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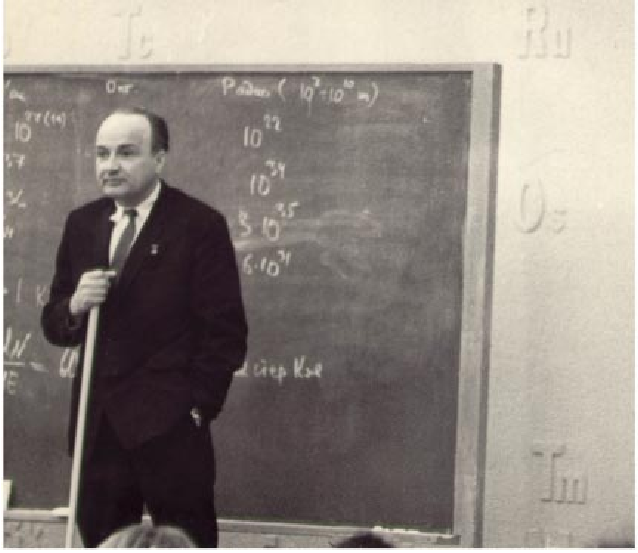

Sergei Ivanovich Syrovatskii. A seminar talk.

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Space research of the Sun

V D Kuznetsov

1. Introduction

When speaking about solar studies, we first mean the Sun, our nearest star, as an astrophysical object that interests us because of both purely scientific (astrophysical) and practical aspects (since the Sun influences Earth and our life). Solar physics embraces various physical areas: nuclear physics, plasma physics and magnetic hydrodynamics (MHD), radiophysics, atomic physics and spectroscopy, and so on. All these physical directions are currently part of modern astrophysics as well.

The Sun is a natural space laboratory accessible for detailed investigation. Solar observations provide vast valuable data for understanding the Sun's composition and workings, and testing current theories and models applied for describing plasma, MHD, and other processes in space conditions, in particular, in distant astrophysical objects (e.g., convection, dynamo, and active phenomena). Currently, we can speak of heliophysics science, because solar and heliospheric physics are inseparably linked with each other [1]. It is appropriate that to mark the 50th anniversary of the International Geophysical Year, 2007 was named the International Heliophysical Year. Recently, the most significant progress in solar studies has been due to spacecraft studies; spacecraft allow observing the Sun in electromagnetic spectral ranges inaccessible from Earth, in the X-ray and ultraviolet ranges (extraterrestrial astronomy), as well as carrying out local measurements of plasma fluxes and particles emitted directly from the Sun. Elimination of the atmospheric influence for observations from space have provided a higher quality of optical observations, even though the size of space telescopes is always limited in comparison with ground-based terrestrial ones.

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In the 1970s, Sergei Ivanovich Syrovatskii's main scientific interests were related to solar studies, magnetic reconnection and solar flares, and space, mostly solar, MHD — the fields where he is one of the classics. He paid considerable attention to observations of the Sun and its active atmospheric phenomena, whose origin and physics were quite interesting and not fully understood. Observations were regularly discussed at his seminar, and the theory of current sheets and magnetic reconnection was originated [1, 2], which was the basis for developed models of solar flares [3, 4] and other active phenomena. Observations with a high spatial resolution were not available at that time; this, on the one hand, provided a base for different approaches to explanations of phenomena and for discussions, and, on the other hand, set out the task of developing high-resolution space observations, which were eventually realized and have confirmed Syrovatskii's ideas.

2. Solar space projects

The current period in solar studies is called the golden era of solar physics in space, because such numbers of spacecraft and related results have never been seen before in the history of space research. Table 1 presents solar space projects of previous years, separated into four parts: recently completed, current, in preparation, and under development. A separate column shows the worthy contributions of Russian projects to this area of research.

In Sections 3–7, a brief review is given of the main results of solar space studies, from the solar interior to the solar wind. In Section 8, future solar space projects are described. A more detailed account can be found in Refs [5–7].

