment and development of IZMIRAN

On 11 October 1939, the Sovnarkom passed a resolution to organize the Scientific-Research Institute of Terrestrial Magnetizm (NIIZM (in *Russ. abbr.*)) under the aegis of the Main Directorate of the Hydrometeorological Service using the Slutsk (Pavlovsk) Magnetic Observatory as the base, with its location in the town of Slutsk. The Magnetic Survey and Cartography Group in Leningrad also became a part of NIIZM. Candidate of physicomathematical sciences, N V Pushkov, was appointed director of the NIIZM.

The main tasks of the Institute were the following: comprehensive complex studies of the phenomena of terrestrial magnetism, terrestrial currents, auroras, and the ionosphere; improvement of the methods and instruments required for studying these phenomena; scientific and methodical supervision over the Magnetic Service of the USSR; provision of data on terrestrial magnetism for the country's economy, cultural development, and defense. The scientific programs of the Institute also comprised observations of the ionosphere and magnetic ionospheric disturbances, short-term forecasts of the state of the magnetic field, and solar observations. This was all due to the need of providing reliable radio communications and predict the conditions for radio wave propagation in the ionosphere in relation to solar and geomagnetic activities. By the beginning of 1940, NIIZM staff numbered slightly more than one hundred people. The Institute's staff comprised 45 scientists, including two professors, eight candidates of sciences, and 34 junior scientific associates.

The founder and the first director of the Institute Nikolai Vasil'evich Pushkov (Fig. 5) was a student of the Physicomathematical Department of Moscow State University (beginning in 1926) and subsequently became one of the first postgraduate students of the Department of Magnetometry (1930) of the Physicomathematical Department of Leningrad State University, chaired by N V Roze. In 1934, N V Pushkov defended his candidate's thesis, entitled "Teorii Kosmicheskogo Magnetizma" ("Space Magnetism Theories") and became a senior scientific associate of the Slutsk Magnetic Observatory and later (in 1937) its director. He made a decisive contribution to the organization of the Institute, the formation of its subject area and staff, and equipping the Institute with scientific instrumentation. N V Pushkov — a laureate of the Lenin Prize, an honored worker in science and technology of the Russian Soviet Federative Socialist Republic (RSFSR), a holder of three Orders of Labor Red Banner and an Order of Honor, one of the founders of Soviet geophysics and world solar-terrestrial physics — was in charge of the Institute for 30 years. In 2004, the Presidium of the RAS conferred the name of N V Pushkov on the Institute. His name was also given to a street in the town of

**Figure 5.** Nikolai Vasil'evich Pushkov (1903–1981), the organizer and the first Director of IZMIRAN.

Troitsk (Pushkovs street, after the father and son) and the first school in the town (presently a gymnasium); there are memorial plaques on the institute building and in the town, which were placed in memory of N V Pushkov as the founder of IZMIRAN and the science campus.

One and a half years after the Institute was set up, the Great Patriotic war broke out, and NIIZM became a paramilitary institution of the Red Army. The Institute was evacuated from blockaded Leningrad to the Urals, to the site of a magnetic observatory in the village of Kosulino near Sverdlovsk (Ekaterinburg). There, the staff members undertook ionospheric and solar observations and set up a solar and ionospheric forecast service, made maps of magnetic declination along an important air route across the Chukotka peninsula, and prepared long-term ionosphere state forecasts for the needs of the Red Army.

E I Mogilevskii and N P Ben'kova, who worked in the institute for many years, made a major contribution to the development of the solar and ionospheric services in the country. They arrived in Krasnaya Pakhra (now Troitsk — *Translator's comment*) in December 1944 among the first staff members of the future Institute which first established the town as a city of science.

A small group of staff members stayed in Leningrad. Scientific associates N N Trubyachinskii, A Ya Bezginskii, P E Fedulov, B P Veinberg, and others perished during the blockade; N V Roze was groundlessly repressed and also perished. The Pavlovsk Observatory was completely ruined by the war.

In 1944, the Institute was transferred to Krasnaya Pakhra and moved into an unfinished building of the Moscow Geophysical Observatory. The first scientific 'landing' (1944) originated the scientific settlement and subsequently the scientific center in Troitsk. (In connection with this event and the 75th anniversary of the Institute, a decision was made to lay a memorial stone at the center of Troitsk.) A start was made on the construction of the main building and others of the Institute and the Magnetic Observatory; the staff members would construct the first Finnish dwelling houses. Many staff members lived in the main building of the Institute.

The magnetic survey and cartography groups returned to Leningrad from evacuation to become the foundation of the Leningrad (presently St. Petersburg) Branch of IZMIRAN, organized in 1946. Since 1946, a new Magnetic Observatory and an Ionospheric Station commenced their operation at the Leningrad Branch in Voeikovo. A Design Bureau was organized in the Institute and work on pilot instrument-making was undertaken. In particular, quartz magnetometers were made for the Geophysics Department in the new building of Moscow State University.

The second decade of the Institute's activities was full of important events, which made for its further development and consolidation. There is no escape from mentioning the campaign, which was commenced in the late 1940s-early 1950s, aimed at oppressing physicists as some continuation of the oppression of geneticists. This campaign did not pass by N V Pushkov, who experienced, together with Academician E K Fedorov and other physicists, the so-called court of honor. They were charged, in particular, with the continuation of scientific contacts with foreign researchers, which were, of course, necessary during World War II. This was overcome, and N V Pushkov even managed, against all odds, to employ the physicists Ya L Al'pert and Ya I Likhter, who had been dismissed from the P N Lebedev Physical Institute (LPI), as well as nuclear physicists from amongst the MSU graduates, who organized in the Institute the Department of Cosmic Ray Variations, which was headed by L I Dorman for many years.

In 1951, the Murmansk Branch of the Institute was set up for comprehensive studies of magnetic ionospheric effects, which are most intense in high latitudes, as well as auroras. In 1953, the Institute received a nonmagnetic schooner *Zarya* (Fig. 6) for measuring magnetic fields in sea water. Its yearly expeditions permitted obtaining a wealth of data for plotting magnetic maps; features of global geomagnetic field distribu-

**Figure 6.** Nonmagnetic schooner *Zarya* (1953–1988).

tion and ionospheric processes were studied, and previously unknown magnetic anomalies were discovered. Unique data were accumulated over the 35 years of the schooner's operation.

In 1956, the Institute was turned over to the USSR Ministry of Communications in connection with a significant increase of the ionosphere and radio wave propagation investigations in its scientific projects. A new name was attached to the Institute: Research Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (NIZMIR in *Russ. abbr*.). The number of research areas in radio communication and radio wave propagation increased, and a start was made on Antarctic research expeditions.

The International Geophysical Year (IGY) in 1957, a major international project, became a turning point for the development of the Institute, which turned from a more or less specialized institute into an academic one. Under the leadership of the Institute, extensive research was started in solar-terrestrial physics with the participation of many institutes of the Academy of Sciences and state's Ministry institutions. New scientific centers concerned with solar-terrestrial physics research were set up all across the country: Siberian Branch of IZMIRAN in Irkutsk (presently, the Institute of Solar-Terrestrial Physics of the Siberian Branch of the RAS), the Polar Geophysical Institute in Murmansk based on the Murmansk Division of NIIZM, and the Institute of Cosmophysical Research and Aeronomy in Yakutsk.

On N V Pushkov's and Yu D Kalinin's initiative, an academic journal, *Geomagnetizm i Aeronomiya* (*Geomagnetism and Aeronomy*) was set up in 1960, which became the leading world periodical on geophysics and solar-terrestrial physics. One of the two IGY World Data Centers — MTsD-B2 — was organized at the Institute, which accumulated the materials of numerous observations from around the world to be used for scientific research. In 1971, this center was turned over to the Interdepartmental Geophysical Committee.

With the launch of the first artificial Earth satellite (AES) and the onset of the space era, the Institute turned out to be at the threshold of a new scientific area, which we now refer to as basic space research [6]. Immediately after the launch of the first satellite, President of the USSR Academy of Sciences M V Keldysh asked V A Kotel'nikov to consider the question of whether it was possible to obtain some scientific data using the satellite. V A Kotel'nikov addressed himself to IZMIRAN to Ya L Al'pert, who did this by using the satellite's radio beacon signal for studying the outer layers of the ionosphere in radio occultation observations as the satellite rises above and sets below the horizon. This was the first-ever scientific space experiment [7–9].

It is also pertinent to note that even prior to the launch of the first satellite, A V Gurevich [10], then a staff member at IZMIRAN, performed the first theoretical calculations of the interaction of a metal satellite body with the rarefied ionospheric plasma. He obtained density and electric potential distributions in the neighborhood of the satellite. These calculations were of significance for formulating and interpreting different satellite-borne experiments and underlay the more detailed subsequent experiments concerning this problem [11–13].

The world's first magnetic experiment in space was carried out with the third AES in 1958. It involved the first comparison of space measurements with the data of geomagnetic field models, as well as an analysis of the field of the East-Siberian magnetic anomaly. Data were obtained concerning the possibility of exploiting the geomagnetic field for determining the orientation of a space vehicle [14, 15]. For these investigations, N V Pushkov and the head of the Institute's magnetic laboratory Sh Sh Dolginov, together with S N Vernov and A E Chudakov of MSU, were awarded the Lenin Prize, the first in the area of space research. In the subsequent years, satellite magnetic measurements were carried out in the terrestrial magnetosphere, in interplanetary space, and in the vicinity of the Moon, Venus, and Mars, and data were obtained about the magnetic fields of these planets.

In 1959, the Institute was turned over under the aegis of the USSR Academy of Sciences and obtained its present-day name IZMIRAN. The justification for this was the Institute's active work during the IGY, its important role in space research, the significant contribution to the general line of research, and the high scientific potential of the Institute. At the 1960 annual meeting of the Academy of Sciences, its President, A N Nesmeyanov, said in his opening speech that the Academy had been replenished with one more scientific institution — the Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation — with its 'dowry', a Lenin Prize.

IZMIRAN played a major part in the deployment of a network of complex magnetic ionospheric stations in different regions of the country and in the elaboration of unified recommendations for running the corresponding measurements. By the 1960s, 37 magnetic observatories and 35 ionospheric stations were operating in the USSR. V N Bobrov designed a universal quartz magnetosensitive element (sensor) with high metrological parameters. V N Bobrov and N D Kulikov, a quartz glass blower, fabricated a large series of quartz magnetometric sensors and instruments based on this measuring unit. Many domestic magnetic observatories, as well as those in more than 20 countries in the world, were equipped with these devices. The first domestic serial production of an automatic ionospheric station (AIS), which worked for more than 50 years in several complex observatories in the country and several foreign observatories, aboard research vessels of the USSR Academy of Sciences, and in the Vostok Station in the Antarctic, was made at the Institute in those days.

Apart from space research, undoubtedly among the Institute's scientific priorities is the determination of the shape of the aurora domain, as carried out by Ya I Fel'dshtein, of the so-called aurora oval [16], or the Fel'dshtein oval (Figs 7 and 8), which gained worldwide recognition.

In the 1960s, the Institute appreciably enlarged the scale of research both on geomagnetic fields and on near-Earth space; in addition, the scientific-organizational and material-technical basis of the Institute became firmer. A Special Design Bureau of physical instruments (SDBPI) was set up, in which a series of unique instruments was made — magnetic variation stations, ionoprobes, and several of the world's largest extra-eclipsing coronagraphs designed by G M Nikol'skii, which were successfully used for solar observations in domestic and foreign observatories.

Organized in 1965 near the town of Ladushkin in the Kaliningrad region was the Kaliningrad Complex Magneto-Ionospheric Observatory (KCMIO), which is the most western point of domestic observations. Today, KCMIO is part of the Kaliningrad Branch of IZMIRAN.

**Figure 7.** Yakov Isaakovich Fel'dshtein.

In 1966, on N V Pushkov's initiative and under his chairmanship a Scientific Council on the Solar-Terrestrial Relationship (the Sun–Earth Council) was organized at the General Physics and Astronomy Division of the USSR Academy of Sciences, which operates at the present time.

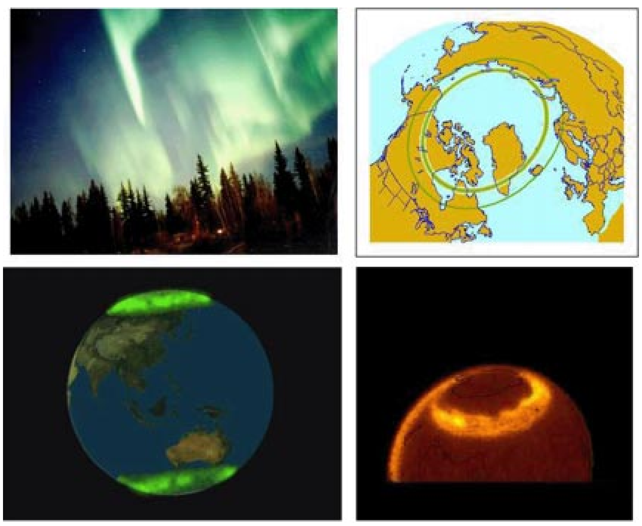

**Figure 8.** Aurora oval, which was discovered for the first time by Ya I Fel'dshtein.

The task of the Sun–Earth Council is the coordination of work on solar-terrestrial physics in our country and the realization of international cooperation. At that time, E I Mogilevskii developed a solar vector magnetograph, which permitted the world's first simultaneous measurements of all components of the magnetic field in active solar regions, and a neutron supermonitor — a detector with enhanced sensitivity for recording cosmic ray variations — was put into operation. The entire Soviet network of cosmic ray stations was equipped with such monitors, and new stations were added to the network. In the 1960s, a field magnetic variation station (IZMIRAN-4) was developed at the Institute, which found wide use both in the USSR and abroad: about 400 of these stations were placed at many points around the globe.

For IZMIRAN, the 1960s–1970s and the subsequent years were the 'Big Bang' years as regards space science (Fig. 9). The Institute participated in many space projects and carried out investigations of the ionosphere, the magnetic fields of Earth, the Moon, and the planets, and a solar research. As a result of these investigations, local ionospheric properties were studied, a global magnetic survey was conducted covering 75% of the terrestrial surface, a contribution was made to the construction of the first analytical International Geomagnetic Field Model, and numerous other results were produced [6, 17].

With the beginning of manned space flights (1961), the Institute participated in providing the radiation safety of the cosmonauts proceeding from solar observations, by forecasting solar flares and their impacts on the near-Earth space. The Institute's participation in the development and implementation of complex scientific programs became a characteristic feature of its activities. In the 1960s, IZMIRAN collaborated actively in the International Quiet Sun Year and International Active Sun Year programs.

In 1969, N V Pushkov appealed to the Presidium of the USSR Academy of Sciences to accept his resignation from his directorship for health reasons, and the position of IZMIRAN's director was filled by an MSU professor, V V Migulin (Fig. 10), a direct pupil of L I Mandelstam and N D Papaleksi, a well-known radiophysicist, and subsequently a Corresponding Member and Academician of the USSR AS [18–20]. By that time, the Institute's staff had increased nine-fold in number, there were approximately 900 staff members in IZMIRAN and 360 staff members in the IZMIRAN SDBPI.

With V V Migulin's arrival, an impetus was given to radiophysical ionospheric research with the aid of modern facilities developed at the Institute [Soika-600 Digital Ionospheric Station, Bazis Ionospheric Station (ionoprobe), Multifrequency Radiophysical Facility, Experimental Facility for Multifrequency Phase Ionosphere Probing, etc.], which permitted performing detailed investigations of ionospheric processes, radio wave propagation conditions, and the effects of the interaction of high-power radio-frequency radiation from heating facilities with the ionospheric plasma.

In the 1970s, the Institute participated widely in active experiments in space with the use of rockets, which were implemented under the auspices of the Space Research Institute (IKI in *Russ. abbr*.), RAS. In these experiments, a study was undertaken of the physical effects that take place when electron beams and plasma jets are injected into the ionosphere from on board a rocket, and an artificial aurora was observed [21]. During that period, IZMIRAN took also part in the international programs International Investiga-

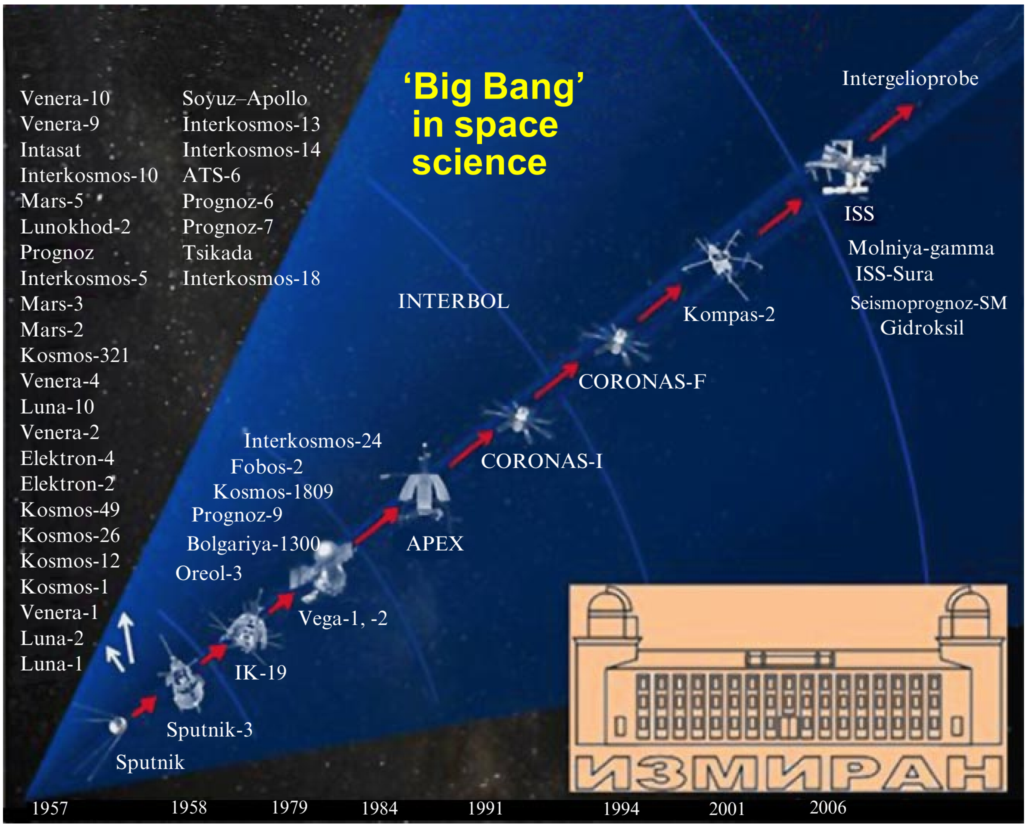


**Figure 9.** IZMIRAN's space research.

tions of the Magnetosphere and Solar Maximum Year. During the flight of the *Soyuz* and *Apollo* mission, G M Nikol'skii performed successfully the first exoatmospheric experiment involving the observation of an artificial solar eclipse, in which it was possible to observe the solar corona far away from the Sun and examine the corona

**Figure 10.** Vladimir Vasil'evich Migulin (1911–2002).

brightness distribution along the ecliptic at a long distance from the Sun.

In IZMIRAN's space investigations, mention should be made of the most significant domestic space project in ionospheric research — Interkosmos-19 (1979–1982) — with a topside sounding of the ionosphere. The investigations were executed over a vast territory of the globe and a wealth of data was obtained. This data set is still being processed and analyzed at the present time; earthquake effects in the ionosphere were also discovered [22].

In the 1980s, ionospheric research was continued with several other satellites. During these years, the Institute also participated in Vega-1 and Vega-2 space experiments on the investigation of Halley's comet. In these experiments, original data on the electromagnetic wave processes in the near-Earth region were gathered and measurements were made of the magnetic field near the comet [23]. Also, a unique series of magnetic field measurements in the vicinity of Mars was made from aboard the Fobos-2 space vehicle [24].

A Theoretical Department has been working in the Institute since 1969. Initially, it was supervised by a well-known theorist, Professor V I Karpman. Over the years, the Institute's theorists have studied nonlinear wave phenomena in space plasma physics, collective effects in the generation and propagation of radio waves in the ionosphere, plasma effects emerging in the execution of active experiments, and other phenomena in related research areas, including astrophysics and nuclear physics [25, 26].

In 1989, Professor V N Oraevskii became IZMIRAN's Director (Fig. 11). Implemented under his supervision was the Active Plasma Experiments in Space (APEX) project involving the injection of charged particle beams into the magneto-

**Figure 11.** Viktor Nikolaevich Oraevskii (1935–2006).

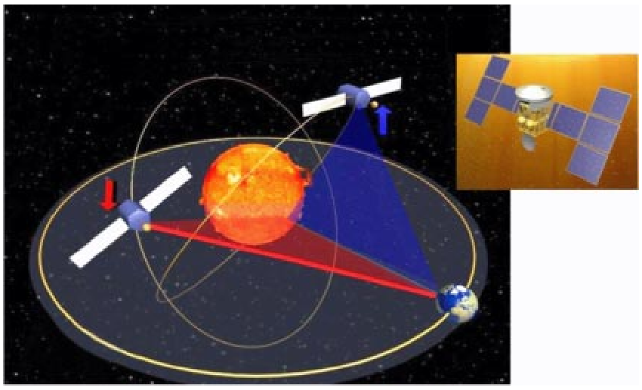

**Figure 12.** Intergeliozond project intended for investigating the Sun and the inner heliosphere, with the participation of IKI RAS, IZMIRAN, FIAN, the A F Ioffe Physicotechnical Institute RAS, the D V Skobeltsyn Institute of Nuclear Physics MSU, the National Research Nuclear University MEPhI, and the Radiophysical Research Institute.

spheric plasma [27]. He also started, jointly with I I Sobel'man of the LPI, the CORONAS [CORONAS — Kompleksnye ORbital'nye Okolozemnye Nablyudeniya Aktivnosti Solntsa (Complex orbital near-Earth observations of solar activity)] program concerned with solar research and the effects of solar activity on the near-Earth space [28]. IZMIRAN scientists were awarded a State Prize and a prize from the Russian Federation Government for the implementation of the APEX and CORONAS-F projects.

In recent years, IZMIRAN, in collaboration with other partners, performed a series of experiments with a Sura heating facility with the use of optical observations from aboard the Russian Segment of the International Space Station (ISS). These experiments point to the possibility of initiating a magnetic substorm under radio wave heating of the ionosphere and thereby of controling the characteristics of the geophysical medium [29]. A number of other experiments aboard the ISS have been prepared and implemented.

Today, continuous observations of the geomagnetic field and ionosphere are pursued at the Institute's laboratories in Moscow (Troitsk), near St. Petersburg, in Kaliningrad, and in Vladikavkaz, from an observation site in Karpagory in Arkhangel'sk region, and at cosmic ray stations. These observations are integrated into the Russian and international observational network and are employed for carrying out research and for studying and monitoring space weather.

Unique balloon-based geomagnetic investigations make use of the gradient technique of measurements along a long route — from Kamchatka to the Urals. As a result, magnetic anomalies were studied and valuable data were obtained for the improvement of modern models of the terrestrial magnetic field [30].

The motions of terrestrial magnetic poles, which are of significance by themselves and for magnetic navigation and terrestrial climate studies, are continuously monitored and analyzed by magnetologists from the Institute with the use of all available magnetic data [31]. The polarity reversal of the terrestrial magnetic field (whereby the northern and southern magnetic poles change places), which has occurred many times in the past, also occupies the attention of IZMIRAN's magnetologists today. As before, the data on magnetic declination are nowadays requested by many organizations in the country (aviation, defense and cadastral services, geodesy and cartography, oil companies, etc.). A general magnetic survey with the participation of IZMIRAN and other organizations is planned in the framework of the Geophysical Monitoring of the Territory of the Russian Federation program, beginning in 2016.

