CONFERENCES AND SYMPOSIA

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

75th ANNIVERSARY OF IZMIRAN

Space solar research: achievements and prospects

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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]

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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

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

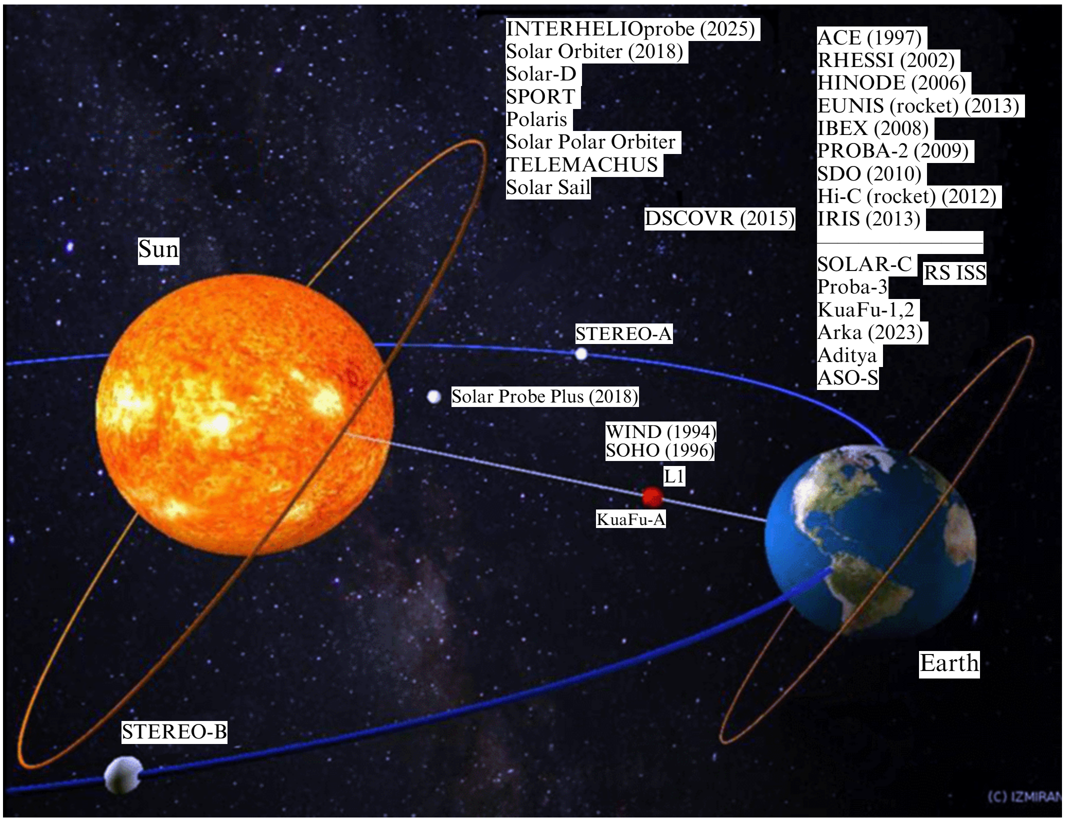

Figure 1. Ongoing and future solar and heliospheric missions (see Table 1) and their orbital positions (in geocentric and heliocentric orbits).

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

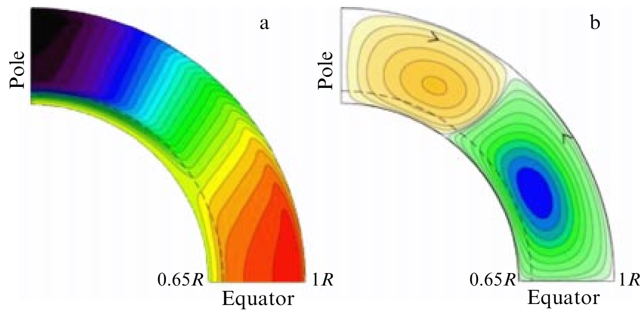

Figure 2. (a) Differential rotation pattern of subphotospheric solar layers [12]. Light-to-dark color transition corresponds to an increase in angular rotation velocity. (b) Meridional circulation pattern generated by this differential rotation and turbulent viscosity [13].

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 (~ 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 micro-loops. 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

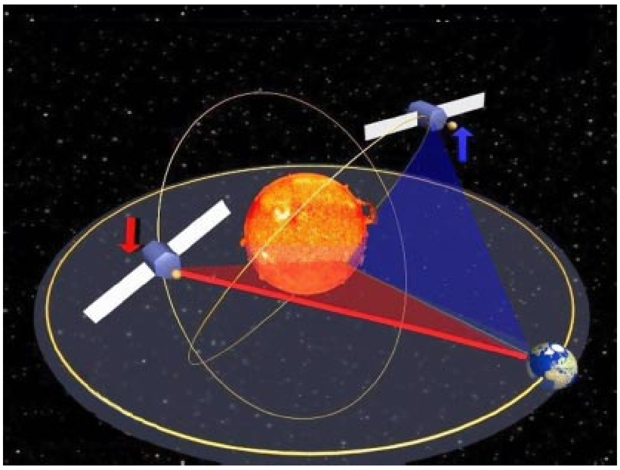

Figure 3. Ballistic scheme of the Interhelioprobe project for the study of the inner heliosphere and of the Sun at close distances and from out-of-the ecliptic positions.

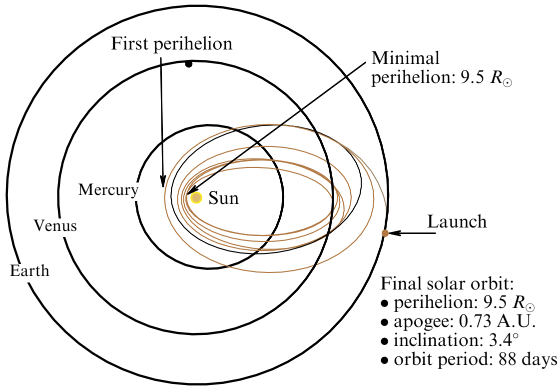

Figure 4. Ballistic scheme of Solar Probe Plus SC's approach to the Sun using multiple gravitational maneuvers near Venus (NASA).

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 $60-70R_\odot$ 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 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 $9.5R_\odot$ 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 0.2×2.5 astronomical units (A.U.) using a gravitational maneuver near Venus, twice near Earth, and

[4] European Space Agency.

[5] National Aeronautics and Space Administration.

[6] Japan Aerospace Exploration Agency.

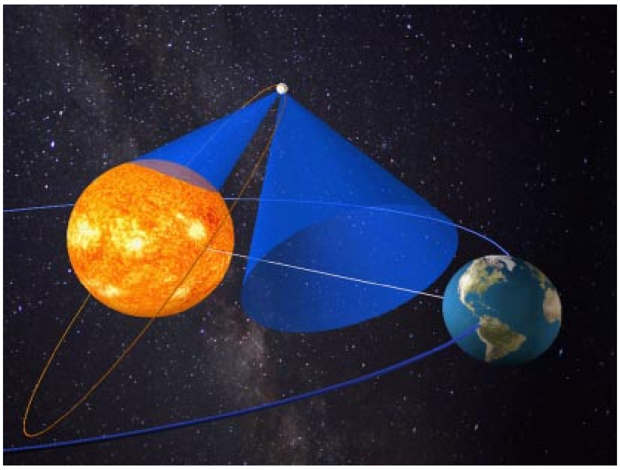

Figure 5. Future Solar Sail project with a high orbit inclination to the ecliptic plane.

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_{α}), 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.

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