According to the current model, the Sun has a core where energy releasing thermonuclear fusion reactions occur; a radiation zone, throughout which the radiation energy released in the core is transferred to outer regions; the convective zone, the most outward invisible shell where the

Table 1. Recent solar space projects *

	USA, Europe, Japan	Russia
Completed	Ulysses (1990 – 2009)	CORONAS-F (2001 – 2005) CORONAS-FOTON (2009)
Current	SOHO (1995) TRACE (1998) RHESSI (2002) Hinode (2006) STEREO (2006) SDO (2009)	
In preparation	Solar Probe + (2018)	Interhelioprobe (> 2014)
Under development	Solar orbiter (> 2017) Sentinels Polaris, etc.	Polar–Ecliptic Patrol (PEP)
* In brackets are spacecraft launching years and operation periods.		

energy transfer to external regions occurs through convection; the atmosphere, including the visible solar outer shells: the photosphere, chromosphere, transition region, and corona transiting to solar wind. The presentation below follows this solar structure, from the core to the solar wind.

3. Solar interior and helioseismology

The Sun's interior is investigated from space by observing its global oscillations, whose amplitude, manifested in fluctuations of radiation fluxes, plasma density, and velocity, is small enough to require high-precision measurements (10^{-6}) achieved in extraterrestrial observations. There are two types of solar global oscillation modes transferring information about the solar interior: G-modes (with a period greater than 30 min), which are yet undetected, and p-modes (with a period of the order of 5 min), which are actively being investigated by helioseismology methods [8]. About 10–15 high-amplitude p-mode harmonics can be detected simultaneously [9, 10]; with time, some modes disappear and others appear. One of the interpretations invokes the convection effect, which has a wide noise spectrum, on natural harmonic oscillations inside the Sun. Frequency splitting of p-mode global oscillations due to the Sun's rotation has been recorded; this provides information on the angular velocity of the inner region rotations.

Figure 1 shows the solar rotation and inner layer current picture according to helioseismology data [MDI (Michelson Doppler Imager) instrument aboard the SOHO (Solar and Heliophysics Observatory) spacecraft]. The rotation is differential, with the angular velocity depending on the radius and latitude, which makes the pattern of motions quite complex. The darker color corresponds to velocities above the average, and the lighter color to velocities below the average. At the equator, the rotation speed is higher, decreasing in moving to the poles. On the Sun's surface, bright zones rotate slightly faster, and sun spots tend to appear at the boundaries of these regions. There is a slow meridional current flowing from the equator to the poles; it is closed at the bottom of the convective zone. This flow plays an important role in the solar dynamo and in the description of the solar cycle.

With the use of acoustic tomography methods (local helioseismology), it is possible to reconstruct the pressure (or speed of sound) distribution in subphotospheric layers and on the invisible solar side surface [11, 12]; this is important for localization of magnetic fluxes emerging from under the photosphere and that of active regions before they appear on the visible solar side and for increasing the longer-term forecast reliability for solar sporadic activity.

Figure 1. Structure of the current inside the Sun and on its surface (SOHO result).

4. Solar atmosphere

The solar atmosphere, ranging from the photosphere to corona (photosphere, chromosphere, transition zone, and corona), is observed in various spectral lines, each of which corresponds to a particular plasma temperature and a solar atmosphere slice at a particular altitude. Multiwave observations thus provide a possibility to reconstruct the altitudinal (three-dimensional) picture of the solar atmosphere and various formations. This imaging spectroscopy method was successfully used in a number of solar projects: SOHO, CORONAS-F (Russian for complex orbital near-Earth observations of solar activity), STEREO (Solar–TErrestrial RElation Observatory), CORONAS-FOTON, Hinode, and SDO (Solar Dynamics Observatory).