In the area of space research, the Institute is participating in the framework of a broad cooperation program in the preparation of a complex of scientific instrumentation for the Interhelioprobe space project to investigate the Sun and solar sources of space weather [32]. The Institute began work on this priority project in 1995. This project plans for the first time to execute continuous out-of-the ecliptic observations of the solar polar regions for studying the solar dynamo and the solar cycle, as well as to carry out several unique scientific experiments (Fig. 12).

IZMIRAN is engaged in broad international cooperation with different scientific organizations and unions, and it participates in the implementation of several international programs and projects. When V V Migulin became Director of the Institute and was familiarizing himself with its research areas, he said jokingly: "IZMIRAN is like a department store: it has everything." Astronomy and astrophysics, solar-terrestrial physics and geophysics, plasma physics and radiophysics, high-energy and cosmic ray physics — these are the realms of science that are represented, to one extent or another, in the research activities of the Institute. And so the width of the circle of cooperation is also large: International Association of Geomagnetism and Aeronomy (IAGA), Committee on Space Research (COSPAR), Scientific Committee on Solar-Terrestrial Physics (SCOSTEP), International Astronomical Union (IAU), International Union of Radio Science (URSI), and other international organizations.

Today, the topicality of the research areas related to IZMIRAN's activities is increasing; they are becoming progressively more demanded from the practical standpoint as well. This is due to the expansion of ground-based and space technologies and infrastructures, which are becoming vulnerable to the factors of space weather owing to their large scale [33], while IZMIRAN is concerned with the science of space weather, which must be studied, monitored, and predicted. Today, the task of the Institute is to realize these opportunities for maintaining and developing the Institute and for continuing research work.

The Space Weather Forecasting Center set up at the Institute delivers information to organizations of the space-related industry — to the Space Flight Control Center and to space launching sites, to medical institutions, oil and gas companies, and the media. Information about space weather forecasts is transmitted by Central TV every day. The progress in the study of solar activity and the terrestrial magnetic field is used for developing forecasting methods, improving prediction reliability, and eventually mitigating the effect of solar activity and space weather factors on the ground and space activities.

Today, the traditional lines of the scientific activities of the Institute — terrestrial and planetary magnetism, the ionosphere and radio wave propagation, solar-terrestrial physics, and scientific instrument making — are being filled with new substances, leaning upon new experimental data of ground- and space-based observations, their modern development trends being permanently analyzed by the Institute's staff members. The Institute possesses a high scientific potential and vast experience for solving the tasks set before it. However, the problem of involving additional young staff remains urgent.

Prepared for celebrating the 75th anniversary of the Institute was the book, *Elektromagnitnye i Plazmennye Protsessy ot Nedr Solntsa do Nedr Zemli* (*Electromagnetic and Plasma Processes From the Solar Interior to Earth's Interior*) based on the results of research over many years, which was a continuation of the book published 25 years ago when celebrating the 50th anniversary of the Institute [34].

IZMIRAN was the founder of the scientific settlement which is now the town of Troitsk, a city of science, and this role, now honorary, of the Institute in originating the city of science is part and parcel of the history of Troitsk itself. Many parcels of land and buildings of the Institute were turned over to the town and other institutes for development. Today, as earlier in the history of magnetic measurements, the Institute is facing the problem of moving the magnetic observatory, which bears the name Moscow Observatory, to a more distant place, which is void of trams and other sources of interference for magnetic measurements.

## 5. Conclusions

Over the 75 years of its activity, IZMIRAN has passed through several development stages to go from a highly specialized institute to a modern research institute of the Russian Academy of Sciences. To a large extent, this was due to the demand for and topicality of IZMIRAN's research area, its active and diversified scientific activity for many years, its contribution to the incipient space research and the general research areas, and the high scientific potential of the Institute.

In the area of geomagnetism, the Institute developed a wide variety of magnetometric instruments for studying the terrestrial magnetic field and its variations, and performed the first-ever magnetic measurements in space. The Institute participated actively in the deployment of a domestic network of magnetic ionospheric observatories, including Arctic and Antarctic stations. IZMIRAN has participated directly in the organization of other institutes with related research profiles.

The Institute has performed complex experimental investigations of the ionosphere and radio wave propagation conditions with the exploitation of developed radiophysical facilities, and constructed theoretical models which permitted understanding the basic physical features of radio wave–ionosphere interactions of significance for a number of practical applications. In a series of space ionospheric projects ranging from the first AES to problem-oriented satellites (Interkosmos-19), studies have been done of global and local ionospheric properties, the ionospheric effects of lithospherical processes, and anthropogenic activity.

In the area of solar-terrestrial physics, the Institute has designed and made coronagraphs, telescopes, magnetographs, radio spectrographs, and cosmic ray detectors, which permitted studying active processes on the Sun, their effect on the terrestrial magnetic field, and the state of the ionosphere. IZMIRAN was the leading organization in the implementation of the first Russian complex solar projects (CORONAS-I, CORONAS-F), which laid a firm basis for institutes' cooperation in this area. A large-scale solar space project, Interhelioprobe, which was developed at IZMIRAN, is now in the preparatory stage with the participation of a broad range of Russian and foreign institutes. The results of research in this area enjoy practical applications in the study and prediction of space weather, which exerts progressively greater influence on ground- and space-based infrastructure of society as its scale increases.

Like many other scientific institutes, today IZMIRAN continues to exist and work in the framework of the Federal Agency of Scientific Organizations, while remaining inseparably tied to the Russian Academy of Sciences.

## References


1. Raspopov O M et al. *Istoriya Nauk o Zemle* **2** (2) 18 (2009)
2. Simonoff I M *J. Reine Angew. Math.* **16** 197 (1837)
3. Simonoff I M "O zemnom magnetizme" ("About terrestrial magnetism"), in Gauss C F *Izbrannye Trudy po Zemnomy Magnetizmu* (Selected Works on Terrestrial Magnetism) (Moscow: Izd. AN SSSR, 1952) p. 245
4. Gauss C F *Resultate aus den Beobachtung des magnetischen Vereins im Jahre 1838* Bd. 1 (Göttingen: Dieterichsche Buchhandlung, 1839)
5. Krylov A N *O Zemnom Magnetizme* (About Terrestrial Magnetism) (Petrograd: Red.-izd. otd. Morsk. kom., 1922)
6. Kuznetsov V D *Phys. Usp.* **53** 528 (2010); *Usp. Fiz. Nauk* **180** 554 (2010)
7. Al'pert Ya L *Usp. Fiz. Nauk* **64** 3 (1958)
8. Al'pert Ya L et al. *Usp. Fiz. Nauk* **65** 161 (1958)
9. Alpert Y *Making Waves: Stories from My Life* (New Haven: Yale Univ. Press, 2000)
10. Gurevich A V *Tr. Inst. Zemn. Magn. Ionosf. Rasprostr. Radiovoln* **17** (27) 173 (1960)
11. Gurevich A V *Iskusstv. Sputniki Zemli* (7) 101 (1961)
12. Al'pert Ya L, Gurevich A V, Pitaevskii L P *Sov. Phys. Usp.* **6** 13 (1963); *Usp. Fiz. Nauk* **79** 23 (1963)
13. Al'pert Ya L, Gurevich A V, Pitaevskii L P *Space Physics with Artificial Satellites* (New York: Consultants Bureau, 1965); Translated from Russian: *Iskusstvennye Sputniki v Razrezhennoi Plazme* (Moscow: Nauka, 1964)
14. Dolginov Sh Sh, Zhuzgov L N, Pushkov N V *Iskusstv. Sputniki Zemli* (2) 50 (1958)
15. Dolginov Sh Sh, Pushkov N V, in *Uspekhi SSSR v Issledovanii Kosmicheskogo Prostranstva* (USSR Advances in Space Research) (Ed.-in-Chief A A Blagonravov) (Moscow: Nauka, 1968) p. 173
16. Fel'dshtein Ya I, in *Elektromagnitnye i Plazmennye Protsessy ot Solntsa do Yadra Zemli* (Electromagnetic and Plasma Processes

from the Sun to the Core of the Earth) (Exec. Ed. V V Migulin) (Moscow: Nauka, 1989) p. 108
17. Kuznetsov V D *Phys. Usp.* **53** 947 (2010); *Usp. Fiz. Nauk* **180** 988 (2010)
18. Gulyaev Yu V *Phys. Usp.* **55** 301 (2012); *Usp. Fiz. Nauk* **182** 323 (2012)
19. Vyatchanin S P *Phys. Usp.* **55** 302 (2012); *Usp. Fiz. Nauk* **182** 324 (2012)
20. Kuznetsov V D *Phys. Usp.* **55** 305 (2012); *Usp. Fiz. Nauk* **182** 327 (2012)
21. Oraevskii V N, Mishin E V, Ruzhin Yu Ya, in *Elektromagnitnye i Plazmennye Protsessy ot Solntsa do Yadra Zemli* (Electromagnetic and Plasma Processes from the Sun to the Core of the Earth) (Exec. Ed. V V Migulin) (Moscow: Nauka, 1989) p. 77
22. Karpachev A T, in *Entsiklopediya Nizkotemperaturnoi Plazmy* (Encyclopedia of Low Temperature Plasma) Vol. I–3 *Ionosfernaya Plazma* (Ionospheric Plasma) Pt. 1 (Eds V D Kuznetsov, Yu Ya Ruzhin) (Moscow: Yanus-K, 2008) p. 381
23. Riedler W et al. *Nature* **321** 288 (1986)
24. Riedler W et al. *Nature* **341** 604 (1989)
25. Karpman V I, in *Elektromagnitnye i Plazmennye Protsessy ot Solntsa do Yadra Zemli* (Electromagnetic and Plasma Processes from the Sun to the Core of the Earth) (Exec. Ed. V V Migulin) (Moscow: Nauka, 1989) p. 162
26. Kuznetsov V D *Geomagn. Aeronom.* **49** 691 (2009); *Geomagn. Aeronomiya* **49** 723 (2009)
27. Oraevsky V N, Tríska P *Adv. Space Res.* **13** (10) 103 (1993)
28. Kuznetsov V D (Ed.) *The CORONAS-F Space Mission: Key Results for Solar Terrestrial Physics* (New York: Springer, 2014); Translated from Russian: *Solnechno-Zemnaya Fizika: Rezul'taty Eksperimentov na Sputnike CORONAS-F* (Moscow: Fizmatlit, 2009) p. 34
29. Ruzhin Yu Ya et al. *Geomagn. Aeronom.* **53** 43 (2013); *Geomagn. Aeronomiya* **53** (1) 46 (2013)
30. Tsvetkov Yu P et al. *Dokl. Earth. Sci.* **436** 117 (2011); *Dokl. Ross. Akad. Nauk* **436** 262 (2011)
31. Zvereva T I *Geomagn. Aeronom.* **52** 261 (2012); *Geomagn. Aeronomiya* **52** (2) 278 (2012)
32. Kuznetsov V D, in *Proekt Intergeliozond. Trudy Rabochego Soveshchaniya, Tarusa, 11–13 Maya 2011 g.* (Intergeliozond Project. Workshop Proc., Tarusa 11 – 13 May 2011) (Ed. V D Kuznetsov) (Moscow: IZMIRAN, 2012) p. 5
33. Bothmer V, Daglis I A *Space Weather: Physics and Effects* (Berlin: Springer, 2007)
34. Migulin V V (Exec. Ed.) *Elektromagnitnye i Plazmennye Protsessy ot Solntsa do Yadra Zemli* (Electromagnetic and Plasma Processes from the Sun to the Core of the Earth) (Moscow: Nauka, 1989)

*Physics – Uspekhi* **58** (6) 601 – 605 (2015) 

*CONFERENCES AND SYMPOSIA* PACS numbers: 07.55.Db, **41.20.–q**, **91.25.–r**, 96.12.Hg, 96.60.Hv

*75th ANNIVERSARY OF IZMIRAN*

# Problems of magnetic dynamo

D D Sokoloff

DOI: 10.3367/UFNe.0185.201506h.0643

## Contents



**Abstract.** **In what is famously known as the solar activity cycle, every 11 years a wave from a quasistationary magnetic field propagates in the solar convective zone from the middle latitudes equatorwards, driven by the dynamo jointly produced by differential rotation and mirror-asymmetric convection. Similar processes occur in other celestial bodies and can to some extent be reproduced in the lab environment. This paper reviews the current status of and future trends in the study of the dynamo phenomenon.**

**Keywords:** magnetic fields, dynamo, solar activity

## 1. Introduction: the dynamo on the Sun and elsewhere

The best known manifestation of the physical process recognized for the magnetic dynamo (hydrodynamic) is the solar activity cycle during which an activity wave propagates every 11 years over the surface of both solar hemispheres from the middle latitudes equatorwards. The wave is identified by various tracers, of which the most widely known is the number of sunspots, apart from other characteristics. This activity wave is generated by a wave from a quasistationary magnetic field propagating beneath the Sun's surface, in its convection zone. Certainly, the propagating magnetic structure gives rise to a weak electric field, but the parameters of the wave themselves, viz. an unusually large period, a spatial scale matching the size of the Sun, a magnetic energy density commensurate with the kinetic energy density of convective movements of the solar plasma, suggest that the phenomenon in question is something other than usual electromagnetic waves. On the other hand, the appearance of the activity wave can hardly be attributed to relativistic or quantum-mechanical processes; in classical physics, only electromagnetic induction can take on the role of a process exciting a magnetic field. In such general terms, researchers came to an understanding of the solar cycle very soon after its magnetic nature was demonstrated in the early 20th century when this process was termed the dynamo, by analogy with the now obsolete name of a car engine part.

Magnetic activity reminiscent in a certain sense of solar activity is known to occur in many celestial bodies, even though it takes essentially different forms there due to peculiar observation conditions or problem geometry. Specifically, the dynamo process is associated with the initiation and evolution of Earth's magnetic field on the geological time scale, as well as the origin of large-scale magnetic fields of spiral galaxies, including the Milky Way.

Little by little, it became clear that the magnetic dynamo is essentially different from the familiar process in the theory of electricity, the difference being due to an unusual parameter called the magnetic Reynolds number, Rm. Indeed, inductive effects in the dynamo process must prevail over dissipation and the ordered estimate of the ratio between the respective terms in Ohm's law in a moving media leads to the condition

$$\mathrm{Rm} = \frac{vl}{\nu_{\mathrm{m}}} \gg 1\,, \qquad (1)$$

where $v$ is the characteristic velocity, $l$ is the characteristic dimension of the problem, and $\nu_{\mathrm{m}}$ is the magnetic diffusion coefficient of the medium.

It was estimated that the huge $l$ is responsible for the value of $\mathrm{Rm} \approx 10^6$ in the solar convective zone, whereas in the interstellar medium Rm can be higher than $10^8$. At the same time, under usual lab conditions and in technical devices with moving liquid conductors, Rm is much smaller than unity. The dynamo phenomenon occurs when Rm exceeds a threshold value that depends certainly on the system's geometry. In the best case, described by Yu B Ponomarenko [1] of the

**D D Sokoloff** Faculty of Physics,
Lomonosov Moscow State University,
Leninskie gory 1, str. 2, 119991 Moscow, Russian Federation;
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences,
Kaluzhskoe shosse 4, 142190 Troitsk, Moscow, Russian Federation
E-mail: sokoloff.dd@gmail.com

Received 20 March 2015
*Uspekhi Fizicheskikh Nauk* **185** (6) 643 – 648 (2015)
DOI: 10.3367/UFNr.0185.201506h.0643
Translated by Yu V Morozov; edited by A Radzig

N V Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences (IZMIRAN) in 1973, the critical value of Rm equals 17. It took almost half a century and targeted efforts of researchers in different countries to reach this critical value in lab experiments and observe self-excitation of the quasistationary magnetic field in the laboratory at the turn of the new millennium. Practically all operating and projected laboratory facilities for the study of the dynamo effect in one way or another make use of Ponomarenko's ideas, while reproduction of dynamo versions more plausible in the astrophysical context under laboratory conditions is still a long way in the future. The development of dynamo research, from astronomical models to dynamo experiments, has been overviewed in recent publication [2] and references cited therein. The present paper deals with the dynamo question insofar as it concerns solar physics.

To recall, researchers in this country have been traditionally involved in dynamo research. Suffice it to say that dynamo experiments initiated way back in the 1960s by a group based in Riga (then Latvian SSR) were successfully completed, even if in a different country. The decision taken in the 1960s to choose Soviet Latvia as the most suitable place for the development of magnetohydrodynamics created serious problems 30 years later for Russian specialists engaged in this branch of science, problems that were, however, resolved in the course of time. Dynamo experiments at the Institute of Continuous Media Mechanics, Ural Branch of the Russian Academy of Sciences, based in the city of Perm', have now taken their place along with research in Latvia, Germany, France, and the USA.

## 2. Solar dynamo scenario in the context of current observations

Large Rm values by themselves are insufficient for a magnetic field to be self-excited by the dynamo mechanism. According to the Lenz rule, the magnetic field produced by electromagnetic induction is not added to the existing weak priming field but is subtracted from it. Therefore, the dynamo process must involve at least two coupled circuits, one of which induces a magnetic field in the other and vice versa, the signs of these fields being such that the overall result of inductive effects chosen gives self-excitation.

In the solar dynamo and dynamos of other celestial bodies, the magnetic field in the first circuit has the form of a usual dipole (possibly, a quadrupole), while the field in the second circuit inside the solar convective zone is directed azimuthally. The former field is referred to as poloidal, and the latter as toroidal. A poloidal magnetic field is transformed into a toroidal one during differential rotation of the medium into which the field is frozen. Half a century and efforts of several research teams were needed to find the motion that restores the poloidal magnetic field from the toroidal one. In 1955, the American astronomer E N Parker [3] intuitively derived equations relating the two components of the field for a thin convective shell. It follows from these equations that the solar dynamo system actually has its own frequency, which can be identified with the solar cycle frequency.

Ten years after Parker's article, equations for the evolution of the mean magnetic field in the case of mirror-a symmetric convection (or turbulence) were developed by the eminent German physicist M Steenbeck and his graduate students F Krause and K-H Rädler [4]. Steenbeck had formerly been affiliated with Siemens military projects and afterwards worked for 10 years in Sukhumi, in all probability with V V Migulin, the future director of IZMIRAN, before he took an interest in more academic matters. It was shown that convective flows in rotating bodies are mirror-asymmetric, because the action of the Coriolis force on the vortices either emerging or submerging in a stratified medium results in a different number of left-hand and right-hand rotating vortices in a given hemisphere of the celestial body.

In less than 10 years, specialists came across article [4] printed in places in Gothic fonts in a poorly known German journal and became aware of the formulas derived by the young co-authors of the President of the GDR Academy of Sciences for the estimation of the so-called $\alpha$-effect just coupling toroidal and poloidal magnetic fields. Their estimates demonstrated that a solar cycle is roughly 10 times shorter than the observed one. This discrepancy has for a long time been regarded as a tragic mismatch between theory and observations, despite the fact that an order of magnitude error in the estimation of a key parameter unknown from experiment is actually a success rather than a failure in studying the process.

In a few years (1972), Ya B Zeldovich explained by an illustrative example of a figure-eight loop the behavior of magnetic lines of force in astrophysical dynamos. First, the magnetic loop stretches to twice its extent (due to differential rotation), then it folds into a figure-eight whose halves overlap by virtue of the $\alpha$-effect. Clearly, the magnetic flux is doubled in the process. In the spirit of that heroic epoch, Ya B Zeldovich confined himself to disclosing this beautiful idea in a discussion at a scientific conference in Krakow, and it was published later together with his other work (see, e.g., Ref. [5]).

In the next decades, this beautiful but somewhat abstract scheme was supplemented by a variety of astronomical observations and, partly, by experimental lab findings. A comprehensive review of these results are far beyond the scope of the present article, because even a brief characteristic of the methods and current state of helioseismology contributing to the retrieval of differential rotation in the inner parts of the Sun would require a special large review. What follows concerns only recent progress in the observational definition of the $\alpha$-effect that has until recently been regarded as an infeasible task. It should be borne in mind that we do not associate the $\alpha$-effect only with its special form considered by Parker but also deal with the form in which mirror asymmetry is related to the magnetic field action (the so-called Babcock–Leighton scheme).

The heart of the issue is that all three velocity field components must be known before and above everything else to enable the observational definition of the $\alpha$-effect, i.e., the degree of mirror asymmetry of the problem. In astronomy, however, the velocity usually estimated from the Doppler effect gives only the line-of-sight component. In the next approximation, the degree of mirror asymmetry related to the magnetic field itself needs to be known. It already simplifies the problem, since the magnetic field is frequently measured based on the Zeeman effect, which can give all three field components. True, they must be differentiated, which poses a nontrivial task, but a viable method for the purpose was proposed by Seehafer [6].

During the past 30 years, several research teams have observed the so-called current helicity determining the magnetic field contribution of the $\alpha$-effect in the active regions of the Sun. These observations are of interest for the solar dynamo question if they cover a large part of the cycle or, better yet, the entire solar cycle. The necessary information was obtained by astronomers of the Huairou Solar Observing Station near Beijing. It should be emphasized that dynamo-related specialists of IZMIRAN supported by the Russian Foundation for Basic Research (RFBR) actively participated in the treatment and interpretation of the data collected by their Chinese colleagues. Their meticulous, laborious work made it possible to reconstruct the latitudinal and temporal evolution of current helicity [7] that fits fairly well into the modern dynamo concept. It is noteworthy that researchers concerned with solar dynamo simulation did not care to theoretically describe what latitudinal and temporal distributions should be expected in the framework of the simplest solar dynamo models. No wonder that they were surprised to discover rather intricate but regular distribution patterns consistent with the above findings [8].

It took some time to understand that the data on the regular distribution of the tilt angles of magnetic bipolar structures associated with groups of sunspots (so-called Joy's law) are sufficient to come to a definitive conclusions [9]. Namely, it proved possible to construct latitudinal–temporal diagrams for the entire variation range of the $\alpha$-coefficient [10]; moreover, helioseismological techniques were adapted for the estimation of the contribution to the $\alpha$-effect from the velocity field [11]. At approximately the same time, researchers learnt to measure the $\alpha$-effect in MHD lab experiments with liquid metals [12]. Bearing in mind the paramount importance of this effect in the context of the dynamo problem, it deserves to be comprehensively studied. Generally speaking, this research area still remains obscure, but prospects have now opened up for practical investigations into what formerly seemed beyond reach.

## 3. Archival data and stellar analogies

No matter how strange it may seem, increasingly more new data are coming from astronomical archives (see, e.g., book [13]). The fact is that soon after Galileo Galilei began to employ the telescope in his astronomical surveys in 1611, observation of sunspots became a favorite pursuit among both scientists and amateurs. In a few decades, the Paris Observatory was established, initially focusing on monitoring the solar activity. An important contribution to the organization of this work was made by King Louis XIV. Indeed, his keen interest in these observations ensured their continuation over a rather long time, even though the net result proved negative. It was the period of a deep, prolonged recession of solar activity, later called the Maunder minimum after the English astronomer of the early 20th century. At the time of E W Maunder, this minimum was a matter of bold conjectures. Later on, its existence was confirmed by the isotopic method, taking advantage of the fact that solar activity affects the dynamics of certain isotopes on Earth. However, the solar activity in the period of the Maunder minimum was completely reconstructed based on archival data only in the last decade of the 20th century.

The investigation of archival materials continues and has revealed some unusual episodes in the solar cycle recorded during the period of instrumental observations of the Sun. These episodes have different scenarios and are of special interest in light of nonstandard patterns of the current activity cycle. The data on isotope dynamics give evidence of earlier activity minima resembling the Maunder minimum They suggest systematic deviations from the normal cycle and demonstrate that the solar dynamo's operation cannot be reduced to self-oscillations of the magnetic field.