At the photospheric level, observations with a high spatial resolution allowed detailed investigations of the convection and the granulation related to it, developed in the form of bright isolated surface regions corresponding to rising hot plasma. These regions are separated by dark 'corridors' forming a continuous network of sinking cooled plasma. A typical granular size is 0.2 arc seconds or 140 km. Between the cells, a background magnetic field about 400 G at the photospheric level is 'grabbed' by the counter-streaming plasma flows, and magnetic flux tubes are formed with a high field intensity up to a few kG. These tubes, predicted earlier [13, 14] and discovered by Hinode data [15], strongly affect the solar atmospheric dynamics, thus demonstrating the important role of the fine structure of the magnetic field.

The subphotospheric structure of plasma flows in a sunspot (the principal magnetized plasma formation of the solar photosphere) was investigated by acoustic tomography methods [11]. It was unclear for a long time how sunspots with high magnetic fields (2000–4000 G) can remain stable, instead of decaying within a few weeks and Sun revolutions (one

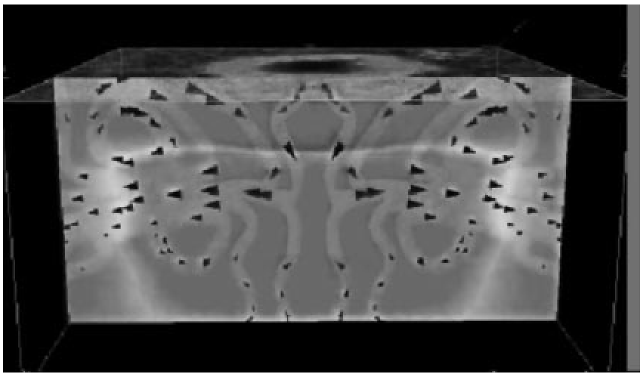

Figure 2. The subphotospheric flow structure around a sunspot providing its long-term stability (SOHO result).

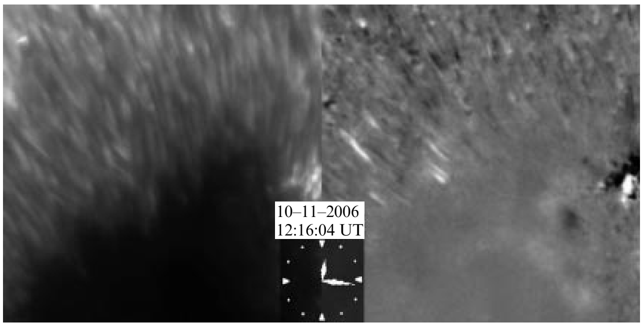

Figure 3. Multiple magnetic reconnection processes in a sunspot, accompanied by plasma ejections (Hinode result).

revolution every 27 days). The sunspots are surprisingly shallow in depth, changing from being colder than their environment to hotter than the environment at only 5000 km below the surface level. At the photospheric level, gas outflow from the sunspot occurs, and at the chromospheric and coronal level, there is gas inflow. Immediately below the surface, theoretically predicted plasma fluxes flowing inside the sunspot have been observed. At various depths under the photosphere, a system of two oppositely circulating toroidal vortices is formed around the sunspot magnetic tube, thus ensuring the long-term sunspot stability (Fig. 2).

According to high-temporal-resolution Hinode observations, numerous micro-ejections due to multiple magnetic reconnection processes of the 'uncombed' (entangled) magnetic field lines near a sunspot (Fig. 3) exist in the sunspot penumbra [16]. These ejections last for about 1 min, their speed is more than 50 km s^{-1}, and they are observed everywhere in the penumbra.

After the photosphere, in the next (by height) solar atmospheric layer, the chromosphere, high-spatial-resolution studies embraced the filamentary structure, spicules, prominences and the motion of substance there, other formations, and plasma heating effects in the vicinity of sunspots.

The structure and dynamics of the solar atmosphere, from the photosphere to the corona, are largely determined by magnetic fields. In the corona, magnetic forces substantially dominate over plasma pressure forces. High-spatial-resolution observations have allowed investigating the magnetic field structure, topology, and dynamics from the photosphere to the corona in detail. All of the Sun's surface is covered by a magnetic 'carpet' [17] with a complex, multiply connected field topology: the field emerging from one source (sunspot) is closed on several other sources. For such a topology, a set of null points and neutral (null) and limit field lines is formed, through which topologically disconnected magnetic fluxes are redistributed. In these regions, according to Syrovatskii's theory, current sheets are formed and the related magnetic reconnection occurs, leading to topological rearrangement of the magnetic field and to phenomena such as flares and mass ejections [3]. In the magnetic field structure, loop magnetic structures dominate at various scales, from the smallest to gigantic ones. Sometimes they form arcades, and the loops are often twisted and undergo eruption. The shapes of plasma structures and plasma dynamics that are determined by magnetic fields are amazing in their originality: surfacing magnetic fluxes, the growth and rise of coronal loops, local ejections and plasma motions along the field, sunspot rotation and related coronal effects, transverse oscillations of coronal loops, ejections of twisted magnetic tubes and prominences, and so on. The Sun's atmosphere clearly demonstrates phenomena and processes that find an explanation in MHD, providing us with a natural plasma laboratory.

In a quiet solar atmosphere, the density monotonically decreases with height, and the temperature starts to increase in the transition zone, increasing in the corona by 200 and more times [$(1-2) \times 10^6$ K] compared with the photospheric temperature (~ 6000 K). One of the solar physical and astrophysical problems is the coronal heating. In addition, there exists the related problem of solar wind acceleration, which we discuss in Section 6.

Despite long-term and intensive studies of the Sun's coronal heating problem, there is still no unique and final answer as regards the coronal heating mechanism. The questions of where the energy comes from, how it is transferred into the corona, and how it dissipates in the corona have not yet been answered. Several mechanisms are being considered. One of them is the heating by waves coming from below: they are generated by the convective zone, converted into Alfvén waves, and propagate upward, into the corona. For a long time, there were no observational confirmations of this mechanism. According to high-temporal-resolution Hinode coronal observations [18, 19], it was possible to detect wave oscillations coming from below, giving support to a more detailed analysis of the wave mechanism contribution to the coronal heating.

Another coronal heating mechanism is related to multiple microreconnection processes in magnetic tubes, where the field is characterized by flux ropes twisted owing to chaotic motions in the photosphere [20]. There are ubiquitous observations by Hinode spacecraft [21] of small local ejections in various directions that accompany the magnetic reconnection process.

On the Sun, an entire hierarchy of energy release processes occurs, from large flares with an energy of the order of 10^{32} erg to micro- and nanoflares, with energies 10^{-6} and 10^{-9} times less. The last are observed as bright X-ray sunspots located even in quiet solar regions and polar zones. They are actually very small loop structures existing almost everywhere. These observations significantly changed the 'quiet Sun' concept, which assumed an equilibrium in the absence of nonthermal processes characteristic for bright X-ray sunspots. From that standpoint, the Sun is never quiet, and coronal heating occurs continuously and at various scales. The Sun's largest-scale hot formations with temperatures 10–20 times higher than the corona temperature were observed by CORONAS-F space-