The reconstruction of the history of solar activity has little in common with the usual work of a physicist or astronomer — it implies the interpretation and criticism of historical records as is more common in the humanities.

The most straightforward explanation of the Maunder minimum and other peculiar features of the solar cycle is based on the fact that the governing parameters of the cycle are some averaged quantities calculated based on the relatively small ensemble of convection cells. Some of these parameters (first and foremost the $\alpha$-coefficient) are rather small; therefore, statistical fluctuations may seriously disrupt operation of the solar dynamo [14, 15].

That the activity cycle is not an intrinsic feature of the Sun alone is confirmed in the first place by observations of temporal variations of the integral stellar stream in certain specially selected spectral lines. The well-known American astronomer O C Wilson followed up these changes in more than one hundred stars for a few decades [16]. The results of this monitoring confirm the existence of stellar cycles comparable with the solar one in many stars resembling the Sun. An incidental result of this study is the demonstration of the difficulty of long-term monitoring in the framework of projects supported by scientific grants. The French astronomers of Louis XIV's reign did not encounter such financial problems — their support was guaranteed by the king's initiative. Specialists concerned with the interpretation of observations did their best to extract as much physical information as possible from the data obtained. In certain cases, they managed to construct latitudinal and temporal activity diagrams [17]. Nevertheless, integral data are of limited value.

It is noteworthy that mapping temperature distributions for individual stars has become possible since the 1980s, despite the fact that these stars are invisible to telescopes. The mapping is realized by solving the inverse problem for a certain integral equation describing the formation of spectral lines in the stars by varying the temperature over their surfaces [18]. This technique, exemplifying a very impressive achievement of Russian science, is now known as inverse Doppler imaging. Up to now, many observatories all over the world have made use of computer codes based on program packages copied from perfocards developed in the USSR at the turn of the 1980s for the then very imperfect domestically produced computers.

It could be expected that the inverse Doppler imaging method used during the past 30 years would yield a wealth of data on the activity wave structure in different types of stars. Unfortunately, this method allows latitudinal–temporal diagrams to be constructed only in very rare cases [19] (see the interpretation of these diagrams in the framework of the dynamo theory in paper [20]). Monitoring the stellar activity with the help of this method thus far remains an unresolved problem.

## 4. Direct numerical simulation of the dynamo

Computer resources and software packages have made possible direct simulation of the dynamo question over the last 20 years without distinguishing equations for large-scale variables of the problem. Such simulation has been first described in Ref. [21] for the geodynamo problems probably because we know less about the hydrodynamics of Earth's outer liquid core than we do about flows in the interior of the solar convective zone. As possibilities for direct numerical simulation are gradually extended, it can be realized at increasingly more realistic values of the governing parameters. At present, several scientific teams in different countries are concerned with direct numerical simulation of the geodynamo; they include M Yu Reshetnyak's group at the O Yu Shmidt Institute of Physics of the Earth and IZMIRAN's team [22]. At the same time, the description of the solar dynamo in the framework of mean-field models is becoming increasingly sophisticated and realistic (see, e.g., paper [23]).

The possibility of scientifically sound forecasting of the solar cycle is becoming a reality. The duration of the cycle is comparable with the active lifetime of specialists engaged in its investigation. The number of sunspots does not give the sign of the magnetic field; therefore, the nominal 11-year cycle corresponds to a 22-year physical cycle. This means that the solution to this ambitious problem will take at least as much time as the lifespan of the entire generation of researchers concerned.

It should be noted that the efforts of geodynamo researchers are largely focused on the methods of direct numerical simulation, i.e., an extremely complicated problem suggesting that the magnetic forces can markedly rearrange flows in Earth's liquid core. Of course, the search for relatively simple (see, e.g., paper [24]) scalings in this field also remains an attractive, if hard-to-reach even goal.

The advantages of direct numerical simulations for solving such problems are obvious. Therefore, it is opportune to mention conceptual difficulties that have emerged in the past 20 years. It turns out that direct numerical simulation is a subject matter of experimental physics to a much greater extent than theoretical physics. In particular, it readily answers the question "what happens?", but does not give a direct answer to the question "why does it happen?"

A more specific difficulty is associated with the post-processing problem. Results of direct numerical simulation in the form of an enormous table of figures, e.g., characterizing magnetic field distribution, is rarely of immediate scientific interest. It is necessary to extract from this huge volume of sometimes logically disordered information a relatively small amount of data of real interest for analysis. It turns out that construction of such quantities from the results of direct numerical simulation often presents a more difficult conceptual and computational problem than the initial modeling [25]. (See paper [26] highlighting post-processing problems associated with the calculation of the $\alpha$-effect from the results of direct simulation).

## 5. Dynamo waves from the standpoint of theoretical physics

Dynamo waves along with other manifestations of the dynamo mechanism are worth studying as objects of theoretical and possibly experimental physics outside of the special astronomical context. In this regard, it would be interesting to draw a formal analogy between probability waves of quantum mechanics and dynamo waves and to use methods and notions of quantum mechanics, first of all the quasiclassical approximation, to study the dynamo waves. As is known, everything new is actually well-forgotten old: the quasiclassical approximation arose in quantum mechanics from the generalization of the short-wavelength approximation in the theory of versatile waves in liquids.

In the framework of this approach, it is possible to write down the dispersion relation for dynamo waves in the solar convective zone [27]. The dispersion relation, or in more mathematized language, the Hamilton–Jacobi equation, even in the simplest case is a fourth-order algebraic equation for a wave pulse with complex coefficients, including the eigenfrequency $\gamma$ as a parameter that is certainly also a complex quantity. The real part of $\gamma$ gives the growth rate proper, and the imaginary one the rotation frequency of the solar cycle. Naturally, the pulse of the dynamo wave is complex, too. It reflects the physical fact that the propagation of a dynamo wave is inseparable from its generation. An acoustic or electromagnetic wave can be excited in a special device to study its propagation, regardless of the excitation mode. In contrast, a dynamo wave rapidly decays in an exponential mode outside the dynamo operation region. Moreover, the wave amplitude in such a region varies appreciably from one point to another. As a result, many familiar phenomena of wave physics manifest themselves in a very unusual form, e.g., resonance, which is the first to attract attention in studies of conventional oscillations and waves. However, the phenomenon of resonance results, according to the differential equation theory, from the coincidence of two or more frequencies, rather than from a concrete form of the equation. Certainly, the resonance occurs in the dynamo phenomenon too, but it is difficult to distinguish it from more striking changes associated with variations of dynamo parameters [28].

The fourth-order dispersion relation naturally has four roots, the values of which vary in a definite manner over the latitude of the convection zone. Joining two of them at the latitude of a highest generation intensity gives $\gamma$. In this case, the maximum wave amplitude is markedly shifted from the magnetic field generation maximum, which means in terms of the quantum-mechanical analogy that a quantum particle in the ground state is located somewhere at the wall of the potential well far from its bottom. The sign of the real part of the pulse in the main frequency range and in the case of a proper sign of the governing dynamo parameters ensures, as observations show, wave propagation from the middle latitudes to the equator. However, the direction of propagation at high latitudes changes, and the wave travels toward the pole. This phenomenon has been confirmed by observations [29].

In more complicated dynamo models, the order of the dispersion equation increases [30] and patterns of dynamo wave propagation become even more intricate [31]. For example, standing dynamo waves [32] and standing activity waves [33] may appear.

The relationship between quantum mechanics and dynamo theory has one more aspect; namely, the $\alpha$-effect is related to the helicities of flows and magnetic fields. In conventional physics, helicity does not play a leading role; at the same time, it is one of the most important quantities in neutrino physics and weak interaction physics. In this respect, the concepts of microworld physics and astrophysics are brought together, and the phenomenon of spatial parity nonconservation in the microworld is manifested in terms of the dynamo theory as the $\alpha$-effect [34].

This work was supported by RFBR project No. 15-02-01407.

## References


1. Ponomarenko Yu B *J. Appl. Mech. Tech. Phys.* **14** 775 (1973); *Zh. Prikl. Mekh. Tekh. Fiz.* (6) 47 (1973)
2. Sokoloff D D, Stepanov R A, Frick P G *Phys. Usp.* **57** 292 (2014); *Usp. Fiz. Nauk* **184** 313 (2014)
3. Parker E N *Astrophys. J.* **122** 293 (1955)
4. Steenbeck M, Krause F, Rädler K-H *Z. Naturforsch. A* **21** 369 (1966)
5. Vainshtein S I, Zel'dovich Ya B *Sov. Phys. Usp.* **15** 159 (1972); *Usp. Fiz. Nauk* **106** 431 (1972)
6. Seehafer N *Solar Phys.* **125** 219 (1990)
7. Zhang H et al. *Mon. Not. R. Astron. Soc. Lett.* **402** L30 (2010)
8. Xu H et al. *Astron. Rep.* **53** 160 (2009); *Astron. Zh.* **86** 182 (2009)
9. Stenflo J O, Kosovichev A G *Astrophys. J.* **745** 129 (2012)
10. Tlatov A et al. *Mon. Not. R. Astron. Soc.* **432** 2975 (2013)
11. Komm R, Gosain S *Astrophys. J.* **798** 20 (2015)
12. Stepanov R et al. *Phys. Rev. E* **73** 046310 (2006)
13. Soon W W-H, Yaskell S H *The Maunder Minimum and the Variable Sun-Earth Connection* (River Edge, N.J.: World Scientific, 2003); Translated into Russian: *Minimum Maundera i Peremennye Solnechno-Zemnye Svyazi* (Moscow–Izhevsk: RKhD, Inst. Komp. Issled., 2008)
14. Moss D et al. *Solar Phys.* **250** 221 (2008)
15. Choudhuri A R, Karak B B *Phys. Rev. Lett.* **109** 171103 (2012)
16. Baliunas S L et al. *Astrophys. J.* **438** 269 (1995)
17. Katsova M M et al. *New Astron.* **15** 274 (2010)
18. Goncharskii A V et al. *Sov. Astron.* **26** 690 (1982); *Astron. Zh.* **59** 1146 (1982)
19. Berdyugina S V, Henry G W *Astrophys. J.* **659** L157 (2007)
20. Moss D, Sokoloff D, Lanza A F *Astron. Astrophys.* **531** A43 (2011)
21. Glatzmaier G A, Roberts P H *Science* **274** 1887 (1996)
22. Pipin V V, Kosovichev A G *Astrophys. J.* **776** 36 (2013)
23. Hejda P, Reshetnyak M *Phys. Earth Planet. Inter.* **177** 152 (2009)
24. Bassom A P, Soward A M, Starchenko S V *J. Fluid Mech.* **689** 376 (2011)
25. Stepanov R A, in *XIX Zimnyaya Shkola po Mekhanike Sploshnykh Sred. Perm', 24–27 Fevralya 2015 g.* (XIX Winter School on Continuous Media Mechanics, Perm, 24–27 February 2015) (Perm: Inst. of Continuous Media Mechanics, Ural Branch of the Russian Academy of Sciences, 2015) p. 354
26. Brandenburg A, Sokoloff D *Geophys. Astrophys. Fluid Dyn.* **96** 319 (2002)
27. Kuzanyan K, Sokoloff D *Geophys. Astrophys. Fluid Dyn.* **81** 113 (1995)
28. Moss D, Sokoloff D *Astron. Astrophys.* **553** A37 (2013)
29. Makarov V I, Sivaraman K R *Solar Phys.* **85** 227 (1983)
30. Popova H, Artyushkova M, Sokoloff D *Geophys. Astrophys. Fluid Dyn.* **104** 631 (2010)
31. Soward A M et al. *Geophys. Astrophys. Fluid Dyn.* **107** 667 (2013)
32. Baliunas S et al. *Mon. Not. R. Astron. Soc.* **365** 181 (2006)
33. Obridko V N et al. *Mon. Not. R. Astron. Soc.* **365** 827 (2006)
34. Semikoz V B, Sokoloff D D *Phys. Rev. Lett.* **92** 131301 (2004)

*CONFERENCES AND SYMPOSIA*

PACS numbers: **94.20 – y**, **94.30. – d**

*75th ANNIVERSARY OF IZMIRAN*

# Some aspects of magnetosphere–ionosphere relations

A A Petrukovich, M M Mogilevsky, A A Chernyshov, D R Shklyar

DOI: 10.3367/UFNe.0185.201506i.0649

## Contents



**Abstract. This paper reviews the characteristics of plasma-wave perturbations produced by wave-particle interactions in the magnetosphere–ionosphere system. These perturbations may, notably, be due to lightning discharges and to radiation from high-power low-frequency transmitters. These can form waveguide channels, i.e., density inhomogeneities, which originate in the ionosphere above the radiation source and extend along geomagnetic field lines in the magnetosphere. Although different in nature, the natural and man-made radiation sources may have similar effects on processes in the circumterrestrial plasma, causing the excitation of a variety of emissions in it and stimulating the precipitation of charged particles from the magnetosphere into the ionosphere.**

**Keywords:** magnetosphere–ionosphere connection, low-frequency emissions, active experiments, lightning discharges, wave–particle interactions, particle heating and precipitation

## 1. Introduction

The study of magnetosphere–ionosphere connection is of great interest and importance both for fundamental physics, expanding our knowledge about processes in magnetoactive plasma, and for solving practical problems related to navigation, communication, radar, and radio astronomy.

The magnetosphere is a region in near-Earth space, where plasma behavior is controlled by the Earth magnetic field. Due to the flow of the solar wind (SW) around Earth's magnetosphere, a magnetic cavity is formed, with its size determined by the dynamic equilibrium of the SW plasma kinetic pressure and the magnetic pressure of the Earth field. As the SW pressure increases, the size of the magnetosphere decreases, its plasma density increases, and the excess plasma is pushed along the magnetic field into the ionosphere. The decrease in the SW pressure leads to an increase in the magnetosphere volume, which becomes filled with the ionospheric plasma.

In this way, the ionosphere is the plasma 'reservoir' for the magnetosphere, and vice versa. Therefore, in order to adequately describe large-scale, global processes in the circumterrestrial plasma, one needs to consider the magnetosphere–ionosphere system as a whole, despite the difference between plasma properties in the ionosphere and magnetosphere. The description of small-scale local processes also needs to consider the magnetosphere–ionosphere system as a whole. In this case, the plasma dynamics are governed mostly by various electrostatic and electromagnetic oscillations and waves, which can be easily excited in the magnetoactive plasma and undergo strong damping [1].

Besides the inner sources of waves in plasma — instabilities — an important role in the magnetosphere–ionosphere system's dynamics is played by external sources. These can be either natural, for example, lightning discharges during thunderstorm activity [2, 3], or artificial (anthropogenic), for example, the radiation of short-wave heating facilities [4–11] and strong low-frequency (LF) emitters [12].

The interaction of high-power radio waves with the magnetosphere–ionosphere system causes the formation of regions with an increased density of charged particles. These regions group into plasma inhomogeneities — ducts — which stretch thousands and tens of thousands of kilometers in the magnetosphere along the magnetic field. These inhomogeneities are waveguides for whistler waves and play a key role in the propagation of low-frequency waves in the magnetosphere.

**A A Petrukovich, M M Mogilevsky, A A Chernyshov, D R Shklyar**
Space Research Institute, Russian Academy of Sciences,
ul. Profsoyuznaya 84/32, 117997 Moscow, Russian Federation
E-mail: apetruko@iki.rssi.ru, mogilevsky@romance.iki.rssi.ru,
achernyshov@iki.rssi.ru, david@iki.rssi.ru

Received 14 May 2015
*Uspekhi Fizicheskikh Nauk* **185** (6) 649 – 654 (2015)
DOI: 10.3367/UFNr.0185.201506i.0649
Translated by A L Chekhov; edited by A Radzig

Both natural and anthropogenic forms of radiation, despite their different nature and sources, can have a similar influence on processes in the near-Earth plasma. These are the questions that will be discussed in this paper.

The layout of the paper is as follows. In Section 2 we analyze the waves which are excited by the lightning discharges and are related to ion cyclotron and whistler modes. Their role in the particle precipitation from the magnetosphere to the ionosphere is discussed. Section 3 deals with the results of active experiments, based on direct measurements of the plasma characteristics and electromagnetic radiation properties, measured aboard spacecraft. Some unsolved problems and their possible solutions are discussed in Section 4.

## 2. Lightning discharge radiation in magnetosphere–ionosphere connection

Lightning discharges with a duration from several dozen microseconds to several milliseconds, which occur on Earth's surface with an average frequency of $10^{-7}$ km$^{-2}$ s$^{-1}$ [13, 14], are the source of a broadband electromagnetic radiation. This radiation, according to the modern conception, propagates in the Earth–ionosphere waveguide and partially penetrates into the ionosphere and magnetosphere, where it propagates as ion-cyclotron and whistler waves. One of the main mechanisms of magnetosphere–ionosphere connection lies in the interaction of these waves with the charged particles of the ionosphere and magnetosphere, which leads both to the precipitation of particles from the magnetosphere to the ionosphere [2] and to the heating of ionosphere ions due to the absorption of the waves [3]. This mechanism and related issues will be briefly discussed in Sections 2.1, 2.2.

### 2.1 Wave packets excited by lightning discharges in the upper ionosphere and magnetosphere

The frequency range of waves that are excited by lightning discharges and that have a large enough intensity in the upper ionosphere and magnetosphere extends from several hundred hertz to several hundred kilohertz [15, 16]. Certainly, this frequency range is not determined by the lightning discharge duration and strongly depends on the problem geometry and dispersive characteristics of the medium.

The problem of defining the spectrum width of excited radiation can be qualitatively solved in the following way. In Earth's atmosphere, radiation propagates up to the lower boundary of the ionosphere at a speed close to the speed of light, but its speed becomes significantly lower in the ionosphere, where the refractive index rapidly increases.

It is clear that after the lightning discharge ends, by the time of the 'last' horizontally propagating beam reaches the lower boundary of the ionosphere, all the emission of the lightning discharge will be concentrated there. Since the lower ionosphere height $h$ is significantly smaller than Earth's radius $R_{\mathrm{E}}$, the vertical dimension $l_{\mathrm{n}}$ of the region occupied by radiation is much smaller than its horizontal dimension. Therefore, if we expand the ionosphere disturbance into the Fourier integral, the dominant components will be the ones with the wave vectors directed almost vertically and their characteristic values are $k_{\mathrm{n}} \gtrsim 1/l_{\mathrm{n}}$. The frequency band of the radiation can now be defined as that corresponding to a frequency band $\omega(k_{\mathrm{n}})$, where $\omega = \omega(\mathbf{k})$ is the dispersion relation in the ionosphere.

Experiment and calculations confirm that waves excited by lightning discharges correspond to ion-cyclotron and whistler modes [17, 18]. Further in this section we will discuss the whistler waves in the magnetosphere. The role of ion-cyclotron waves in the ionosphere–magnetosphere connection was discussed in paper [3]. At the 'initial moment', the electromagnetic field disturbance in the upper ionosphere, caused by lightning discharge, can be represented as wave packets (with the characteristic wave vectors, mentioned above) that are localized in the region with dimensions which are much smaller than Earth's radius. Obviously, this disturbance has a broad spatial spectrum. However, far enough away from this region and, correspondingly, after a long time the radiation can be represented as the wave packet with a slowly varying frequency and a wave vector, which occur at a specific instant of time at a given point.

### 2.2 Resonant interaction of whistler waves with charged particles in the magnetosphere

As the calculated results show [19], in the absence of ducts (density perturbations that are localized near the geomagnetic field line of force and can be a kind of a waveguide for whistler waves), in the near-equatorial region, where the electron–wave interaction is most effective, the whistler wave enters the quasiresonant propagation regime in which the angle $\theta$ between the wave vector and the external magnetic field is close to the resonant cone angle: $\cos\theta \simeq \omega/\omega_{\mathrm{ce}}$ (in the standard notation). In this case, the refractive index $N = kc/\omega$ of the wave greatly increases and the wave becomes quasielectrostatic, with its electric field directed almost along the wave vector and the magnetic field $B \ll NE$ (in the CGS system of units). After the wave reaches the equator and during its propagation in the hemisphere, opposite to that of lightning discharge, the wave refractive index continues to increase, which makes it possible for the wave to resonantly interact with protons at high cyclotron resonances. The quasi-electrostatic wave is linearly polarized, which allows us to consider its resonant interaction with electrons and protons in the same way. (Clearly, the interaction specifics, mostly related to the different ratio between the wave frequency and the particle gyrofrequency, remain in force).

The field of the quasielectrostatic wave packet can be written out in the form

$$\mathbf{E}(\mathbf{r}, t) = -\nabla\Phi(\mathbf{r}, t)\,, \quad \Phi(\mathbf{r}, t) = \Phi_0(\mathbf{r}, t)\sin\Psi(\mathbf{r}, t)\,, \qquad (1)$$

while the local wave vector $\mathbf{k}(\mathbf{r}, t)$ and the local frequency $\omega(\mathbf{r}, t)$ are defined by the relations

$$\mathbf{k}(\mathbf{r}, t) = \frac{\partial\Psi}{\partial\mathbf{r}}\,, \quad \omega(\mathbf{r}, t) = -\frac{\partial\Psi}{\partial t}\,.$$

Due to the azimuthal symmetry of the problem and vertical direction of the initial wave vectors, the waves propagate in the meridional plane, and the equations of particle motion have a first integral $x_0$, which is a transverse (relative to the external magnetic field) coordinate of the particle's guiding center in the meridional plane. At the same time, the equations of particle motion can be written down in the Hamiltonian form with canonical variables: $(p_{\parallel}, z)$ — longitudinal momentum and longitudinal coordinate, and $(\mu, \varphi)$, where $\varphi$ is the particle gyrophase, and $\mu$ is its magnetic moment

$$\mu = \frac{mv_\perp^2}{2\Omega}\,.$$

Here, $m$ is the particle's mass ($m = m_e$ for electrons, and $m = m_i$ for protons), and $\Omega = eB_0/mc$ is the absolute value of the gyrofrequency for the appropriate type of a particle. The transverse coordinate of the particle can be expressed through the canonical variables mentioned above in the following way:

$$x = x_0 + \frac{v_\perp}{\Omega}\sin\varphi \equiv x_0 + \sqrt{\frac{2\mu}{m\Omega}}\sin\varphi\,,$$

and the Hamiltonian takes the form

$$H(p_\parallel, z, \mu, \varphi, t) = \frac{p_\parallel^2}{2m} + \mu\,\Omega(z) + q\Phi(z, \mu, \varphi, t)\,, \tag{2}$$

where $q = e$ and $q = -e$ for protons and electrons, respectively. Under the condition that the gyroradius of the particle be much less than the inhomogeneity scale, the phase of the field is defined by the following expression

$$\Psi = \Psi_0(z, t) + k_\perp(x - x_0) \equiv \Psi_0(z, t) + \lambda\sin\varphi\,,$$

where $\lambda$ is the dimensionless Larmor radius:

$$\lambda = \frac{k_\perp v_\perp}{\Omega} \equiv k_\perp\sqrt{\frac{2\mu}{m\Omega}}\,.$$

At the same time, the local longitudinal wave vector and the local frequency are determined from the relations

$$k_\parallel \simeq \frac{\partial\Psi_0}{\partial z}\,, \quad \omega \simeq -\frac{\partial\Psi_0}{\partial t}\,.$$

The Hamiltonian expansion into the Fourier series in terms of $\varphi$ in the new variables assumes the form

$$H(p_\parallel, z, \mu, \varphi, t) = \frac{p_\parallel^2}{2m} + \mu\,\Omega(z) + q\Phi_0(z, t)\sum_n J_n(\lambda)\,\sin\big(\Psi_0(z, t) + n\varphi\big)\,, \tag{3}$$

where $J_n$ are the Bessel functions of the $n$th order.