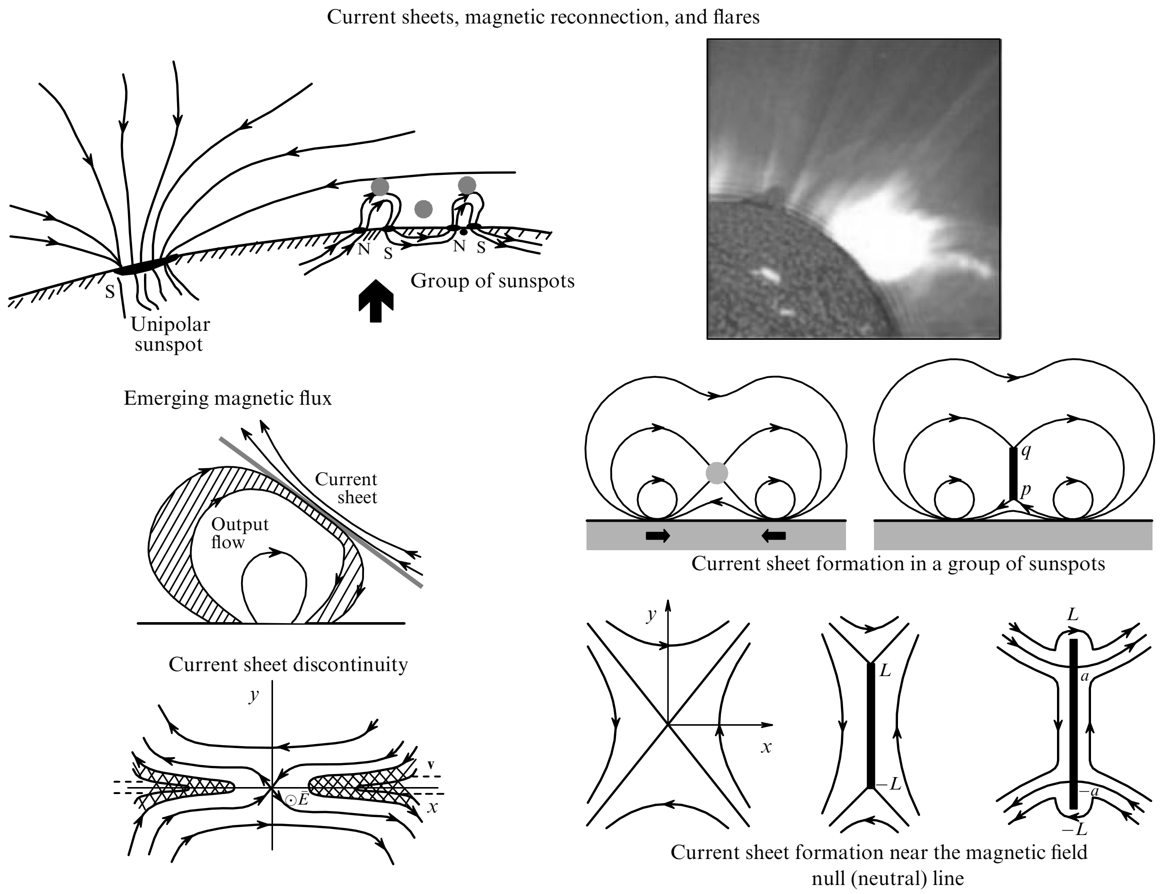

Figure 4. Illustrations of the theory of current sheets and solar flares developed by Syrovatskii.

craft [22, 23]. Their formation is related to the long-lived flare plasma confined by magnetic traps, and they are a manifestation of one of the coronal heating mechanisms, the conversion of magnetic energy into thermal energy in the flares (magnetic reconnection processes).

A statistical analysis of numerous observations according to spacecraft data (Yohkoh, SOHO, TRACE (Transition Region and Coronal Explorer), SMM (Solar Maximum Mission), etc.) showed that events with different energy releases (nanoflares, microflares, and ordinary flares) have common properties, expressed in a power-law distribution of the event number with respect to measured intensities [24]. There are many low-energy events and few high-energy ones. This result underlies the idea that the solar atmosphere is a system with developed turbulence down to very small scales, which sets conditions for dissipation. The role of turbulent vortices is played by reconnection processes at various scales.

5. Active phenomena and coronal heating

Among active solar atmospheric phenomena, the most powerful are solar flares and mass ejections. They are of major interest from both scientific and practical standpoints.