By setting the full derivative of $\Psi_0(z, t) + n\varphi$ equal to zero along the particle trajectory, we can find the condition of resonant wave–particle interaction:

$$k_\parallel(z, t)\,v_\parallel - \omega(z, t) + n\Omega(z) = 0\,,$$

$$\text{or}\quad v_\parallel = v_{\mathrm{res}\,n} \equiv \frac{\omega - n\Omega}{k_\parallel}\,, \tag{4}$$

where it is taken into account that, according to formula (3), $\mathrm{d}\varphi/\mathrm{d}t \simeq \Omega$.

**2.2.1 Isolated resonance approximation.** It is known that the variation of both the energy and the equatorial pitch-angle and, correspondingly, the significance of the pitch-angle scattering are the highest for those resonant particles which fulfill condition (4) for some integer number $n$ giving the order of cyclotron resonance. In a homogeneous medium, the particles can be either resonant or nonresonant, depending on their longitudinal velocity. For the considered case of the particle — wave packet interaction with varying parameters in an inhomogeneous medium, resonant conditions (4) change along the trajectory of the particle, as well as its longitudinal velocity changes. Therefore, in the situation considered the particle passes a cyclotron resonance region. In the approximation of isolated resonances, which can always be applied to the whistler wave amplitudes [20], only one slowly varying term can be kept in Hamiltonian (3), thus yielding the following form of the Hamiltonian:

$$H_n(p_\parallel, z, \mu, \varphi, t) = \frac{p_\parallel^2}{2m} + \mu\Omega(z) + q\Phi_0(z, t)\,J_n(\lambda)\sin\big(\Psi_0(z, t) + n\varphi\big)\,. \tag{5}$$

The equations for the variation of the kinetic energy and the magnetic moment of the particle will have the following form in this approximation:

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \frac{\omega}{n}\frac{\mathrm{d}\mu}{\mathrm{d}t} = -q\Phi_0\omega J_n(\lambda)\,\cos\big(\Psi_0(z, t) + n\varphi\big)\,, \tag{6}$$

and the variations in these quantities (and, correspondingly, of the equatorial pitch-angle) during the passage through isolated cyclotron resonances will be noncorrelated.

**2.2.2 Variation of the equatorial pitch-angle and the precipitation of particles into the ionosphere.** As follows from formulas (4), the spacing between the resonant values of the longitudinal velocity is $\Omega/k_\parallel$. For electrons, this quantity is usually higher or close to the thermal velocity of high-energy particle distribution. Therefore, the most important resonances for electrons are the first cyclotron ($n = 1$) and the Cherenkov ($n = 0$) ones. Since the longitudinal velocities corresponding to these resonances have opposite signs, the electrons, while moving in one direction (during half of the bounce period), can resonantly interact with the wave packet when passing through only one specific resonance. As for the protons, the spacing between the resonant values of the longitudinal velocity is $m_e/m_i$ times that for the electrons. Therefore, the protons during the half of the bounce period can interact with the wave-packet through many different cyclotron resonances.

As the analysis indicates, most of the particles — electrons and protons — are phase untrapped and the time of their interaction with the wave packet at a single resonance is determined by the generalized inhomogeneity parameter

$$\alpha_n = k_\parallel\left(\frac{\mu}{m}\frac{\mathrm{d}\omega_c}{\mathrm{d}z} + \frac{1}{2}\frac{\mathrm{d}v_{\mathrm{res}\,n}^2}{\mathrm{d}z}\right)\,, \tag{7}$$

and is on the order of $1/\sqrt{|\alpha|}$. In this case, it follows from equation (6) that for particles near the loss-cone boundary the variation of the equatorial pitch-angle $\vartheta$, while passing through the cyclotron resonance, is of order

$$|\delta\vartheta| \sim \left|\frac{q\Phi_0\omega J_n(\lambda)}{W\sqrt{|\alpha|}}\right|\,. \tag{8}$$

Expression (8) gives an estimate of the variation of the electron equatorial pitch-angle during half of their oscillation bounce period between the reflection points in opposite hemispheres. As for the protons, it was mentioned above that during half of their bounce period they can pass through many cyclotron resonances, $\Delta n \sim \omega/\Omega_{\min} \gg 1$, where $\Omega_{\min}$ is the minimum value of the proton gyrofrequency along the line of force, for which the resonant interaction with the whistler wave becomes efficient. The value of $\Omega_{\min}$ can be indirectly determined by the relations [20]

$$k_\perp(z)\, v_\perp \gtrsim \omega\,, \quad \Omega_{\min} = \Omega(z)\,.$$

The transverse wave vector $k_\perp$ and the gyrofrequency $\Omega(z)$ in the quasiresonant propagation regime increase together as the distance from the equator increases. Therefore, the relations given define the minimal gyrofrequency and, consequently, the maximum number of the resonance $n_{\max}$, for which the interaction of protons with the whistler waves is effective. The minimum number of the cyclotron resonance $n_{\min}$, obviously, can be determined from the relation $n_{\min} \sim \omega/\Omega_{\max}$, where $\Omega_{\max}$ is the maximum gyrofrequency of the protons along the force line, where the wave packet is situated. As was mentioned above, the variations of the equatorial pitch angle while passing through the single cyclotron resonances are noncorrelated. Therefore, the net change of the angle, which can be either positive or negative, is of the order of

$$|\Delta\vartheta| \sim \sqrt{\Delta n}\,|\delta\vartheta|\,,$$

where $|\delta\vartheta|$ is defined in expression (8), and $\Delta n = n_{\max} - n_{\min}$. This means that the particles, for which the value $\Delta\vartheta$ is negative and the initial equatorial pitch-angle differs from the loss-cone pitch-angle by a value less than $|\Delta\vartheta|$, fall into the loss cone and precipitate into the ionosphere.

## 3. Active experiments

A new line of research in the field of ionosphere–magnetosphere plasma was developed in the 1960s and was based on so-called active experiments (AEs). This line of research combined the efforts of specialists in plasma physics, radio physics, and geophysics, which helped to significantly improve our knowledge about the natural processes in the circumterresrrial plasma and also revealed a number of phenomena caused by the external influence on the magnetosphere–ionosphere system.

The results of the AEs led to discussions about the emergence of a space lab, where plasma and wave processes would be studied [1, 21, 22]. The most productive AEs were those on the influence of strong electromagnetic radiation from ground sources on the ionosphere–magnetosphere plasma. The theoretical aspects of such interaction were discussed in detail earlier in a number of papers, particularly in reviews [23, 24]. Papers [4–11] present reviews of investigations related to the influence of strong high-frequency (HF) radiation (2–12 MHz) on the ionosphere. The results of investigations concerning low-frequency (LF) radiation influence on the magnetosphere–ionosphere system are presented in monograph [12]. In Sections 3.1 and 3.2, we discuss the results of experiments which are based on direct measurements of the plasma and electromagnetic radiation parameters on board spacecraft.

### 3.1 Stimulated precipitation of charged particles under the action of artificial low-frequency radiation

Pitch-angle diffusion and the precipitation of charged particles from the magnetosphere to the ionosphere under the action of natural radiation is observed quite often on satellites [25]. The first measurements of artificially stimulated precipitations were performed in an experiment with the strong LF-emitter UPD-8, operating at the 12 kHz frequency. The precipitation was registered by a modulation photometer installed aboard an airplane and directed towards the ionosphere above the emitter [27]. As the emitter was turned on, an increase in the luminosity of the night sky of $\approx 40$ Rl was observed at the wavelength $\lambda = 3.914 \times 10^{-7}$ m. This is the line of excited nitrogen, and therefore its intensity is proportional to the precipitating particle flux density. Estimations of the total energy flux give the value of 0.13 erg $cm^{-2}$ $s^{-1}$, which corresponds to an electron flux of $5 \times 10^6$ $cm^{-2}$ $s^{-1}$ with an energy of 15 keV.

Direct measurements of stimulated precipitations were performed on the satellite *Arkad-3* together with the LF-emitter UPD-8 [28], which was a source of an amplitude-modulated signal at the 15 kHz frequency. As the satellite passed at the altitude of 1500 – 2000 km above the emitter, fluxes of electrons with energies of 0.6–2 keV increased from $5 \times 10^3$ $cm^{-2}$ $s^{-1}$ (noise level in this experiment) to $2.5 \times 10^4$ $cm^{-2}$ $s^{-1}$.

A similar experiment was performed in the USA on the S81-1 satellite as it passed over an NAA (National Aeronautic Association) emitter [29]. During the experiment, an increase in the electron flux intensity was detected at energies of $E > 6$ keV up to the value of $10^3$ $cm^{-2}$ $s^{-1}$. It should be noted that the NAA emitter is located at mid-latitudes ($L = 3.2$), and the UPD-8 is located more to the north at subauroral ($L = 4.0$) latitudes. The difference in the flux intensities of the precipitating electrons can be explained not only by different geomagnetic conditions but also by the difference in the trapped particle density at different latitudes. Subsequent measurements on the *DEMETER* (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) satellite confirmed these results [30].

The first measurements of precipitating proton fluxes stimulated by artificial low-frequency radiation were performed on the *Arkad-3* satellite. Figure 1 shows the results of these measurements.

The intensity of proton fluxes with an energy of 110 keV becomes 2.5 times higher for optimal observation condi-

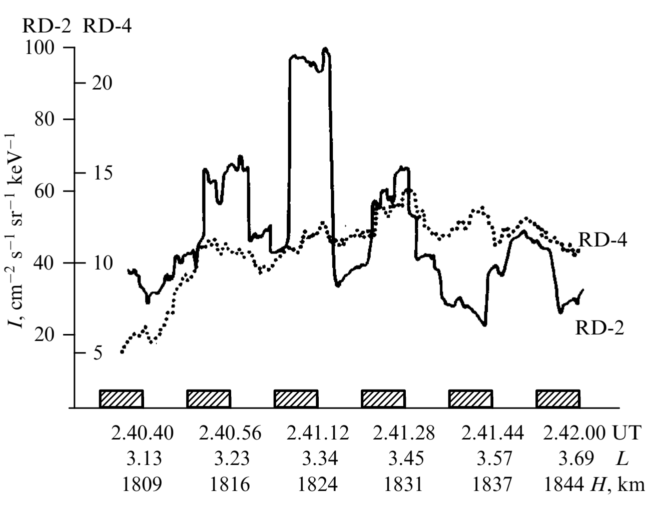


**Figure 1.** Intensity variation of proton fluxes with energies of $\approx 110$ keV (curve RD-2) and $\approx 190$ keV (curve RD-4) as the *Arkad-3* satellite passed over the UPD-8 emitter (taken from Ref. [31]). The time intervals when the emitter was operating are marked by rectangles.

tions — magnetic coupling with the ionosphere above the emitter. In this case, the fluxes of protons with higher energy (190 keV) change insignificantly around the noise level. It should be noted that in different measurement series the stimulated flux intensity of the precipitating protons varied from 80 to 500 $cm^{-2} s^{-1}$, depending on the geomagnetic activity, which may be related to the density of the trapped particles.

Summing up, measurements of the particle fluxes as the satellite passed over the low-frequency ground emitter resulted in:

— precipitating electron fluxes with an intensity of $\approx 10^3 - 10^4$ $cm^{-2} s^{-1}$;

— precipitating proton fluxes with an energy of $\approx 110$ keV. The intensity of the proton fluxes was 80 – 500 $cm^{-2} s^{-1}$.

The mechanism of the proton precipitation under the action of the signal from a very low-frequency (VLF) emitter, suggested in paper [20], is similar to the mechanism of proton precipitation stimulated by lightning discharge radiation, which was discussed in Section 2.

### 3.2 Formation of inhomogeneities stretched along the magnetic field due to low-frequency heating

It was shown in paper [32] that a significant amount of the energy of electromagnetic waves from the low-frequency band goes into the local heating of the ionosphere. During the daytime hours in the summer, these losses can reach 90%. Therefore, the radiation from powerful ground LF-emitters influences the ionosphere in a similar way as the HF-heating facilities [4–11].

Experimental investigations of ionosphere heating under the action of artificial LF-radiation were performed on the *Arkad-3* satellite [33]. Figure 2 depicts the measurement results for the fluxes of three different cold ionosphere ions and for the electromagnetic field when passing over the LF-emitter.

The fluxes of the upgoing ions are maximal when the intensity of the emitted electromagnetic field is maximal (at 15 kHz frequency). The change in the radiation intensity at the frequency of 4.5 kHz (in the vicinity of the local frequency for the lower hybrid resonance (LHR)) indicates the ion heating mechanism is related to LHR-radiation, which is confirmed by the theoretical predictions in monograph [12].

The heating of the ionosphere plasma under the action of HF-radiation leads to particle transport from the ionosphere to the magnetosphere and to the formation of ducts — plasma inhomogeneities stretched along the magnetic field [34, 35]. In a similar way, the ducts can be formed during LF-heating [36, 37].

We should note that some of the problems concerning the duct formation under the action of strong radio emission are still unsolved. Particularly, there is still no theoretical explanation for the fast process of ionosphere plasma reaching heights of several Earth radii [38].

Summing up, the plasma inhomogeneities stretched along the magnetic field can be formed above the low-frequency emitters in two ways:

— as a result of ionosphere plasma heating by LF-radiation;

— as a result of the stimulated precipitation of high-energy particles and the formation of the region with an enhanced ionization.

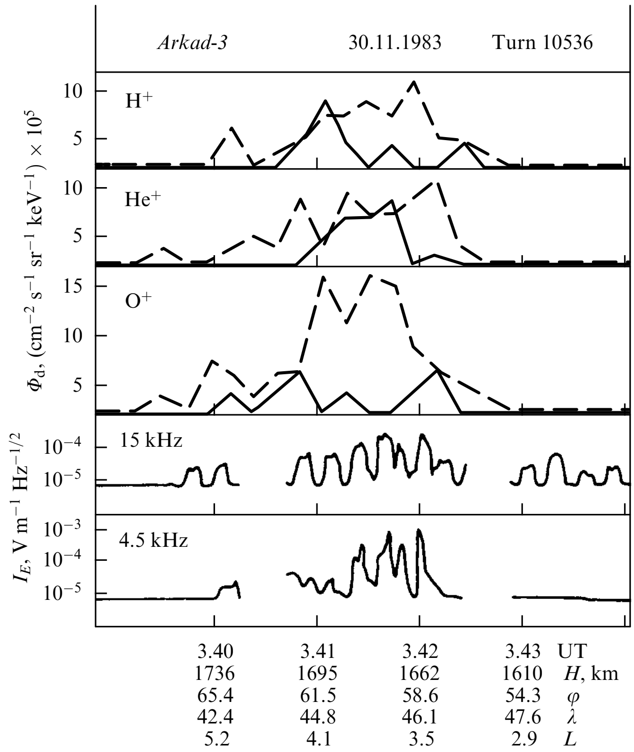


**Figure 2.** Differential fluxes $\Phi_d$ of the hydrogen, helium, and oxygen ions (three upper plots) and the intensity $I_E$ of electromagnetic radiation at 15 and 4.5 kHz frequencies (two lower plots), measured on the *Arkad-3* satellite as it passed over an LF-emitter (taken from Ref. [33]). Solid and dashed lines correspond to two directions of measuring the ion arrival.

The first mechanism is most effective during the daytime in the summer, while the second one is best during the nighttime in winter.

## 4. Conclusions

Theoretical investigations, as well as ground and aboard spacecraft measurements of ionosphere–magnetosphere system parameters have allowed us to obtain an almost complete picture of the dynamical processes in the circumterrestrial plasma. However, a number of key questions remain unanswered: the mechanism of ionosphere ion heating under the action of HF-radiation is not fully understood, the characteristics of ionosphere ion transport to great altitudes are unknown, etc. The Rezonans space project should give answers to these and other relevant questions [38].

In the Rezonans mission, two pairs of satellites will be launched into specially selected orbits, which will allow performing long (up to tens of minutes) measurements of the plasma and electromagnetic field parameters in the chosen magnetic field tube, which has its footprint in the ionosphere above the radiation source. Such an experimental configuration will allow us to investigate the dynamics of processes caused by artificial electromagnetic radiation.

Many results discussed in this paper were obtained by the IZMIRAN researchers, and this Institute is celebrating 75 years since its foundation this year.

This study was partially supported by Program 22 of the Presidium of the Russian Academy of Sciences, and by an RFBR grant (15-35-20364).

## References


1. Artsimovich L A, Sagdeev R Z *Fizika Plazmy dlya Fizikov* (Plasma Physics for Physicists) (Moscow: Atomizdat, 1979)
2. Lauben D S, Inan U S, Bell T F *J. Geophys. Res.* **106** 29745 (2001)
3. Shklyar D R, Kuzichev I V *Geophys. Res. Lett.* **41** 201 (2014)
4. Gurevich A V *Phys. Usp.* **50** 1091 (2007); *Usp. Fiz. Nauk* **177** 1145 (2007)
5. Frolov V L et al. *Phys. Usp.* **50** 315 (2007); *Usp. Fiz. Nauk* **177** 330 (2007)
6. Gurevich A V *Sov. Phys. Usp.* **17** 613 (1975); *Usp. Fiz. Nauk* **113** 728 (1974)
7. Shlyuger I S *Sov. Phys. Usp.* **17** 613 (1975); *Usp. Fiz. Nauk* **113** 729 (1974)
8. Vas'kov V V, Gurevich A V *Sov. Phys. Usp.* **17** 614 (1975); *Usp. Fiz. Nauk* **113** 730 (1974)
9. Belikovich V V et al. *Sov. Phys. Usp.* **17** 615 (1975); *Usp. Fiz. Nauk* **113** 732 (1974)
10. Grach S M et al. *Sov. Phys. Usp.* **17** 616 (1975); *Usp. Fiz. Nauk* **113** 734 (1974)
11. Shvartsburg A B *Sov. Phys. Usp.* **17** 617 (1975); *Usp. Fiz. Nauk* **113** 735 (1974)
12. Molchanov O A *Nizkochastotnye Volny i Indutsirovannye Izlucheniya v Okolozemnoi Plazme* (Low-Frequency Waves and Induced Radiation in Near-Earth Plasma) (Moscow: Nauka, 1985)
13. Christian H J et al. *J. Geophys. Res.* **108** 4005 (2003)
14. Collier A B et al. *J. Geophys. Res.* **116** A03219 (2011)
15. Al'pert Ya L *Usp. Fiz. Nauk* **60** 369 (1956)
16. Al'pert Ya L *Sov. Phys. Usp.* **9** 787 (1967); *Usp. Fiz. Nauk* **90** 405 (1966)
17. Colman J J, Starks M J *J. Geophys. Res.* **118** 4471 (2013)
18. Parrot M et al. *J. Geophys. Res.* **113** A11321 (2008)
19. Alekhin Yu K, Shklyar D R *Geomagn. Aeronomiya* **20** 501 (1980)
20. Shklyar D R *Planet. Space Sci.* **34** 1091 (1986)
21. Genkin L G, Erukhimov L M *Phys. Rep.* **186** 97 (1990)
22. Markov G A, Belov A S *Phys. Usp.* **53** 703 (2010); *Usp. Fiz. Nauk* **180** 735 (2010)
23. Ginzburg V L, Gurevich A V *Sov. Phys. Usp.* **3** 115 (1960); *Usp. Fiz. Nauk* **70** 201 (1960)
24. Ginzburg V L, Gurevich A V *Sov. Phys. Usp.* **3** 175 (1960); *Usp. Fiz. Nauk* **70** 393 (1960)
25. Rosenberg T J, Helliwell R A, Katsufrakis J P *J. Geophys. Res.* **76** 8445 (1971)
26. Zhulin I A et al. *Sov. Phys. Dokl.* **21** 579 (1976); *Dokl. Akad. Nauk SSSR* **230** 1073 (1976)
27. Lyakhov S B, Managadze G G *Prib. Tekh. Eksp.* (3) 200 (1975)
28. Kovrazhkin R A et al. *JETP Lett.* **38** 397 (1983); *Pis'ma Zh. Eksp. Teor. Fiz.* **38** 332 (1983)
29. Imhof W L et al. *Geophys. Res. Lett.* **10** 361 (1983)
30. Sauvaud J-A et al. *Geophys. Res. Lett.* **35** L09101 (2008)
31. Kovrazhkin R A et al. *JETP Lett.* **39** 228 (1984); *Pis'ma Zh. Eksp. Teor. Fiz.* **39** 193 (1984)
32. Aksenov V I et al. *Radiophys. Quantum Electron.* **18** 985 (1975); *Izv. Vyssh. Ucheb. Zaved. Radiofiz.* **18** 1333 (1975)
33. Dzhordzhio N V et al. *JETP Lett.* **46** 405 (1987); *Pis'ma Zh. Eksp. Teor. Fiz.* **46** 322 (1987)
34. Frolov V L et al. *JETP Lett.* **88** 790 (2008); *Pis'ma Zh. Eksp. Teor. Fiz.* **88** 908 (2008)
35. Milikh G M et al. *Geophys. Res. Lett.* **35** L17104 (2008)
36. Milikh G M et al. *Geophys. Res. Lett.* **37** L07803 (2010)
37. Mogilevsky M M et al. *Cosmic Res.* **52** 68 (2014); *Kosmich. Issled.* **52** (1) 71 (2014)
38. Mogilevsky M M et al., in *Dynamics of the Earth's Radiation Belts and Inner Magnetosphere* (Geophysical Monograph, Vol. 199, Eds D Summers et al.) (Washington, DC: American Geophysical Union, 2012) p. 117

*CONFERENCES AND SYMPOSIA*

PACS numbers: 94.05.Sd, **94.20.** – **y**, **94.30.** – **d**

*75th ANNIVERSARY OF IZMIRAN*

# Magnetic and optical measurements and signatures of reconnection in the cusp and vicinity

V V Safargaleev, T I Sergienko, A V Safargaleev, A L Kotikov

DOI: 10.3367/UFNe.0185.201506j.0655

## Contents



**Abstract.** **The study of geophysical processes in the cusp and its nearby magnetospheric regions — the mantle and the low-latitude boundary layer — is a crucial link in the chain of understanding the mechanism of the solar-terrestrial relationship. The magnetic conjugation of these regions with the high-latitude ionosphere permits the study of the solar wind-dayside magnetopause interaction via ground-observed ionospheric phenomena. The major topics covered are the dayside aurora in Spitsbergen and the Alfvén waves detected by an induction magnetometer as high-latitude geomagnetic Pc1 pulsations. The results presented establish a relation between the aurora and pulsation dynamics and the reconnection phenomenon which occurs at negative IMF $B_z$ values and which is commonly accepted to be the most likely way for solar wind energy to penetrate into the inner magnetosphere. The results also suggest that the Spitsbergen optical and magnetic measurements provide an opportunity for the world scientific community to solve the major space weather problem of monitoring the replenishment of the energy expended in the course of magnetospheric substorms.**

**V V Safargaleev** Polar Geophysical Institute, Kola Scientific Center, Russian Academy of Sciences,
ul. Fersmana 14, 184209 Apatity, Murmansk region, Russian Federation
E-mail: Vladimir.Safargaleev@pgia.ru
**T I Sergienko** Swedish Institute of Space Physics,
Box 812, SE-98128 Kiruna, Sweden
**A V Safargaleev** Physical Faculty, St. Petersburg State University,
Universitetskaya nab. 7/9, 199034 St. Petersburg, Russian Federation
**A L Kotikov** Physical Faculty, St. Petersburg State University,
Universitetskaya nab. 7/9, 199034 St. Petersburg, Russian Federation;
N V Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (St. Petersburg Branch),
Universitetskaya nab. 5, lit. B, 199034 St. Petersburg, Russian Federation

Received 14 April 2015
*Uspekhi Fizicheskikh Nauk* **185** (6) 655 – 663 (2015)
DOI: 10.3367/UFNr.0185.201506j.0655
Translated by M V Tsaplina; edited by A Radzig

**Keywords:** cusp, reconnection, dayside auroras, pulsation Pc1

## 1. Introduction

The key link in the formation of cosmic weather is the solar wind energy transfer to the inner magnetosphere. Energy accumulation in the magnetosphere tail can stimulate the generation of magnetospheric substorms and promote their recurrence. Theorists believe that the dominant means of energy transfer through the magnetopause is the reconnection of the magnetopause-forming geomagnetic field lines and the interplanetary magnetic field (IMF) lines, when the $B_z$ component of IMF is negative (further — the South IMF). The reconnected field tubes are pulled away by the solar wind from the cusp through the polar cap to the night side and 'pile up' in portions of the magnetosphere tail, which leads to magnetic energy heightening in the night magnetosphere. The explosive release of this energy generates a magnetospheric substorm.

The geomagnetic field lines forming the magnetopause penetrate the ionosphere near cusps (approximately at 78° of geomagnetic latitude in the Northern hemisphere), thus providing a peculiar 'projection' of the processes proceeding on the magnetopause onto the dayside ionosphere of the arctic latitudes. 'Projection' is realized by charged particle and Alfvén wave propagation along the field lines, so that the auroras and geomagnetic pulsations observed in the vicinity of the cusp may be used for studying the reconnection mechanism.

The observation of auroras as a research instrument is more advantageous than other types of observations, because optical methods can be exploited to examine the structure and dynamics of the phenomenon in a large ionospheric region. The main shortcoming of optical observations lies in their dependence on the level of illumination and on weather conditions. Possibly for this reason, the 'practical' question of solar–terrestrial connection, namely, the question of what particular solar wind–magnetopause interaction process is reflected in dayside auroras has been poorly investigated.

The growing arsenal of observational means allows drawing on the results of other types of measurements (magnetic, radar, and satellite-based) for optical studies in the dayside sector of the high-latitude ionosphere. In particular, statistics show [1] that in day hours, the Spitsbergen archipelago 'passes' under the cusp and the projection of the adjacent magnetospheric formations — the mantle and the plasma low-latitude boundary layer (LLBL). The first question arising in the attempt to relate dayside auroras to processes in the magnetopause is in which magnetospheric domain their source lies. If auroras occur in the region of precipitations typical of the cusp or the mantle and drift towards the pole, then one can assert with high probability that their source lies on the newly reconnected field lines drifting towards the magnetosphere tail.

Analysis of the literature shows that regions of the cusp and its neighborhoods exhibit no direct correlation between auroras and precipitation areas; in near-midday hours, the detection of a weak glow is technically difficult, since the horizon is illuminated by the Sun, and because of frequent cloudiness the intervals accessible for observations are not numerous, even in the darkest season. Analyses of individual events [2–4] point to the possible relation of near-midday auroras and precipitations from these magnetosphere domains, but no reliable statistics have been obtained yet.

As distinct from aurora detection, Pc1 pulsation detection is not impeded by weather conditions, and the time series of continuous observations of such pulsations in Barentsburg (Spitsbergen archipelago) is over 15 years. However, in searching for the Pc1 source, one should bear in mind that waves of this frequency range generated in the magnetosphere can propagate from the place of their fall into the ionosphere through an ionospheric waveguide. To exclude from consideration waves whose source is not located near the magnetopause but in the depths of the magnetosphere, the data from an induction magnetometer in Barentsburg were analyzed together with the data from magnetometers in Scandinavia and on the Kola Peninsula.

The present paper is aimed at demonstrating through particular examples the capability of the measurement facility of Polar Geophysical Institute (PGI) in Spitsbergen to register optical and magnetic phenomena with sources located on open field lines, i.e., in the cusp or the mantle. The positions of cusp and mantle boundaries in the ionosphere were determined by the character of precipitating particles by DMSP (Defence Meteorological Satellite Program) satellites flying above the observation region. The character of ionospheric convection in the course of the investigated events indicates that the source is driven to the magnetosphere tail, which gave grounds to associate the observed phenomenon with reconnection.

## 2. Instrumentations and methods

We use here the data from aurora recording at the Barentsburg PGI geophysical observatory (denoted further as BAB) in the Spitsbergen archipelago by a digital 'all-sky' camera on a CCD (charge coupled device) matrix $540 \times 540$ pixels in size which was used to monitor auroral activity in November 2012. The auroras were detected in white light (WL) with a time resolution of 1 shot a second. To establish the auroral intrusion boundaries by the DMSP satellite data, the automatic algorithm proposed in Ref. [5] and realized for online work on the site http://sd-www.jhuapl.edu/Aurora/dataset_list.html was applied.

An important link in the joint analysis of data is the correct alignment of auroras to the regions of satellite measurements. This is done by projecting the satellite trajectory to the altitude of the lower edge of the auroras with an indication of the domain boundaries. An exact binding of auroras to geographical coordinates was done with reference to stars using the program package worked out for the Swedish project Auroral Large Imaging System (ALIS) (http://www.irf.se/~urban/avh/html/htmlthesis.html). To 'project' the satellite position to the aurora altitude, we applied the IGRF (International Geomagnetic Reference Field) model of a geomagnetic field. To determine the height of the spherical surface on which the satellite trajectory coincides with the position of the auroras, we estimated the altitude of the lower aurora edge relying on the calculations of the altitude profile of luminosity according to data on precipitating particles [6].

Alfvén type waves are related to ion-cyclotron waves, which are registered on Earth's surface as geomagnetic field variations in the Hertz range (Pc1 pulsations). In the BAB observatory, Pc1 pulsations are detected by an induction magnetometer operating at the sample rate of 40 Hz. For a visual representation of wave activity, dynamical spectra (sonograms) were constructed in the investigated range, which reflected the two-dimensional distribution of signal intensity in frequency–time coordinates. To exclude from consideration those waves whose source is not located near the magnetopause but is projected to the auroral or mid-latitude ionosphere, the data of the induction magnetometer in BAB were analyzed together with magnetometer data in Scandinavia (the Kilpisjarvi observatory — KIL) and on the Kola Peninsula (Lovozero observatory — LOZ).

The optical and magnetic measurements in BAB were supplemented with data from the radars EISCAT (European Incoherent Scatter Scientific Association) and SuperDARN (Super Dual Auroral Radar Network) on ionospheric convection, whose character is largely determined by the IMF. This complex approach to the analysis of the phenomenon allows diminishing the ambiguity about its interpretation [2], but then the number of events accessible for analysis turns out to be limited. Nevertheless, the results of the complex analysis of individual events may underlie further research. In Sections 3 and 4, we give several examples demonstrating the ability of optical and magnetic observations in Spitsbergen to investigate the processes on the magnetopause in application to cosmic weather problems.

## 3. Analysis of two flights of DMSP satellites within the camera field of vision in Barentsburg

### 3.1 Aurora response to interplanetary magnetic field variations

Figure 1 presents keograms characterizing aurora dynamics along the geomagnetic meridian on which a camera is

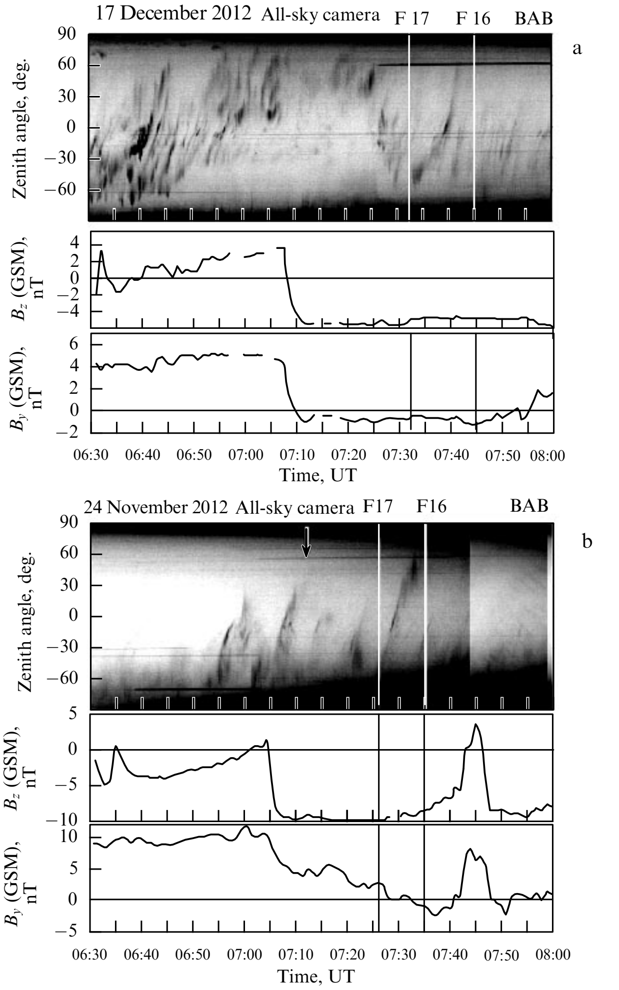


**Figure 1.** Response of auroras to variations of the interplanetary magnetic field. The vertical straight lines show the instants of satellite flights in the camera field of vision in Barentsburg, and the white arrow indicates the beginning of the equatorial auroral shift in the event of 24.11.2012. UT is a universal time.

installed, and also the variations of $B_z$ and $B_y$ components of the IMF in heliocentric solar–magnetic (Geliocentric Solar Magnetospheric, GSM) coordinates at the head point of a shock front. The situation in the interplanetary medium is characterized by the rise of the curve $B_z$ in the direction of positive values at the beginning of the intervals. In the middle of the intervals, $B_z$ begins to turn back towards high negative values, after which the $B_z$ component remains stably negative for some time in both the events considered. The negative $B_z$ component must theoretically shift the cusp southwards from its statistical position, and the cusp will find itself in the field of vision of the camera in BAB. Simultaneously with $B_z$, the $B_y$ component begins to decrease, and during the flights of DMSP satellites F16 and F17 over Barentsburg (see the vertical lines in Fig. 1) the $B_y$ component takes values close to zero. Together with the high negative $B_z$ values, this means the following: the IMF lines are collinear and opposite in direction to the geomagnetic field lines that form a near-midday magnetopause region, which theoretically favors reconnection.

In both events, the auroral activity has a form typical of dayside auroras displacing towards the pole (Poleward Moving Auroral Forms, PMAFs). In the event on 17 December 2012, the southward $B_z$ turn is accompanied by a clear shift of PMAF as a whole in the direction of the equator. The shift begins 10 min after $B_z$ changes sign from plus to minus. In the event on 24 November 2012, the starting point of the aurora response to a $B_z$ movement towards high negative values is not very pronounced, which can be caused by the absence in the prehistory of a long interval of aurora shifts to the pole against the background of positive $B_z$ values. According to the OMNI (Offender Management Network Information system) web-resource, the head point of the shock wave was, in this case, located two Earth radii closer to Earth than in the case considered above, and therefore the delay time of aurora's reaction to $B_z$ will be less than that in the event on 17 December. Judging by the aurora dynamics presented in Fig. 1b, one may believe that their shift towards the equator began at about 07:12 UT (this moment is marked by the white arrow in the keogram).

The occurrence and subsequent poleward drift of a single arc 10 to 15 min after the beginning of PMAF drift to the equator are common to both events. Not long before the occurrence of a single arc and several minutes after its disappearance, DMSP satellites flew through the camera field of vision (the vertical lines in Fig. 1). The spectrograms demonstrating the character of precipitations over Barentsburg are displayed in Fig. 2. One can see that, before the appearance of a single arc, in both cases the F17 satellite registered precipitations typical of the cusp. After the arc disappeared, according to F16 data the interface between the mantle and the low-latitude boundary layer (LLBL) was projected in the field of vision of the camera. A detailed joint analysis of the optical and satellite-based data is presented in the section that follows.

### 3.2 Rayed structures in the cusp region and their related precipitations

To compare the satellite-based and optical data, it is necessary to determine the altitude of auroras to which the satellite trajectory with marked magnetospheric domain boundaries will be further projected. This is normally done proceeding from *a priori* information, but in this case the satellite data made it possible to calculate the altitude luminosity profiles by the method applied in paper [6] and to use them for estimating the luminosity altitude at the time of satellite conjunction with the luminous region.

The data gathered by F17 in Fig. 2 show that in the event of 17.12.2012 the satellite was flying from 07:32:38 to 07:32:45 UT through precipitations typical of the cusp and immediately before crossing the boundary with LLBL detected a burst of electron precipitations. The lower edge of the aurora due to this burst was located at an altitude of 240 km. The result of matching the optical data to the projection of the satellite to this altitude is demonstrated in Fig. 3a. The solid line stands for the projection of the trajectory fragment on which the satellite registered the cusp precipitations. One can see that when the precipitations happened the satellite (the white circle in the trajectory) was conjugated with a weak rayed structure.

During the flight of satellite F17 in the event on 24 November 2012, the $B_z$ value was almost twice as large as that on 17 December, which resulted in a considerably larger shift from the zenith of the equatorial cusp edge, together with auroras. In a joint analysis of the optical and satellite data, we therefore encountered the difficulty of reliable identification

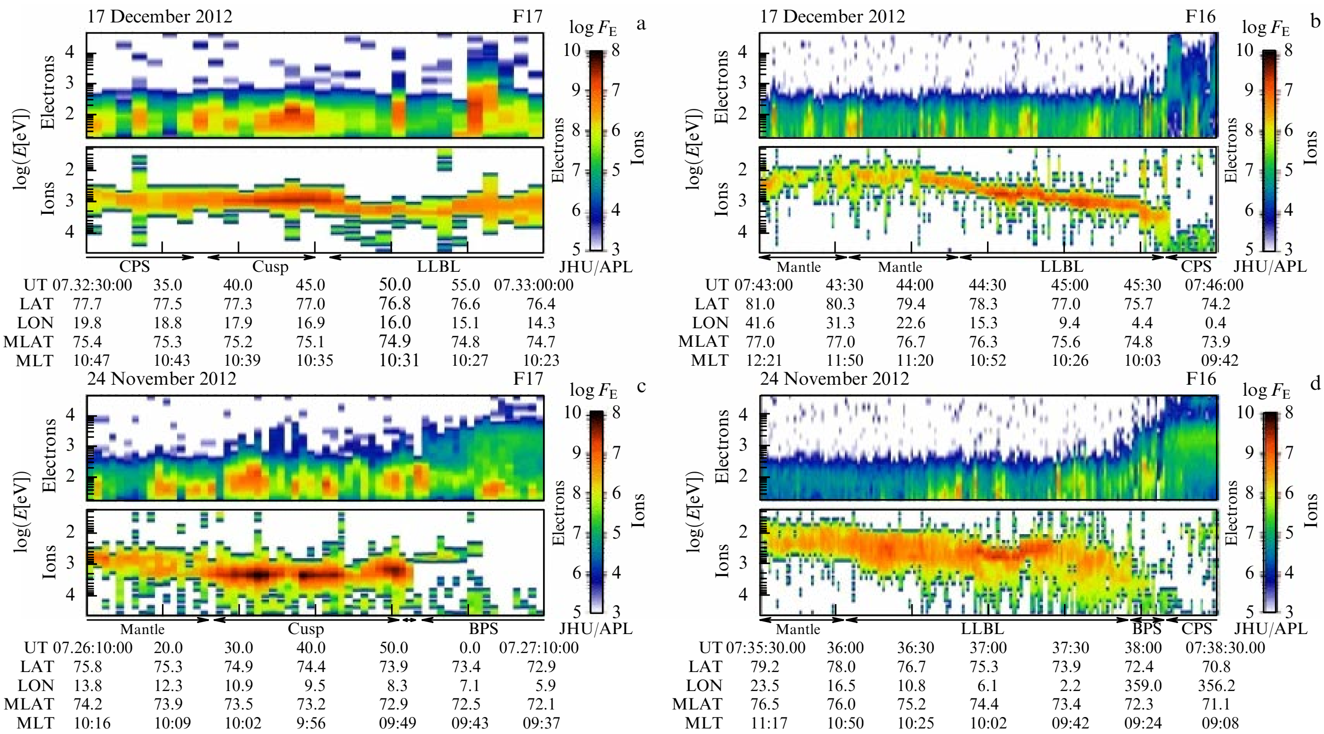


**Figure 2.** Distribution of the magnitude of the differential energy flux of the precipitating particles $F_E$ [eV (eV cm$^2$ s sr)$^{-1}$] along the satellite trajectories during their flight over the region of optical observations (according to the data on the site http://sd-www.jhuapl.edu/Aurora/spectrogram/index.html). CPS is the central plasma sheet, BPS is the boundary plasma sheet, LAT and LON are, respectively, the geographical latitude and longitude of the subsatellite point (satellite projections onto Earth's surface), MLAT is the magnetic latitude of the subsatellite point, MLT is magnetic local time, and JHU/APL is Johns Hopkins University (JHU) Applied Physics Laboratory (APL).

of the lower edge of weak auroras in the cusp against the background of intense rayed structures extended in altitude. This especially concerns the reproduction of auroras on paper media. The spectrogram in Fig. 2c shows that the satellite was flying through the cusp from 07:26:27 to 07:26:51 UT and, immediately after crossing the boundary with the mantle, i.e., at the pole boundary of the cusp, detected intense electron precipitations. The altitude of 255 km is determined as the lower edge of the aurora. The result of matching the optical data to the satellite projection onto this altitude is shown in Fig. 3b. The white line gives the portion of the trajectory in the region of cusp precipitations. One can see that the satellite is projected to the region 'shadowed' by the glow of one of the rays of the bright auroral form at the southwest edge of the camera field of vision.

An interesting feature of the precipitations associated with rayed structures in the cusp is the fact that, along with the electron precipitations, the flow of precipitating ions does not get weaker (Fig. 2a, c). A virtually complete ion 'locking' over the arcs was observed earlier [2]. This was explained by the presence above the arcs of the region of the accelerating potential, i.e., a double layer or an 'anomalous' resistance region. What has been said above suggests that the auroras observed in the cusp should be due to scattered rather than accelerated electrons.

In Section 3.3 we analyze the behavior of auroras, common to both events, after the flight of the F17 satellite through the cusp, namely, strengthening, poleward shift, and disappearance of the rayed arc. Special attention in the analysis is then paid to determining the rayed arc position relative to the magnetosphere domain boundaries.

### 3.3 Hypothetical position of rayed structures at the end of the drift

As can be seen in Fig. 1, the aurora dynamics immediately after the flight of the F17 satellite through the cusp developed similarly in both cases, namely, the single arc strengthened to the south of the zenith and then drifted toward the pole and faded. The beginning of the structure drift was preceded by the interval of a practically unchanged IMF, and so the position of ionospheric projections of magnetosphere domains found from the data of previous F17 flights could not have changed so drastically that the motion of the structure towards the pole might be associated with the poleward shift of the domain boundaries.

Owing to a favorable concourse of circumstances, the F16 satellite flew through the region of optical observations soon after the F17 satellite. The situation with precipitations at the time of the F16 flight differs from the one that took place ten minutes earlier during the F17 flight. The cusp precipitations were absent and the boundary between closed and open field lines that we define as the pole boundary of LLBL in the event of 17.12.2012, and as the equatorial boundary of the mantle in the event of 24.11.2012, shifted towards the pole. Hence, to estimate the position of the rayed structures at the end of their drift, we will take advantage of the data from the F16 satellite that give the position of precipitation boundaries $\approx 2$ min after the trail of the structures could no longer be identified on keograms.

Results of the alignment of arcs and the domain boundaries are presented in Fig. 4. Because of aurora weakness immediately before their disappearance, the frames refer to the instant of time when the structure was

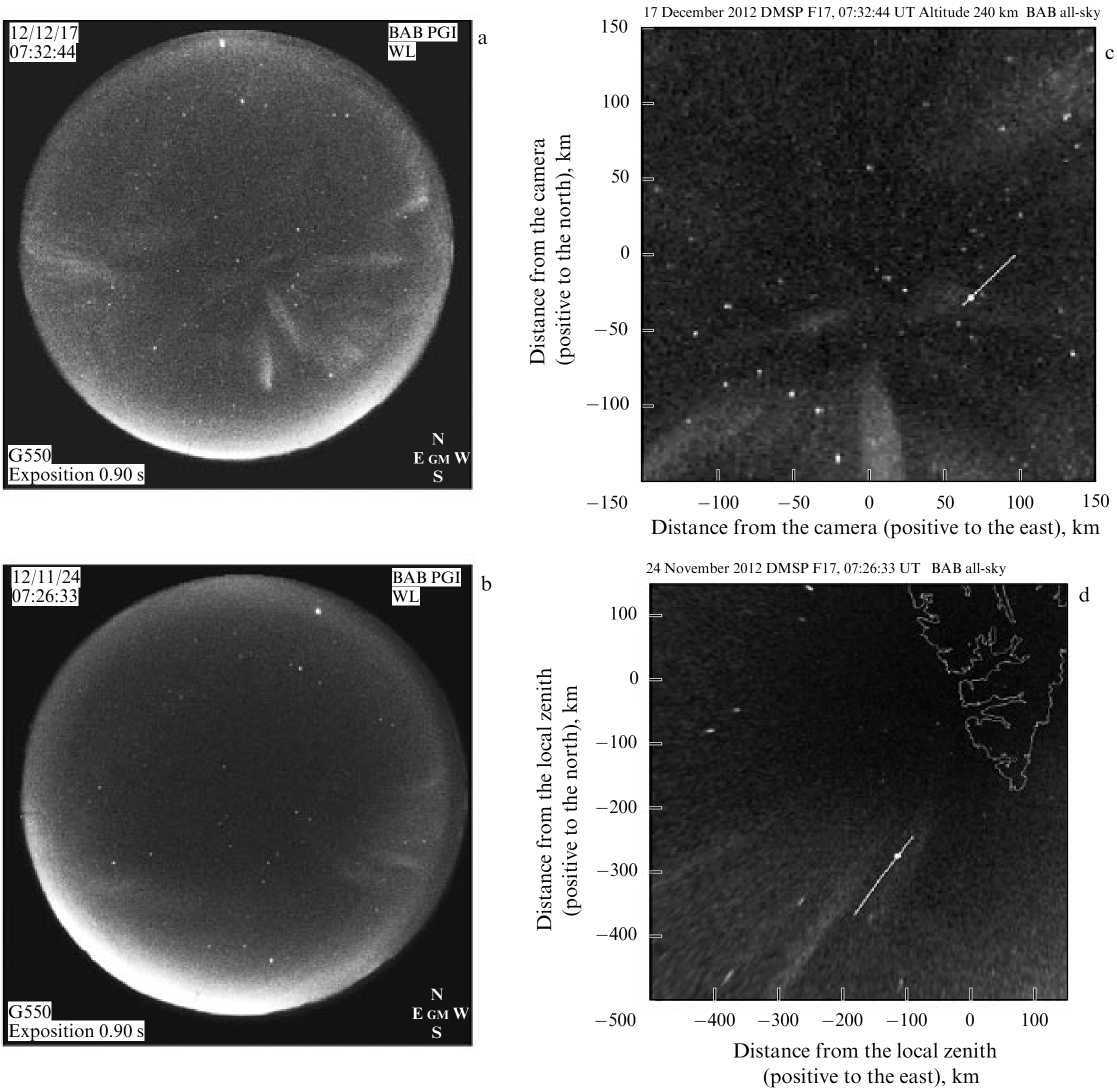


**Figure 3.** Original photos (a, b) taken by the G550 camera and their corresponding projections (c, d) onto the plane together with a part of the trajectory of the DMSP F17 satellite in the cusp. The white circle shows the satellite position at the instant of detection of precipitating particle flux strengthening.

still drifting, i.e., 3.5 min prior to the instant when the F16 satellite left the mantle precipitation region. The form of the drifting structure is identified more clearly in the event of 24.11.2012. To make the identification of the very weak arc in the event of 17.12.2012 easier, when combining the optical and satellite data, we had to resort to artificial accentuation ('dyeing') of four of its rays (Fig. 4b). The dashed line with the arrow in Fig. 4 points to parts of the F16 trajectory projected together with the auroras onto a plane whose altitude is assumed to be equal to 250 km (the lower edge of the aurora). Recall that in the photos taken by an 'all-sky' type objective the lower edge of the aurora in natural conditions corresponds to the far edge (from the frame center) of the luminescent region in the frame. The satellite position at the instant of time the equatorial boundary of the mantle is crossed is shown by the white circle. The white solid line passing through the satellite and oriented approximately along the geomagnetic latitude (parallel to the arcs) marks the assumed position of the boundary between closed and open field lines. Considering that the photos were taken 3.5 min before the satellite crossed the equatorial boundary of the mantle and the arc was moving towards the pole within these 3.5 min, it may be assumed that in both events the source of the drifting auroras was located in the open field lines. In Section 3.4, we shall discuss possible versions of the interpretation of the result obtained.