Syrovatskii made a fundamental contribution to the theory of solar flares and their adequate physical model [4]. According to Syrovatskii's theory, current sheets — high current concentrations — appear in the magnetic field structure near null points and neutral lines (Fig. 4). Free magnetic energy in the form of the current magnetic field energy is associated with this layer. It was demonstrated that this energy is sufficient for a flare to occur [25].

The flare itself is associated with the destruction of the current sheet due to various plasma instabilities [26], accompanied by magnetic reconnection in the sheet, a pulsed electric field appearing in the reconnection region, and particle acceleration by this field.

There have been attempts to identify pre-flare current sheets in the solar atmosphere based on their emission [27], in particular, radio emission [28, 29] characteristics. However, recent high-spatial-resolution space observations in the ultra-violet (UV) and X-ray ranges provided clear and demonstrative evidence of the existence of current sheets in solar active regions and their relation to solar flares, thus confirming the fundamentals of Syrovatskii's theory. In Fig. 5, an image obtained by the superposition of two SOHO (UV range, the structure of a magnetic field in the corona) and RHESSI (Reuven Ramaty High-Energy Solar Spectroscopic Imager) (X-ray range, nonthermal energy release) images demonstrates the formation of a current sheet in the solar atmosphere and an accompanying energy release during a flare.

As was already noted in Section 4, numerous magnetic reconnection events followed by ejections of two oppositely directed jets were found to be ubiquitous according to Hinode high-spatial-resolution observations [21]. Every increase in spatial resolution discloses new details of the small-scale solar atmospheric picture, the various forms of magnetic reconnection being one of its characteristic features. A large-scale rearrangement of the magnetic field structure in the solar corona was observed by CORONAS-F spacecraft [the SPIRIT (Russian for heliographic spectral investigations by

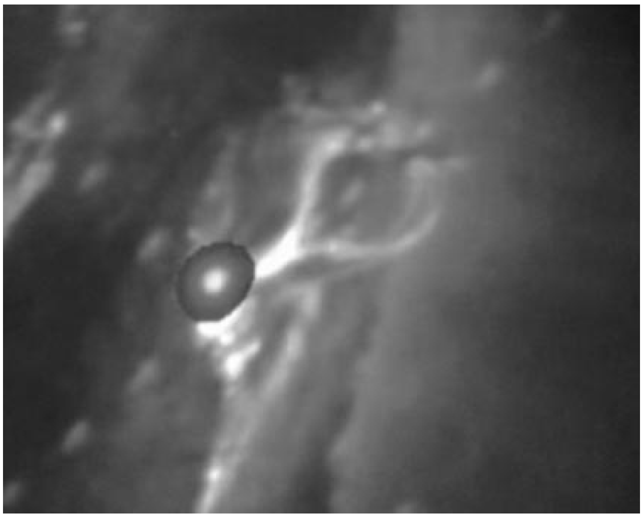

Figure 5. Superposed images of a solar flare illustrating the magnetic configuration with a current sheet (SOHO, UV radiation) and energy release in the flare associated with the sheet (RHESSI, hard X-rays).

an X-ray imaging telescope) experiment] during a very powerful flare on September 7, 2005 that occurred at the east limb [30]; this provided good visibility of the field structure. An initially closed loop field configuration became open after the flare, i.e., the field topology changed, thus indicating a magnetic reconnection.

In solar flares, charged particle acceleration occurs up to high energies (to a few dozen or hundred keV for electrons, and to 1–10 GeV for protons). In the current sheet theory, the initial charged-particle acceleration is related to strong pulsed electric fields that appear at the current sheet discontinuity and magnetic reconnection of field lines [26]. In the CORONAS-F spacecraft observations (the SPR-N experiment), the linear polarization of hard X-rays at the maximum of powerful solar flares was detected [31, 32]; this is related to bremsstrahlung in interactions of pulse-generated electron beams with the background plasma of the solar atmosphere [33]. These observations not only provide direct evidence of the existence of accelerated particle beams themselves, but also confirm that these particles are accelerated by the pulsed electric field during magnetic reconnection, and not by a stochastic mechanism.