### 3.4 Generalization of the results of optical observations

We have analyzed two cases of aurora observations in the vicinity of the dayside cusp together with the data of DMSP satellites F17 and F16 that flew one after another through the camera field of vision in Barentsburg with an interval of about 10 min. Keograms show that the auroral activity in both events developed by analogous scenarios, because the character of IMF variation was also similar. The movement of the $B_z$ component towards negative values was accompanied by a reconstruction of the dayside part of the magnetosphere, as a result of which the cusp appeared to be in the zenith of the Barentsburg observatory.

We have shown that the weak bursts of electron precipitation registered by the satellite inside the cusp precipitation correspond to the weak 'red' rayed structures which were located near the pole and equatorial cusp boundaries and were generated by scattered rather than accelerated electrons.

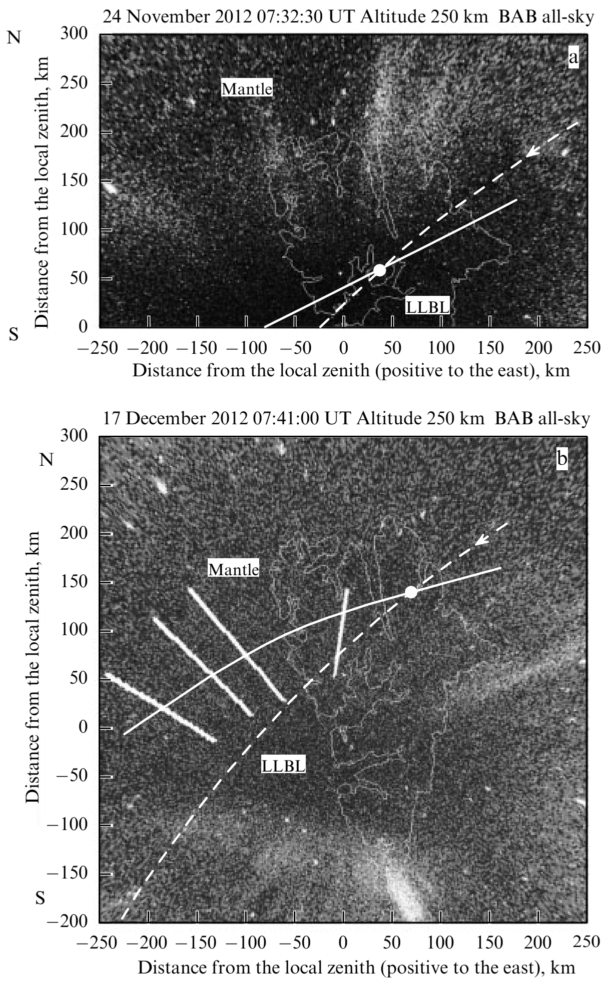


**Figure 4.** Drifting arc position relative to the boundary between closed and open field lines by DMSP data from F16 on 24 November 2012 (a) and 17 December 2012 (b). The dashed line is a part of the trajectory, the solid line is the geomagnetic latitude where the boundary passes between the mantle and the low-latitude boundary layer; the weak arc rays in Fig. b are accented by white lines.

Another element of similarity of auroral activity is a notable poleward shift of the rayed arc which began almost immediately after the flight of the first satellite (F17) and ended several minutes before the flight of the second one (F16). According to the data from F16, the source of the drifting arcs is located in the region of open field lines, for which reason the reconnection of IMF lines of force with geomagnetic lines of force is assumed to be the most probable mechanism of the observed phenomenon. According to the data from the F16 satellite, the character of ionic precipitations (Fig. 2b, d) testifies in favor of this hypothesis. The precipitations have a pronounced dispersive form when the particle energy increases with satellite motion from high to lower latitudes, which is traditionally associated with a satellite's crossing the tubes drifting in the antisolar direction.

Of particular interest are the dispersion structures observed in the intervals of 07:44:05 to 07:44:35 UT (17 December 2012) and 07:35:55 to 07:36:26 UT (24 November 2012). The structures cross the mantle/LLBL boundary, and in view of what has been said above they can be associated with the field tubes penetrating the mantle from the low-latitude boundary plasma sheet.

## 4. High-latitude geomagnetic Pc1 pulsations as a signature of reconnection

Pc1-range (0.1–2 Hz) geomagnetic pulsations are customarily associated with Alfvén type waves generated due to the development of ion-cyclotron instability of anisotropic plasma. Their main peculiarity is 'attachment' to the geomagnetic field lines, which essentially permits an observer on Earth to find the position of the source of pulsations in the magnetosphere (under the condition that the detected pulsations have not come to the observer through an ionospheric waveguide).

From the point of view of the formulated problem, high-latitude Pc1 pulsations are of a particular interest. For example, the authors of paper [7] proposed the use of high-latitude Pc1 pulsations for finding the cusp position. In the interplanetary medium, emissions in this range are observed in the part of the transition region known as the magnetic barrier [8]. According to paper [9], it theoretically possible for pulsations to move from the transition layer to the magnetosphere. In the course of reconnection, the anisotropic plasma from the magnetic barrier can appear in the geomagnetic field lines connected with the ionosphere in the cusp region, and the ion-cyclotron waves propagating along the field lines can be detected on Earth's surface in the form of Pc1 pulsations.

If reconnection takes place under negative $B_z$ conditions, the source of pulsations remains in open field lines carried away by a solar wind stream to the magnetosphere tail. To register these pulsations, a magnetometer must be located in the polar cap. According to statistics [1], the cusp is typically projected closer to the pole relative to Spitsbergen. When the $B_z$ component of IMF is negative and large in absolute value, the cusp shifts towards the equator (an example of an extreme case is given in Fig. 1b) and Spitsbergen appears to be inside the polar cap in the region of open field lines. Continental magnetometers can still remain in closed field lines. Several such situations were analyzed in paper [10]. Below, we shall briefly review the results of this paper.

### 4.1 Midday Pc1 in the polar cap. Description of an individual event

The event chosen for demonstration occurred during the main phase of a moderate magnetic storm which was caused by Earth passing through a magnetic cloud characterized, in particular, by high negative values of the IMF $B_z$ component. The geomagnetic field variations in the frequency range of 0 to 40 Hz were measured in three observatories: Barentsburg (Spitsbergen archipelago), Kilpisjarvi (the north of Finland), and Lovozero (the center of the Kola Peninsula). Within the time of the event under consideration, two DMSP series satellites flew over the region of magnetic measurements almost simultaneously (Fig. 5a). The data from the satellites showed that, because of the large negative $B_z$ component (−10 nT), the cusp had shifted by approximately 10° southward relative to its statistical position. As a result, the BAB observatory found itself at the foot of open field lines, in the region of the polar cap, while the KIL position can be identified with the position of the cusp or a part of LLBL east of the cusp. The LOZ observatory was located inside the projection of LLBL or the boundary plasma sheet (BPS).

The time evolution of geomagnetic activity in the ultra-low-frequency (ULF) range is demonstrated in Fig. 5b–d in sonograms. One can see that Pc1 pulsations were observed at BAB only (Fig. 5b), which at that time resided in the polar

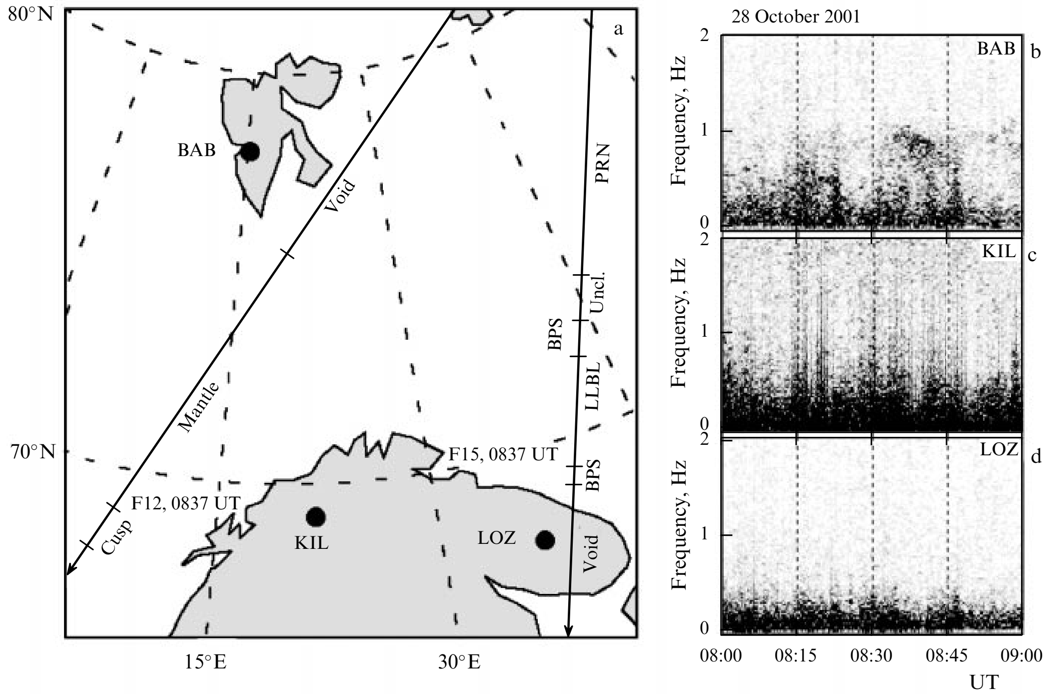


**Figure 5.** Positions of BAB, KIL, and LOZ observatories relative to the magnetospheric domain boundaries according to the data from DMSP satellites F12 and F15; PRN is polar rain, Uncl. (unclassified) means that the online recognition program failed to assign, using particle characteristics, the precipitation source to a certain magnetospheric domain. (b–d) The form of ULF activity at these observatories.

cap. At the KIL (Fig. 5c) and LOZ (Fig. 5d) stations located at the foot of closed field lines, pulsations were absent. We believe that such spatial distribution of Pc1 pulsations implies that the emissions in BAB were not a result of simple signal propagation in an ionospheric waveguide. Consequently, the source of Pc1 pulsations was situated on open field lines.

Data from the Wind satellite show that before the beginning of pulsations in Barentsburg the $B_y$ component decreased almost to zero. That is, before the beginning of Pc1 pulsations, the region of reconnection on the magnetopause shifted in the direction of the midday meridian, where the $y$-component of the Earth field is also insignificant and the conditions (opposite directions of the fields) are the most favorable for reconnection.

The ionospheric conditions over Spitsbergen were monitored by the SuperDARN radar system. The diagrams in Fig. 6 demonstrate the main peculiarities of the behavior of large-scale convection within the considered time interval, including the Pc1 activity time interval. Before the beginning of pulsations, the convection over Spitsbergen had an azimuthal direction (along the latitude), and so the observatory was in the path of magnetic field tubes drifting from the magnetosphere tail (Fig. 6a, d). The appearance of pulsations coincides in time with the change in the character of convection. Figure 6b, e indicates that the drift over Spitsbergen took the meridional direction. The dashed line gives the trajectory of the DMSP F12 satellite at an altitude of 300 km. The white circle in Fig. 6b stands for the cusp position. The plasma stream along the meridian may imply that BAB now resides in the path of the newly reconnected magnetic field tubes. This means that Pc1 activity in the polar cap may have resulted from the penetration of anisotropic plasma into the magnetosphere from the transition region (more precisely, from the magnetic barrier). The diagrams in Fig. 6c, f correspond to the instant of pulsation termination. One can see that convection over BAB has again acquired the azimuthal direction.

### 4.2 Midday Pc1 in the polar cap. Statistics and scenario of the phenomenon

We looked through the data gathered by the Wind satellite from October 2001 to October 2002 and selected those cases when the $B_z$ component of IMF assumed high negative values near a local midday in BAB.

The analysis of all the events revealed the following basic regularities (the results are presented in more detail in paper [10]).

— For all the cases, the data of DMSP satellites show that the BAB magnetometer was located in the polar cap, while the other two magnetometers (KIL and LOZ) were in the region of closed field lines.

— KIL and LOZ exhibited pulsations in none of the cases.

— During the 10-min interval that included the moment of pulsation observation, the $B_y$ component of IMF diminished almost to zero.

— In three cases, the data from the SuperDARN radar were accessible, which showed that before the beginning of Pc1 pulsations the direction of convection over Spitsbergen changed to antisolar.

— About 10 min before the beginning of Pc1, the IMAGE (International Monitor for Auroral Geomagnetic Field) magnetometer network exhibited pulsations of the Pc5 range with increasing amplitude. The intensity of pulsations was higher at the boundary between closed and open field lines. No pulsations were observed in the direction from the boundary to the pole.

Thus, in the considered seven cases of Pc1 pulsations observed at high latitudes in day hours in the periods of high negative values of the IMF $B_z$ components, the high-latitude

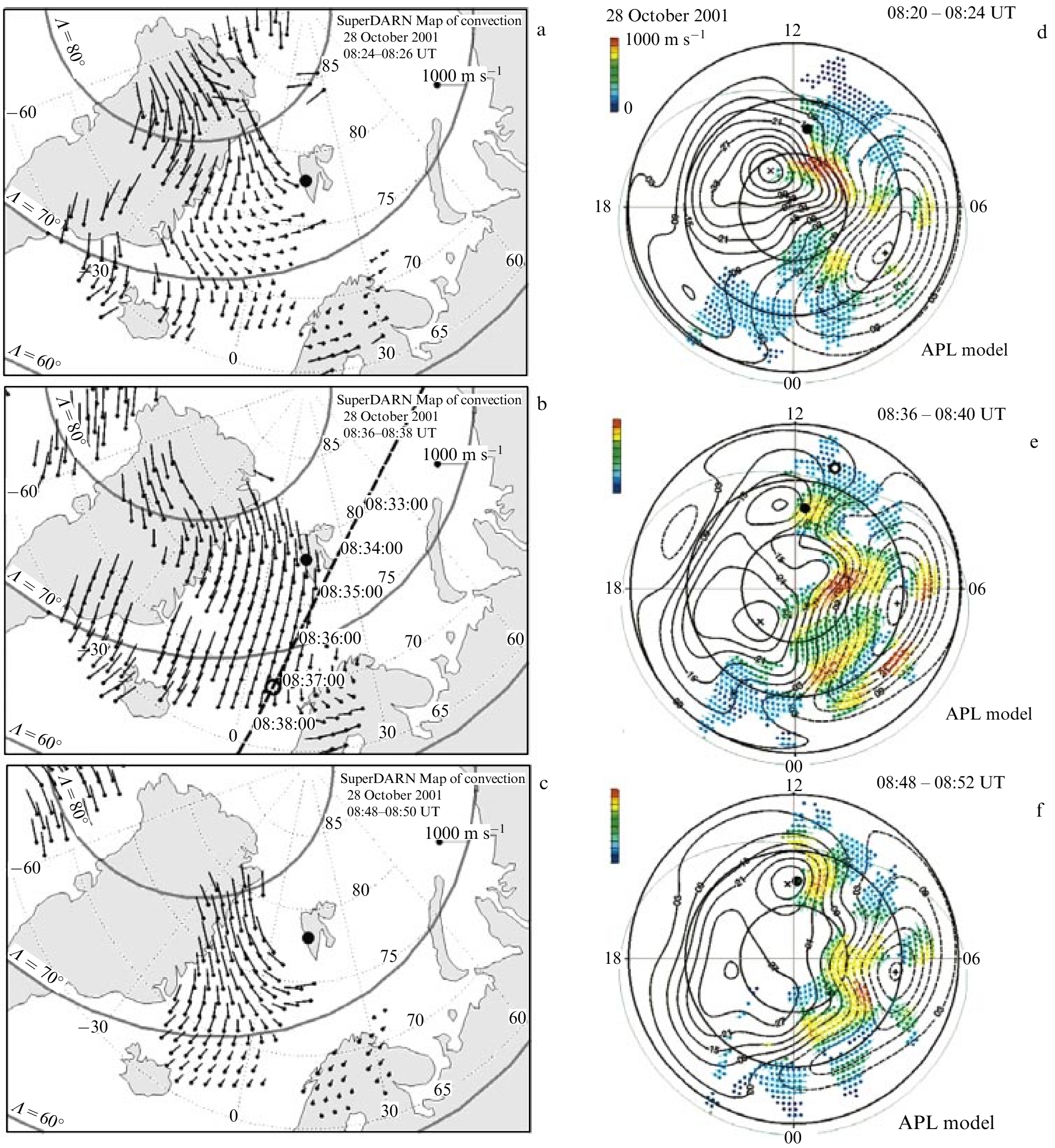


**Figure 6.** (Color online.) Character of ionospheric convection over Spitsbergen before (a, d), in the course of (b, e), and after (c,f) the interval of pulsations in Barentsburg by SuperDARN measurements (a–c) and reconstruction of this convection by SuperDARN data with allowance for IMF (d–f). The dashed line is the DMSP satellite trajectory, the white circle on the trajectory is the cusp position, and the black circle is the Barentsburg observatory. The arrows show the direction of convection rate, and $\Lambda$ is geographic latitude.

observatory (BAB) was at that time in the polar cap, while the auroral zone observatories (KIL and LOZ) remained in the region of closed field lines. Pulsations were detected in the polar cap only. (A similar result had been reported before in papers [11, 12]). This could be caused by a very strong decrease in the Pc1 amplitude with increasing distance (about 10 dB each 100 km according to Ref. [11]). Taking into consideration the possibility of such weakening of pulsations, the authors of paper [12] concluded that the observed Pc1 must be generated in a spatially limited region. Thus, the absence of pulsations to the south of BAB may mean that pulsations could not have come from low latitudes along the ionospheric waveguide, and their source must be located on open field lines and must have limited spatial dimensions.

The opinion that anisotropic proton plasma may be the source of Pc1 is widespread. Since parts of the magnetosphere tail are generally characterized by a low plasma content, the question arises as to where it appeared from in the cases considered. We believe that the anisotropic plasma has been ‘brought in’ from the transition region (the solar wind region immediately before the dayside magnetopause) by newly reconnected field lines drifting through the polar cap from the cusp towards the night side. The specific IMF effect on the Pc1 regime in the BAB data, namely, their relation with the decrease in the $B_y$ component of IMF, confirms this hypothesis.

## 5. Conclusion

The energy and matter transfers through the dayside magnetosphere are reflected in various ionospheric perturbations observed over Spitsbergen in day hours. Therefore, the observational facility located here involves optical magnetometric equipment and can efficiently be used to study a whole number of important questions about cosmic weather. In this paper, we demonstrate, using concrete examples, the possibility of using optical and magnetic phenomena for diagnostics of reconnection.

We emphasize the importance of a precisely complex ('multi-instrumental') approach to the analysis of daytime ionospheric perturbations and the necessity in this connection of a more thorough comparison of different measurements in space. In the case of auroras, this is the binding of auroras on stars allowing error minimization in finding the aurora position with respect to the magnetosphere domain boundaries. In the case of Pc1 pulsations, this is exclusion of situations of pulsation propagation in the region of observations along the ionospheric waveguide.

An important supplement to the optical and magnetic data are the results obtained by DMSP satellites on precipitating particles, which make it possible to determine the position of cusp boundaries in the ionosphere and, therefore, the position of the boundary between closed and open geomagnetic field lines, as well as radar data concerning the character of ionospheric convection in the observational regions. The 'monoinstrumental' approach may lead to misinterpretation of the observed phenomena (see paper [2]).

**Acknowledgments**
The authors are grateful to research workers at PGI whose professional activity promoted the development of Barentsburg observatory and obtaining high-quality data, and to N N Safargaleeva (PGI) for her help in selecting intervals of optical observations. The authors thank P T Newell (Johns Hopkins University, APL US) for preparing and distributing on the Internet the observational data from satellites of the DMSP series. The particle detectors for DMSP satellites were designed by D Hardy (Air Force Research Laboratory). The program package for aurora binding on stars was prepared by B Gustavsson (Swedish Institute of Space Physics) in the framework of the ALIS project. The data on the interplanetary magnetic field were obtained through the OMNI CDA Web data array.

## References

1. Newell P T, Meng C-I *Geophys. Res. Lett.* **19** 609 (1992)
2. Safargaleev V et al. *Ann. Geophys.* **26** 517 (2008)
3. Sandholt P E et al. *Ann. Geophys.* **19** 487 (2001)
4. Jacobsen B et al. *J. Geophys. Res.* **100** 8003 (1995)
5. Newell P T et al. *J. Geophys. Res.* **96** 5877 (1991)
6. Sergienko T I, Ivanov V E *Ann. Geophys.* **11** 717 (1993)
7. Menk F W et al. *J. Atmos. Terr. Phys.* **54** 1021 (1992)
8. Anderson B J, Fuselier S A *J. Geophys. Res.* **98** 1461 (1993)
9. Lyatskii V B, Safargaleev V V *Geomagn. Aeronom.* **29** 665 (1989)
10. Safargaleev V et al. *Ann. Geophys.* **22** 2997 (2004)
11. Neudegg D A et al. *Geophys. Res. Lett.* **22** 2965 (1995)
12. Sato M et al. *J. Geophys. Res.* **104** 19971 (1999)

 

*CONFERENCES AND SYMPOSIA* PACS numbers: **07.87.+v**, **96.60.–j**

*75th ANNIVERSARY OF IZMIRAN*

# Space solar research: achievements and prospects

V D Kuznetsov

DOI: 10.3367/UFNe.0185.201506k.0664

## Contents



Abstract. **Space-based solar observations continue to provide new insights into the structure and dynamics of the Sun's interior and atmosphere. This paper uses helioseismic and magnetic data from the Helioseismic and Magnetic Imager of the Solar Dynamic Observatory (SDO) to present results on the Sun's subphotospheric and meridional flows and on the simulation of the solar dynamo and of the solar magnetic field variation. High spatial resolution observations of the solar atmosphere with SOHO, Hinode, SDO, IRIS, Hi-C, EUNIS, etc. provide detailed clues about the dynamics and fine structure of magnetic fields, flare energy release, and coronal mass ejections. Space projects with the potential to solve topical solar physics problems are briefly reviewed.**

**Keywords:** Sun, space research, magnetic fields, dynamo, flares, mass ejections

## 1. Introduction

Space research nowadays makes the determinative contribution to solar research — to the acquisition of key observational data and the explanation of how the Sun is structured and how it works. A variety of solar physics problems ranging from the solar interior to the boundary of the Solar System is still at the focus of researchers' attention and is the subject of the scientific programs of solar space missions, both ongoing and planned.

In recent years, the most significant progress in heliophysics was made in precisely space research (see, for instance, Refs [1–4]). Spacecraft-based solar observations and local heliospheric measurements during modern solar missions are aimed: at the study of the internal solar structure, the mechanism of the solar dynamo and the solar cycle (elucidating the problem of why the cycle amplitude and duration vary and what determines them), and the fine structure and dynamics of the solar atmosphere (micro- and nanoflares, magnetic rope structure); in the explanation of the trigger mechanisms of initiating solar flares (elucidation of what motions and processes are responsible for the explosive energy release and eruption of magnetic structures), the mechanisms of solar corona heating, solar wind acceleration, particle acceleration, and particle propagation through the heliosphere. Apart from these fundamental problems of solar astrophysics, of steadily increasing practical importance today is the study of space weather, which affects different spheres of human activity on Earth and in space [5–9]. The main source of space weather variation is the Sun and its activity [5, 10].

Table 1 presents solar and heliospheric space projects, both already implemented (completed or ongoing) and being prepared for realization or in the development stage. Figure 1 shows ongoing and future solar space projects with reference to their orbits.

The conception of modern solar missions proceeds from the necessity of solving specific problems of solar physics and from the set of available scientific instruments and those under development. This conception implies the use of spacecraft (SCs) in near-Earth orbits, as a rule, with large telescopes for observing the solar atmosphere with a high spatial resolution and of SCs placed at observationally advantageous points (the L1 Sun–Earth libration point, heliocentric orbits with an approach to the Sun, positioned outside the Sun–Earth line, inclined to the solar ecliptic plane for solar polar observations, etc.).

## 2. Latest accomplishments in solar space research

Recent progress in the area of solar space research is reviewed in Refs [1–3]. The results of the CORONAS-F[1]

[1] CORONAS — Kompleksnye ORbital'nye Okolozemnye Nablyudeniya Aktivnosti Solntsa (Complex orbital circumterrestrial observations of solar activity).

**V D Kuznetsov** N V Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Kaluzhskoe shosse 4, 142190 Troitsk, Moscow, Russian Federation
Tel. +7 (495) 851 01 20. Fax +7 (495) 851 01 24
E-mail: kvd@izmiran.ru

Received 18 April 2015
*Uspekhi Fizicheskikh Nauk* **185** (6) 664 – 672 (2015)
DOI: 10.3367/UFNr.0185.201506k.0664
Translated by E N Ragozin; edited by A Radzig

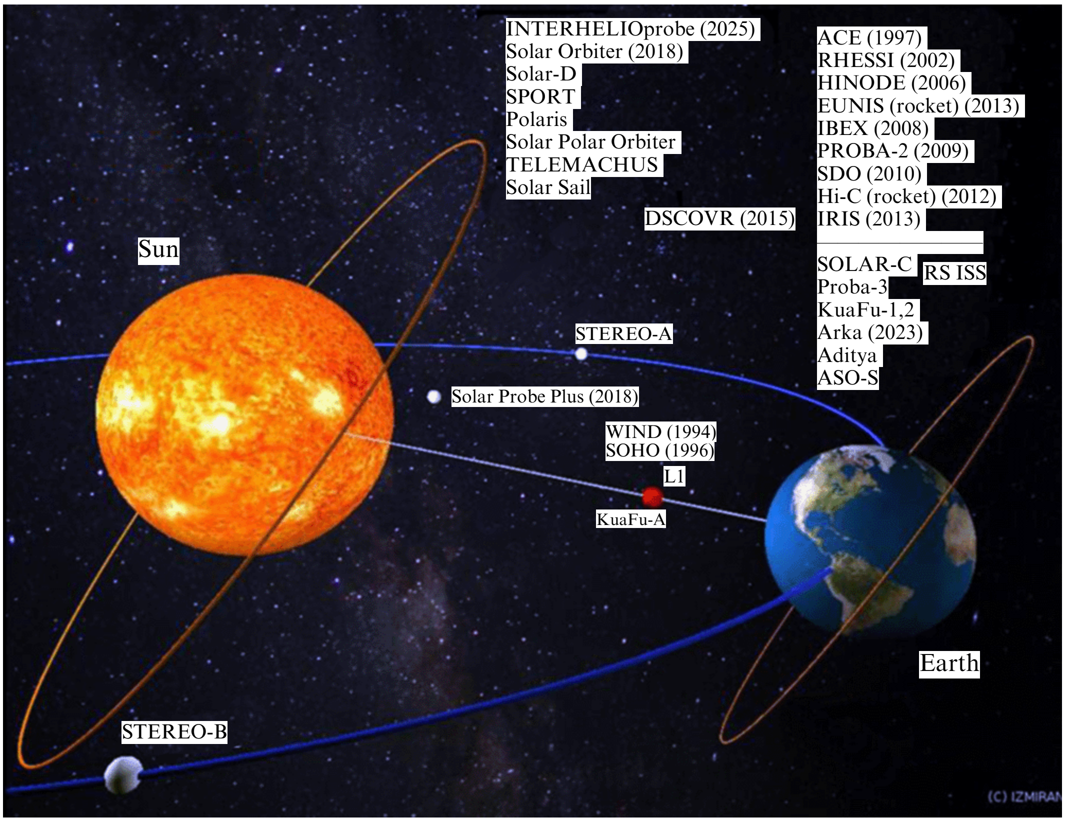


**Figure 1.** Ongoing and future solar and heliospheric missions (see Table 1) and their orbital positions (in geocentric and heliocentric orbits).

**Table 1.** Main solar-heliospheric space projects of recent years*.

| Implementation stage | Project |
|---|---|
| Completed | Yohkoh (1991 – 2001), CORONAS-I (1994 – 2001), Ulysses (1990 – 2009), TRACE (1998 – 2010), CORONAS-F (2001 – 2005), CORONAS-Foton (2009 – 2010), Hi-C (2012), EUNIS (2013) |
| Ongoing | Voyager-1, -2 (1977), Wind (1994), SOHO (1996), ACE (1997), RHESSI (2002), Hinode (2006), STEREO (2006), IBEX (2008), Proba-2 (2009), SDO (2010), IRIS (2013), DSCOVR (2015) |
| Under preparation for realization | Proba-3 (2017), Solar Probe Plus (2018), Solar Orbiter (2018), Interhelioprobe (2025), Arka (2023), Kortes (RS ISS) (2018), Takhomag (RS ISS) (2020) |
| Under development | POLARIS, Solar Polar Orbiter, SPoRT, Solar-C, Solar-D, KuaFu, ASO-S, Aditya-1, Telemachus, Solar Sail, Sun-Terahertz (RS ISS) |

* Shown in parentheses are the operation periods of completed missions and the launch years of the ongoing missions and those under preparation: TRACE — Transition Region And Coronal Explorer, ACE — Advanced Composition Explorer, RHESSI — Reuven Ramaty High Energy Solar Spectroscopic Imager, STEREO — Solar-TErrestrial RElations Observatory, IBEX — Interstellar Boundary Explorer, DSCOVR — Deep Space Climate Observatory, RS ISS — Russian Segment of the International Space Station. Other acronyms are explained in the text.

space project are outlined in monograph [4]. Among the operating solar space projects, a large stream of observational data and scientific results is provided by the Helioseismic and Magnetic Imager (HMI) instrument of the Solar Dynamic Observatory (SDO) mission, which is intended for studying magnetic fields and photospheric and subphotospheric flows [11].

The nature of the solar cycle is related to the action of the solar magnetic dynamo, the generation of a toroidal magnetic field in the convective zone by differential solar rotation, and the equator-to-poles transfer of poloidal magnetic fields by meridional circulation. Studying the properties of these varying and poorly studied flows in the Sun is one of the most important tasks of solar physics. Doing so will provide answers to the questions of why solar cycles vary in duration and amplitude and whether it is possible to predict future cycles of solar activity and their influence on Earth from these flow observations.

The theoretical simulation of large-scale flows on the Sun, which are responsible for the generation and transfer of magnetic fields, relies on helioseismologic and magnetic observations, which are presently provided, in particular, by the HMI/SDO instrument.

Proceeding from the differential rotation pattern of subphotospheric solar layers (Fig. 2a) [12], which was obtained from helioseismologic data, a stationary meridional circulation pattern was calculated in the framework of a magnetohydrodynamic (MHD) model [13]. As was established, it depends heavily on the degree of density decrease with reduction in the radius: it contains a single circulation

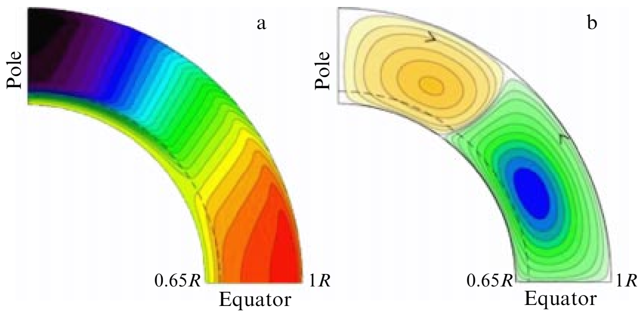


**Figure 2.** (a) Differential rotation pattern of subphotospheric solar layers [12]. Light-to-dark color transition corresponds to an increase in angular rotation velocity. (b) Meridional circulation pattern generated by this differential rotation and turbulent viscosity [13].

cell with a poleward surface flow assuming a density decrease by less than about four orders of magnitude from the bottom to the top of a convective zone, and two cells with reverse circulation at high latitudes (Fig. 2b), assuming a stronger density decrease, including the case of an adiabatically stratified solar convective zone. The radial and latitudinal components of the Coriolis force, which give rise to this meridional circulation, turned out to be very strong, so that the cells encompass the entire depth of the adiabatically stratified solar convective zone. Thermodynamic effects were neglected.

A comparison of the calculated and observed rates of the poleward meridional flow in the main cell revealed a significant discrepancy between them. For turbulent viscosity (turbulent Reynolds stress) typical for solar conditions, the calculated value turned out to be much greater than the observed one. This poses questions for the theories of solar meridional circulation and points to the necessity of including other forces that are specific for the solar convective zone and which slow down the meridional flow, notably, the forces caused by thermal conditions: negative buoyancy, anisotropic small-scale turbulent diffusion of momentum and heat, and latitude-dependent radial thermal flux of solar convection with the inclusion of solar rotation.

The development of the model in use implies reproducing two meridional circulation cells in the convective zone depth [14] and four cells in latitude [15], as well as considering the question of whether this circulation pattern emerges as a transient one or persists for a long time, on a temporal scale of several dozen years.

The discordance between the amplitudes of convective velocities at a depth of $r/R_{\odot} = 0.96$ ($R_{\odot}$ is the solar radius) observed by helioseismologic techniques and the global convection simulation data for the same convective zone depths was revealed in Ref. [16] on the base of processing a huge number of wave field observations acquired by HMI/SDO. Subphotospheric flows break the symmetry of wave propagation along and against the flow, which gives rise to a difference in the time these waves take to transit the same distance. Using the statistics of these wave transit times, it was possible to obtain an upper bound ($< 1$ m s$^{-1}$) on the convective velocities in the solar interior as functions of depth and the degree of spherical harmonic. The resultant seismological limitations on the values of convective velocities at a depth of $r/R_{\odot} = 0.96$ correspond to the extrapolation of observed velocities to the interior of the domain of large-scale plasma flows at the level of the solar photosphere ($\sim 8-20$ m s$^{-1}$) [17] with the inclusion of density variation with depth.

Observations of low convective velocity amplitudes ($\sim 10$ m s$^{-1}$) — low in comparison with the model ones — cast doubt on our present-day notion of thermal transfer and angular momentum transfer on the Sun. The questions arise of how differential rotation and meridional circulations are sustained on the Sun and how solar radiation is transferred outside through the convective zone. Still unexplained is the photospheric convective spectrum which shows a fall in power for spherical harmonics with degrees $L < 120$, and for spherical harmonics of very low degree the power decreases linearly with decreasing $L$. The reason why the power tends to zero on the largest scales is not quite clear.

Lord et al. [18] performed numerical simulations of the power peak for supergranulation scales and the subsequent decrease in the power spectrum of surface convection for low $L$. Contrary to observational data, it was ascertained that the power should accumulate for low $L$. As a result, a conclusion was reached that the Sun transfers energy through the convective zone with a sustainment of large-scale flows with a very low amplitude, and modern theoretical notions of solar convection under the photosphere therefore need refinement.

Using the EULAG (Eulerian/semi-LAGrangian fluid solver) numerical code, Guerrero et al. [19] carried out numerical simulations of the global model of the solar and stellar dynamos, which was based on the system of MHD equations in spherical geometry subject to the corresponding boundary conditions. It was determined that the formation of stationary flows depends on a subtle balance between the buoyancy and Coriolis forces, which is defined by the dimensionless Rossby number. For large Rossby numbers (the prevalence of convective flows), the differential rotation profile is antisolar — the poles rotate faster than the equator. In this case, the collective action of small-scale flows in the meridional direction produces a coherent counterclockwise-rotating meridional circulation in the Northern Hemisphere (in the Southern Hemisphere the rotation is clockwise). These circulation cells transfer the angular momentum towards higher latitudes. For small Rossby numbers (prevalence of rotation), the equator rotates faster than the poles, as is observed on the Sun. Here, the meridional flow has a complex multicell structure, which corresponds to helioseismic observations [14, 20].

The decrease in angular velocity in the upper part of the convective zone (the so-called near-surface shear layer) may be due to the fact that the surface flows — granulation and supergranulation — evolve in characteristic times much shorter than the characteristic rotation times [19]. A poleward migration, which is observed in the plasma flow at all latitudes, may result from this negative surface shear due to the mechanism of gyroscopic pumping.

In the large-scale dynamo case, the solutions describe a toroidal winding of the reversed polarity field in the equatorial region for models with the prevalence of convection over rotation, as well as magnetic cycles with different periods and field configurations for models with rotation prevalence [21]. The models that correspond to the solar conditions adequately reproduce the latitudinal differential rotation and the tachocline; however, the rotation isolines exhibit cylindrical shapes, while they are conically shaped on the Sun. Although a model with the capacity to fully reproduce all observable features of the solar dynamo is yet to be constructed, the results of simulations performed for global dynamo models are encouraging and give hope for an adequate description of the solar and stellar interiors in the framework of the approach in use.

Based on HMI/SDO data, a slow change of sign of the polar magnetic field, asymmetric in the North–South direction was discovered early in 2014 [22]. To analyze the process of a field sign change, use was made of the data of line-of-sight observations during the 24th cycle of solar activity. Average radial fields in different latitudinal intervals were calculated for every magnetogram, assuming that all field vectors were radial, and weighted averaging over the area was performed to estimate the average field. This analysis showed that the magnetic activity, which is characterized by the SunSpot Number (SSN), was low and symmetric about the Northern and Southern Hemispheres. The maximum hemispheric SSN value amounted to about 60% of that for the 23rd cycle, and for the Northern hemisphere it was reached almost two years earlier than for the Southern one. The polar magnetic fields were also symmetric. The changes of sign in the Northern and Southern Hemispheres occurred in November 2012 and March 2014, respectively, i.e., with an interval of about 16 months.

The asymmetry was obviously related to the poleward asymmetric magnetic surge flux, which was the residual magnetic flux of the active region. Individual surges were of either polarity, which was related to the varying inclination angle of bipolar loops in the active regions. Using helioseismic observations [23], it was possible to establish an appreciable anticorrelation between the mean field of these surges and the rate of near-surface meridional flow at medium latitudes, i.e., the poleward flow is usually slower when the magnetic field of the surge is guided by the sunspot polarity and is faster in the opposite case. It was shown that this characteristic dependence may be explained in the framework of the surface flux transport (SFT) [24] model, having in view the observable magnetic field-dependent flux which converges in the direction of active regions according to Joy's law [25]. The inclusion of this observation-based two-dimensional meridional flow profile may improve SFT simulations of the cycle amplitude.

Wilcox Solar Observatory data suggest that the past change of sign of the solar magnetic field turned out to be the slowest over the last three cycles of solar activity. The recovery of the magnetic field of the new solar cycle also proceeds slowly. The Northern Hemisphere exhibited numerous changes of sign of the magnetic field near a latitude of 60°, the northern polar magnetic field remaining close to zero even two years after the instant of sign change. Since the polar field maximum is a good indicator of the amplitude of the next solar cycle [26], the 25th cycle may turn out to be quite weak if the observed trend persists.

The twist of magnetic fields in sunspots was studied from AIA/SDO[2] and HMI/SDO data [27]. In some spots, the magnetic field is twisted in such a way that it becomes similar to a helical structure corresponding to counterclockwise rotation. Higher in the solar atmosphere, the magnetic fields of a sunspot are seen as a set of magnetic structures usually twisted in all directions. While in the chromosphere and corona the twist direction is clearly visible, there are no direct twist observations at photospheric altitudes and below. In the passage of active regions across the disk, the sunspot twist pattern persists.

To determine the twist of the magnetic field at the photospheric level — the spatially averaged signed shear angle (SASSA) — use was made of HMI/SDO vector magnetograms [28]. For the active region AR 11092, this parameter had negative values corresponding to a counterclockwise twist visible in the higher layers of the solar atmosphere. The twist of the magnetic field below the solar surface was estimated from the twist of the subsurface flow, proceeding from the ring-diagram analysis applied to HMI/SDO dopplerograms.

The calculated density of kinetic helicity was adopted to the twist measure in these flows [29]. In the lower layers of the solar atmosphere, the twist of the NOAA[3] AR 11092, determined by the SASSA method, had the same direction as the twist visible higher in the solar atmosphere. However, the twist was directed oppositely under the surface, as testified by the positive kinetic helicity density. Another sunspot, which had a clockwise twist (AR 11084), yielded the same result: twists of opposite sign below and above the solar surface.

In a check experiment with six sunspots without a stable helical structure, the direction of magnetic field twist in the solar atmosphere coincided for four active regions out of six with the directions of flow under the solar surface. For active regions without sunspot helicity, the same rule of hemispheres was always observed for both their kinetic and their current helicities: the existence of positive values in the Southern hemisphere, and of negative values in the Northern one. This signifies that the opposite twist directions above and below the solar surface are actually the characteristic of active regions with a twist of the magnetic field. Observations and analysis of a larger number of active regions will permit verifying the established features of the sunspot helical structure.

In combination with theoretical modeling, the detailed maps of photospheric magnetic fields obtained by the observations of the HMI/SDO instrument permit performing a comprehensive study of magnetic fields in the solar atmosphere and determining the role they play in flare initiation and mass ejection. By analyzing the variations of the photospheric magnetic field on the base of HMI/SDO data, Liu et al. [30] studied the processes of energy release in flares and their manifestation in magnetic field variations. The variation of the coronal magnetic field was calculated by nonlinear force-free field (NLFFF) modeling. The three-dimensional restructuring of the magnetic field in the active region is consistent with the scenario of coronal implosion (an inward-directed explosion) in the lower atmosphere. The notion of 'implosion' in coronal transients implies the inward-directed compression of the coronal magnetic field, which must take place simultaneously with a magnetic energy release [31].

The formation of a photospheric magnetic field configuration that is closer to a horizontal configuration must be a direct consequence of coronal implosions. This is supported by the fact that the transverse magnetic field around the polarity inversion line (PIL) at the center of a flaring region, as established, quite often exhibits a fast and stable rise immediately after a flare and mass ejection [32]. This

[2] AIA — Atmospheric Imaging Assembly.

[3] National Oceanic and Atmospheric Administration, USA.

inward-directed collapse of the central magnetic field may supposedly be attended by an upward-directed rotation of the peripheral magnetic field in the active region and with the decay of the spot penumbra in the outer parts of the flaring region, which was observed [33]. The implosion may exert numerous effects on the lower solar atmosphere, which have not been adequately studied so far.

Coronal implosion was observed and studied by the example of homologous flares of class X2.1 on 6 September 2011, and of class X1.8 on 7 September 2011 in NOAA AR 11283. Both flares took place near a strong-shear PIL along which the flares usually occur. Clearly observed in this case was a step-like rise (respectively by 26% and 38%) of the horizontal field $B_h$.

Of greater interest is the fact that the central part of the $B_h$-rising region was surrounded by an annular domain with a decreased $B_h$ value, which largely corresponded to the peripheral region of the penumbra and was more strongly pronounced on the northern side.

When describing the internal evolution, the distance between the centers of gravity (flux-weighted average) of opposite magnetic polarities was also determined. The result revealed a clear shortening of this distance by 0.85 Mm and 1.4 Mm immediately after the X2.1 and X1.8 flares, respectively, for a short time interval prior to the recovery of the long-term evolution trend. It was hypothesized that this could be a surface manifestation of coronal implosion. With the use of the NLFFF method, it was also determined that the X1.8 flare, unlike the X2.1, could be related to better-formed twisted rope, which was reflected in the presence of a thicker fiber. The observations of rope evolution allowed the following conclusions:

(1) the rope collapsed in the direction of the surface after the X2.1 flare, then it gradually rose to a higher altitude for one day to collapse once again after the X1.8 flare. Both the amplitude of motion and the velocity of rope fall motion in the X1.8 flare were two times greater than in the X2.1 flare, testifying to a stronger implosion and correlation with greater variations of the photospheric magnetic field (the increase in $B_h$ and the shortening of the distance between the centers of gravity of opposite magnetic polarities);

(2) prior to the X2.1 flare, the rope was at the photospheric level, but prior to the X1.8 flare it had risen above the surface. The rope eruption could, therefore, proceed several times up to the onset of its complete eruption, when the rope detaches from the surface and escapes to the interplanetary space;

(3) the rope was not symmetric at its central vertical cross section and became thinner in the northward direction at an angle of 66° relative to the surface. Together with the surrounding fields, the ropes rapidly turned southwards after both flares, causing a decrease in $B_h$ in the peripheral regions at the surface.

Therefore, the data of observations and numerical simulations describe a consistent picture of implosion in the lower corona, in which the central magnetic field of a magnetic configuration collapsed towards the photosphere, while the peripheral field relaxed to a more vertical configuration. The manifestation of implosion at the photospheric level consisted in the fact that the center-of-gravity separation of the main magnetic polarities of opposite sign also becoming smaller. The changes in the magnetic field come about more abruptly when the implosion involves a complete eruption of the rope.

Using the Hinode satellite data on the magnetic field at the solar surface, the observations by the Solar and Heliospheric Observatory (SOHO) and Paris Observatory, as well as the data of theoretical simulations, Amari et al. [34] conducted a detailed study of the initiation of the coronal mass ejection (CME) observed by the SDO observatory on 14 October 2012. In this event, the mass ejection development scenario was related to the existence of a magnetic field rope in the active region and its subsequent evolution. Observed four days prior to the ejection were the accumulation of magnetic energy and evidence for the rise of magnetic flux tubes. The magnetic rope, which was not formed until the last day, had a store of magnetic energy sufficient to initiate the mass ejection, with only a minor external perturbation being required for this to occur.

From the magnetic data gathered in the active region, it was possible to evaluate the critical amount of energy stored by the rope, exceeding which the rope may depart from equilibrium and produce a mass ejection. The equilibrium of magnetic rope is also broken when it reaches the critical altitude during its rise in the solar atmosphere. The investigated indications of the initiation of mass ejection in the form of magnetic ropes may be employed in observations for predicting its occurrence.

Some other results obtained with HMI/SDO are reviewed in recent paper [1].

Observations of the solar atmosphere with a high spatial resolution are aimed at the study of energy transport to the corona and solar wind, as well as at explaining the mechanisms of corona heating and solar wind acceleration. These observations are made using the UV multichannel telescope Interface Region Imaging Spectrograph (IRIS) in the emission lines from the transition region with a 1/3 arcsecond spatial resolution (a spatial scale of 240 km on the Sun) and a temporal resolution of 1 s. The first observations permitted discovering a complex magnetic field structure in the form of a multitude of thin magnetic fibers ranging widely in density and temperature, as well as flares which flash and die out rapidly, which are reflective of small-scale energy releases in the solar atmosphere [35]. Furthermore, IRIS observations will permit studying different types of nonthermal energy, which may be present in the chromosphere and outside of it, mass and energy transfer to the corona and heliosphere, and the rise of magnetic flux tubes and their role in mass ejection and flare initiation.

Observations of the solar atmosphere with a high spatial resolution were also performed in Hi-C (High Resolution Coronal Imager) and EUNIS (Extreme Ultraviolet Normal Incidence Spectrograph) rocket experiments during a short flight beyond the atmosphere. UV Hi-C telescope observations at a wavelength of 19.3 nm with a spatial resolution of 150 km on the solar surface also showed the existence of thin magnetic ropes in the solar atmosphere — twisted and braided magnetic flux tubes and numerous magnetic microloops. Powerful UV radiation flares, which formed groups along the magnetic field lines, had characteristic dimensions of up to 700 km, a glow duration of up to 25 s, and an energy on the order of $10^{31}$ erg, which provides an energy flux sufficient for corona heating [36–39].

Exoatmospheric rocket observations (in the $\lambda = 592.2$ Å line of Fe XIX excited at a temperature $T \approx 8.9$ MK) with a high-sensitivity EUNIS spectrograph also demonstrated the significance of the contribution from numerous small-scale

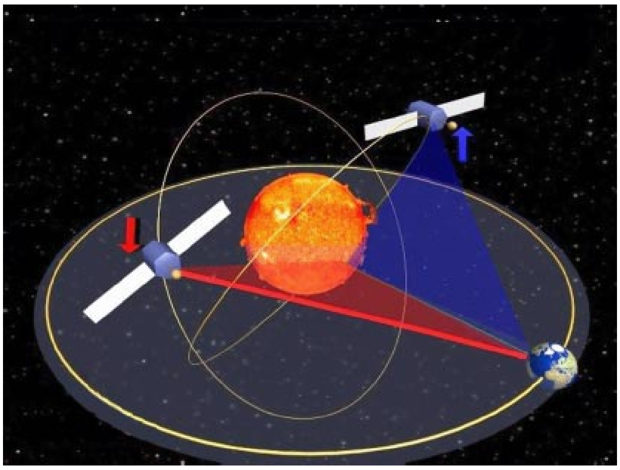

**Figure 3.** Ballistic scheme of the Interhelioprobe project for the study of the inner heliosphere and of the Sun at close distances and from out-of-the ecliptic positions.

pulsed energy releases in the solar atmosphere — nanoflares — to solar corona heating [40].

## 3. Prospects of solar space research

Future solar space projects are aimed at solving a variety of scientific problems in solar physics — from determining the structure and dynamics of the solar interior, which are responsible for the generation of solar magnetic fields and the solar cycle, to studying solar corona heating and solar wind acceleration due to the release and transfer of energy in the solar atmosphere from its inner layers to the outer ones. Solar flares, mass ejections, and particle acceleration are the different manifestations and forms of this energy release, and their mechanisms are also the subject of investigations on solar space missions and in experiments being prepared and planned (see Table 1 and Fig. 1).

Solar observations from out-of-the ecliptic positions offer a number of advantages, which involve the possibility of studying the polar solar regions, the heliolatitude structure of ecliptic corona and mass ejections, their heliolongitude directivity in the propagation to Earth, the heliolongitude dependence of solar luminosity, the possibility of monitoring the solar sources of space weather, etc. In the preparation stage are the Solar Orbiter (ESA [4]) [41] and Interhelioprobe (Roscosmos) [42] projects, in which the spacecraft will approach the Sun at a distance of $60-70 R_{\odot}$ while being in heliocentric orbits inclined (by about 32°) to the ecliptic plane due to multiple gravitational maneuvers near Venus.

In the Interhelioprobe project, it is planned to deploy two SCs (Fig. 3) separated by a quarter period in orbital phase in order to provide continuous out-of-the ecliptic observations of the Sun and its near-polar regions.

The main objectives of these projects are related to the investigation of polar and equatorial regions from out-of-the ecliptic positions: the study of polar magnetic fields, plasma motion and the solar dynamo, the ecliptic corona and heliolatitude structure of mass ejections, the mechanisms of corona heating and solar wind acceleration, the trigger

[4] European Space Agency.

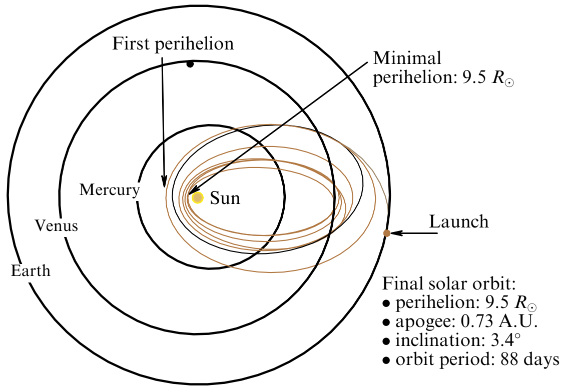


**Figure 4.** Ballistic scheme of Solar Probe Plus SC's approach to the Sun using multiple gravitational maneuvers near Venus (NASA).

mechanisms of flares and mass ejections, the mechanisms of particle acceleration in the Sun and in the heliosphere, the solar wind sources in the Sun, and the connection between solar transient phenomena and variations of the heliosphere. The payload consists of two main sets: instruments for remote observations of the solar atmosphere (magnetograph, X-ray telescopes and spectrometers, a coronagraph, a heliospheric telescope) and instruments for local heliospheric measurements of the main parameters of the medium (detector of ions and electrons in the solar wind, detector of solar wind plasma and dust, radiofrequency and plasma–wave complex, magnetometer, and energetic particle detector).

The ballistic scheme of SC's approach to the Sun by multiple gravitational maneuvers near Venus (Fig. 4) was also used in the NASA [5] Solar Probe Plus project [43] to achieve an approach at a distance of $9.5 R_{\odot}$ in the motion in an orbit near the ecliptic plane. The tasks set are the following: using observations and measurements near the Sun to determine the acceleration mechanisms and sources of fast and slow solar wind at the maximum and minimum of solar activity; determining the sources and fluxes of energy which heat the corona; bringing acceleration mechanisms into correlation with the sources of energetic particles; and estimating the role played by plasma turbulence and dust plasma in the generation of solar wind and energetic particles. The complex of scientific payload comprises instruments for local measurements (a fast ion analyzer, two fast electron analyzers, an ion composition analyzer, an energetic particle detector, a magnetometer, a plasma–wave instrument, a gamma-neutron spectrometer, a dust detector) and a heliospheric white-light telescope for solar corona observations.

In the stage of development is the Solar-D project (Plan A, JAXA [6]) [44] — an out-of-the ecliptic mission with a small SC, which will accommodate a Doppler vector magnetograph, an X-ray and a UV telescope, a monitor of general solar radiation flux, and instruments for local measurements. The heliocentric inclined orbit with a period of one year will be timed to Earth's orbiting.

In the NASA Telemachus project [45], it is planned to place the SC into a heliocentric polar orbit with a perihelion/apogee of $0.2 \times 2.5$ astronomical units (A.U.) using a gravitational maneuver near Venus, twice near Earth, and

[5] National Aeronautics and Space Administration.

[6] Japan Aerospace Exploration Agency.

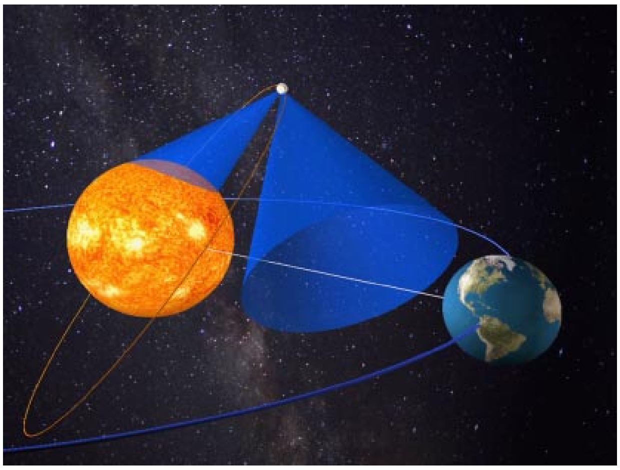

**Figure 5.** Future Solar Sail project with a high orbit inclination to the ecliptic plane.

near Jupiter. The SC will pass at a distance of 0.37 A.U. above the solar poles with a period of 1.5 years. The project is aimed at studying the solar polar flows and their role in magnetic field transfer, as well as at tracing the chain of events from magnetic field generation by the dynamo mechanism to the formation of active regions, the emergence of coronal mass ejections, solar wind generation, flare production, energetic particle acceleration, and eventually inner heliosphere dynamics. The scientific payload of the project comprises instruments for remote observations (a Doppler magnetograph, an X-ray spectrometer, a heliospheric telescope, a white-light coronagraph) and instruments for local measurements (a magnetometer, plasma composition and accelerated plasma analyzers, an energetic particle detector, a cosmic-ray telescope, and a wave analyzer).

To achieve heliocentric orbits with a higher inclination to the ecliptic plane (about 75°) for the purpose of performing helioseismological and magnetic observations of the polar solar regions and the picture of solar perturbation propagation in the ecliptic plane, under development are projects reliant on solar sail technology: POLARIS (POLAR Investigation of the Sun) (NASA) [46], Solar Polar Orbiter [47] and Solar Polar Imager (ESA) [48], and Solar Sail (Roscosmos) (Fig. 5). The main objectives of these projects include investigations of polar magnetic fields, of surface and subphotospheric motions, which are responsible for the dynamo and solar cycle; of the polar corona, the heliolongitude and three-dimensional structure of the corona and mass ejections; of solar radiation as a function of the heliolatitude; and of the properties of the polar solar wind and energetic particles and their connection with coronal structures.

Several solar space projects are under development in China. The KuaFu project [49] is aimed at investigations of the physical processes responsible for space weather. It is planned to place two SCs (KuaFu-B1 and B2) in a near-Earth polar orbit with close instrument sets for investigating magnetic storms and auroras; and one SC (KuaFu-A) equipped with the corresponding set of instruments to be placed before the magnetosphere at the L1 libration point for observing the Sun and measuring solar wind fluxes and perturbations propagating to Earth. The ASO-S (Advanced Space-based Observatory Solar) project [50] is being developed for studying solar magnetic storms, flares, mass ejections, and their interrelation. The main instruments involve: a full-disk vector magnetograph, an optical telescope ($Ly_\alpha$), and a hard X-ray telescope. In the developed Solar Polar ORbit Telescope (SPORT) project [51], which is now at the stage of discussing how to carry it out, it is planned to place the SC in a heliocentric out-of-the ecliptic orbit, similar to the Ulysses SC orbit, using a gravitational maneuver near Jupiter. The objective is to study solar magnetic fields at high latitudes, the high-velocity solar wind, and the propagation of mass ejections from the Sun to Earth. The suggested scientific payload comprises an extreme ultraviolet telescope (121.6 nm), a magnetograph, a coronagraph, a heliospheric telescope, an aperture synthesis radio telescope, a solar wind analyzer, a magnetometer, a radio and plasma wave detector, and an energetic particle detector.

In the Proba-3 (ESA) technological project [52], two SCs placed in a highly elliptical orbit will provide observations of the inner solar corona by forming a space coronagraph — an artificial solar eclipse: one SC will accommodate a telescope, and the other will play the role of an eclipse disk. The possibility of achieving in space a high spatial resolution and obtaining high-definition images of the inner corona is of interest in studying the fine magneto-plasma structure of the inner corona, mass and energy transport, corona heating, and the formation and acceleration of the solar wind.

Several projects, in particular those which will be realized aboard the ISS, are planned to investigate the Sun from near-Earth orbits. The Arka (Roscosmos) project is aimed at investigations of small- and ultrasmall-scale (about 75 km) activity in the transition region (micro- and nanoflares, transient processes and corona heating, flare and mass-ejection trigger mechanisms) based on X-ray observations with a high spatial resolution using two telescopes. The SC of the Solar-C (Plan-B, JAXA) project [53] is planned for launch into a polar solar-synchronized near-Earth orbit for studying the dynamics of the chromosphere and transition region using spectral images with a high temporal and spatial resolutions in the ultraviolet, hard ultraviolet, and visible ranges. These observations will be focused on studying the mechanisms of corona heating and fast solar wind acceleration, as well as on investigating basic plasma processes in the outer atmosphere of the Sun: reconnection, shock wave production, particle acceleration, and turbulence.

In the Indian Aditya-1 solar space project, it is planned to use a modern solar coronagraph [54] as the main instrument, as well as a UV telescope, an X-ray telescope, a detector of solar wind particles, and a soft X-ray spectrometer. The main objectives of the mission are to study coronal mass ejections, solar magnetic structures, and the basic processes underlying solar corona heating.

In the Russian segment of the ISS, the space experiments (SEs) Kortes and Takhomag-MKS are under preparation, and the Solntse-Teragerts experiment is in the development stage. The Kortes SE is aimed at investigating the solar corona, eruptive phenomena, flares and preflare conditions, and at developing new X-ray instrumentation, which comprises three extreme ultraviolet telescopes (195, 305, and 584 Å), three spectroheliographs (170–210 Å, 240–280 Å, 280–330 Å), and three soft X-ray instruments (0.5–15 keV) (a pinhole camera, a polarimeter, and a fast spectrograph). The Takhomag-MKS SC will be arranged for developing a space vector magnetograph (6300 Å) and investigating the structure and dynamics of magnetic fields in the photosphere and chromosphere. The Solntse-Teragerts SC is designed for recording (eight receivers and filters in eight frequency channels in the 1–20 THz range) and investigating the discovered but little-studied terahertz solar radiation.

## 4. Conclusions

Today, spacecraft-based observations make the main contribution to solar research and the solution of key solar physics problems. The ongoing and recently completed solar space missions and experiments provide researchers with a large and diversified set of new data which form the basis for the theoretical analysis and numerical simulations of solar phenomena and physical processes on the Sun.

The helioseismic and magnetic observations by the HMI/SDO instrument permitted us to clarify the structure and dynamics of subphotospheric convective flows and meridional circulation in the form of differential rotation and multicell structure with depth and heliolatitude, to simulate the solar dynamo using the flows studied, and to establish limitations on theoretical models and the yet unknown deeper flows proceeding from the correspondence between modern models, observational data, and solar cycle properties.

Observations of the solar magnetic field throughout the 24th solar cycle permitted recording its polarity reversal and making an estimate of the presumably low amplitude of the forthcoming 25th solar cycle, which is of importance for predictions of the storminess of near-Earth space during the next decade.

To study the fine structure of the solar atmosphere, observations were, and still are, performed with a high spatial resolution in a number of solar missions and experiments (SOHO, Hinode, SDO, IRIS, Hi-C, EUNIS, etc.). These experiments are important for understanding the processes of solar corona heating and solar wind acceleration, as well as the solar flare and mass ejection trigger mechanisms. They permitted determining the special role of the twist of solar magnetic fields in the form of helical magnetic structures and magnetic ropes. As shown by observations and theoretical analysis, in many cases this twist plays the key role in magnetic energy release in flares, eruptive phenomena, and the observed effects of coronal implosion.

Future solar space missions and experiments equipped with higher-performance instruments will permit observing the Sun and making local measurements of the solar wind, mass ejections, and energetic particles, with SCs placed into different working orbits (see Fig. 1), each of which is selected based on the formulated scientific tasks and resource limitations.

Spacecraft placed in heliocentric orbits will be capable of making measurements from out-of-the ecliptic positions near the Sun and in orbits with a high inclination to the ecliptic plane, using solar sail technology which permits reaching these orbits in an acceptable time period and simultaneously providing an acceptable project cost. In the solar missions and experiments in near-Earth orbits that rely on the exploitation of large telescopes and the capabilities of the International Space Station, the solar atmosphere will be observable with a still higher spatial resolution.

Analysis of the observational data of each solar experiment and the aggregate data from different missions will make possible an advancement towards the understanding of how our Sun is structured and how it works.

## References


1. Kuznetsov V D *Adv. Space Res.* **55** 879 (2015)
2. Kuznetsov V D *Phys. Usp.* **53** 947 (2010); *Usp. Fiz. Nauk* **180** 988 (2010)
3. Kuznetsov V D, in *Pyat'desyat Let Kosmicheskikh Issledovanii: po Materialam Mezhdunar. Foruma 'Kosmos: Nauka i Problemy XXI Veka', Oktyabr' 2007, Moskva* (Fifty Years of Space Research: Materials of the Intern. Forum 'Space: Science and the Problems of the XXI Century', October 2007, Moscow) (Ed. A V Zakharov) (Moscow: Fizmatlit, 2009) p. 60
4. Kuznetsov V D (Ed.) *The CORONAS-F Space Mission: Key Results for Solar Terrestrial Physics* (New York: Springer, 2014); Translated from Russian: *Solnechno-Zemnaya Fizika: Rezul'taty Eksperimentov na Sputnike CORONAS-F* (Moscow: Fizmatlit, 2009) p. 10
5. Bothmer V, Daglis I A *Space Weather: Physics and Effects* (Berlin: Springer, 2007)
6. Kuznetsov V D *Phys. Usp.* **55** 305 (2012); *Usp. Fiz. Nauk* **182** 327 (2012)
7. Kuznetsov V D *Kosm. Tekh. Tekhnol.* (3) 3 (2014)
8. Marov M Ya, Kuznetsov V D, in *Handbook of Cosmic Hazards and Planetary Defense* (Eds J N Pelton, F Allahdadi) (New York: Springer, 2015) p. 47
9. Kuznetsov V D, Makhutov N A *Herald Russ. Acad. Sci.* **82** 36 (2012); *Vestn. Ross. Akad. Nauk* **82** 110 (2012)
10. Kuznetsov V D, in *Vliyanie Kosmicheskoi Pogody na Cheloveka v Kosmose i na Zemle: Trudy Mezhdunar. Konf., 4–8 Iyunya 2013* (Effect of Space Weather on Humans in Space and on Earth: Proc. Intern. Conf., 4–8 June 2013) (Eds A I Grigor'ev, L M Zelenyi) (Moscow: IKI RAN, 2013) p. 11
11. Scherrer P H et al. *Solar Phys.* **275** 207 (2012)
12. Corbard T, Thompson M J *Solar Phys.* **205** 211 (2002)
13. Dikpati M *Mon. Not. R. Astron. Soc.* **438** 2380 (2014)
14. Zhao J et al. *Astrophys. J.* **774** L29 (2013)
15. Schad A, Timmer J, Roth M *Astrophys. J.* **778** L38 (2013)
16. Hanasoge S M, Duvall T L (Jr.), Sreenivasan K R *Proc. Natl. Acad. Sci. USA* **109** 11928 (2012)
17. Hathaway D H, Upton L, Colegrove O *Science* **342** 1217 (2013)
18. Lord J W et al. *Astrophys. J.* **793** 24 (2014)
19. Guerrero G et al. *Astrophys. J.* **779** 176 (2013)
20. Schad A, Timmer J, Roth M *Astrophys. J.* **778** L38 (2013)
21. Ghizaru M, Charbonneau P, Smolarkiewicz P K *Astrophys. J.* **715** L133 (2010)
22. Sun X et al. *Astrophys. J.* **798** 114 (2015)
23. Zhao J, Kosovichev A G, Bogart R S *Astrophys. J.* **789** L7 (2014)
24. Wang Y-M, Nash A G, Sheeley N R (Jr.) *Science* **245** 712 (1989)
25. Gizon L, Duvall T L (Jr.), Larsen R M, in *Recent Insights into the Physics of the Sun and Heliosphere: Highlights from SOHO and Other Space Missions* (Proc. of IAU Symp., Vol. 203, Eds P Brekke, B Fleck, J B Gurman) (San Francisco, Calif.: Astronomical Society of the Pacific, 2001) p. 189
26. Svalgaard L, Cliver E W, Kamide Y *Geophys. Res. Lett.* **32** L01104 (2005)
27. Komm R, Gosain S, Pevtsov A *Solar Phys.* **289** 475 (2014)
28. Tiwari S K, Venkatakrishnan P, Sankarasubramanian K *Astrophys. J.* **702** L133 (2009)
29. Komm R et al. *Astrophys. J.* **605** 554 (2004)
30. Liu C et al. *Astrophys. J.* **795** 128 (2014)
31. Hudson H S *Astrophys. J.* **531** L75 (2000)
32. Wang H, Liu C *Astrophys. J.* **716** L195 (2010)
33. Liu C et al. *Astrophys. J.* **622** 722 (2005)
34. Amari T, Canou A, Aly J-J *Nature* **514** 465 (2014)
35. De Pontieu B et al. *Solar Phys.* **289** 2733 (2014)
36. Cirtain J W et al. *Nature* **493** 501 (2013)
37. Testa P et al. *Astrophys. J.* **770** L1 (2013)
38. Winebarger A R et al. *Astrophys. J.* **771** 21 (2013)
39. Peter H et al. *Astron. Astrophys.* **556** A104 (2013)
40. Brosius J W, Daw A N, Rabin D M *Astrophys. J.* **790** 112 (2014)
41. "Solar Orbiter Exploring the Sun-Heliosphere connection", Definition Study Report ESA/SRE(2011)14 (Frascati: European Space Agency, 2011); http://sci.esa.int/solar-orbiter/48985-solar-orbiter-definition-study-report-esa-sre-2011-14/#

42. Kuznetsov V D, in *Proekt Intergeliozond. Trudy Rabochego Soveshchaniya, Tarusa, 11–13 Maya 2011* (Intergeliozond Project. Workshop Proc., Tarusa, 11–13 May 2011) (Ed. V D Kuznetsov) (Moscow: IZMIRAN, 2012) p. 5
43. "Solar Probe Plus: Report of the Science and Technology Definition Team", NASA/TM–2008–214161 (Greenbelt, MD: National Aeronautics and Space Administration, Goddard Space Flight Center, 2008)
44. Tsuneta S "JAXA plan for solar and heliospheric observations", in *ILWS Tenth Anniversary Symp., Vienna, February 14, 2013*; http://hinode.nao.ac.jp/SOLAR-C/Documents/2013_ILWS10.pdf
45. Roelof E C et al. *Adv. Space Res.* **34** 467 (2004)
46. Appourchaux T et al. *Exp. Astron.* **23** 1079 (2009)
47. Tsuneta S et al. *J. Spacecraft Rockets* **43** 960 (2006)
48. Liewer P C et al., in *NASA Space Science Vision Missions* (Progress in Astronautics and Aeronautics, Vol. 224, Ed. M S Allen) (Reston, Va.: American Institute of Aeronautics and Astronautics, 2008) p. 1
49. Tu C-Y et al. *Adv. Space Res.* **41** 190 (2008)
50. Gan W, in *40th COSPAR Scientific Assembly, Moscow, 2–10 August 2014*, Abstract D2.3-14-14
51. Wu J et al., in *ILWS Workshop. The Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects, February 19–24, 2006, Goa, India*
52. PROBA-3: Project for On-Board Autonomy-3, https://directory.eoportal.org/web/eoportal/satellite-missions/p/proba-3
53. Suematsu Y, SOLAR-C Working Group, in *1st SOLARNET–3rd EAST/ATST Meeting, Oslo, 5–8 Aug. 2013*; http://folk.uio.no/matsc/oslo-13/suematsu.pdf
54. Rao V K, in *61st Intern. Astronautical Congress 2010, IAC 2010. Proc. of a Meeting, 27 September–1 October 2010, Prague, Czech Republic* (Paris: Intern. Astronautical Federation, 2011) p. 398