RHESSI observations [34] gave answers to those flare physics questions that had previously been formulated and modeled in theoretical studies [33]. Together with TRACE observations, they allowed determining that energy release in flares in most cases occurs in loops and helmet-shaped configurations of plasma heated up to temperatures of a few tens of million degrees, as well as in the form of high-energy electrons moving downward from upper coronal layers and heating the plasma of lower layers. High-spatial-resolution observations of nonthermal X-rays (30–80 keV) allowed localizing the radiation source as the region of accelerated particle precipitation into dense layers of the solar atmosphere at the base of a magnetic loop, such that sources at different bases of the same loop have a different temporal profile and nonsimultaneous brightness increase.

Significant progress was achieved in the investigation of the most powerful phenomena of solar activity, the so-called coronal mass ejections observed in detail by SOHO, CORONAS-F, STEREO, and SDO. Most often, they have loop forms, and are typically twisted. Their origin is related to the global instability of a large-scale magnetic configuration [35].

In one of his last papers, Syrovatskii suggested a formation mechanism for the coronal mass ejection as the result of an outburst of the emerging magnetic flux into the corona [36]. A new emerging magnetic flux is accompanied by the appearance of a null point that moves upward with increasing the velocity, tending formally to infinity (taking the plasma into account, to the Alfvén speed). At some height, reconnection occurs at the null point, the magnetic field restructures, and a new magnetic flux via reconnection bursts out into the corona, leading to an ejection of mass together with the magnetic field (Fig. 6a). Later, with new observations taken into account, the model involving the null point and the current sheet as an inseparable part was detailed by other authors [37] (Fig. 6b), and this improved model soundly describes the actual picture of the ejection development and structure. The model of twisted loop ejections was proposed in Refs [38, 39].

6. Solar wind

The corona generates solar wind that continuously flows into the heliosphere. Local measurement on the Ulysses spacecraft allowed investigating the heliosphere above the ecliptic plane and studying the three-dimensional structure of the solar wind and the inner heliosphere, the magnetic field, the cosmic ray propagation in the heliosphere, and so on.

Figure 7 shows the helio-latitude dependence of the solar wind velocity, which for the minimum solar cycle phase showed a clear difference in the solar wind properties between the polar and equatorial regions: a high-speed (about 800 km s^{-1}) and stable solar wind from the polar regions and a low-speed (about 400 km s^{-1}) and variable solar wind from the near-equatorial regions [40]. For the maximum solar cycle phase, it is difficult to clearly distinguish between polar and equatorial regions according to the solar wind properties. The magnetic field topology distinctly affects the outflowing solar wind velocity. In polar regions, the field lines are mostly open and the wind speed is high here, whereas in near-equatorial regions, the closed field lines dominate and the wind speed is approximately two times lower. The twenty-third solar activity cycle (1995–2007) had maxima around 2000–2001, and two Ulysses spacecraft flights over the poles (north and south poles, at the distance 2 a.u.) were in the solar cycle maximum, and three were over the cycle minimum (two over the north pole and one over the south pole).

The question of solar wind sources on the Sun remains unexplained. In a recent model, it is assumed that the solar wind is formed along the boundaries (where the outflowing velocity is from 5 to 12 km s^{-1}) and at points (where the outflowing velocity is from 10 to 20 km s^{-1}) of the chromospheric magnetic network [41, 42] (Fig. 8). The solar wind plasma is delivered to the cell boundaries by closed magnetic loops dragged by convection in the funnel (magnetic tunnel) — regions of open field lines where they reconnect with the existing open magnetic field lines. The plasma initially stored inside the closed loops is released and accelerated, thus forming the solar wind. High-spatial-resolution observations of the Sun at short distances that are planned for future solar space missions (Interhelioprobe, Solar Orbiter, Solar Probe +) will allow answering the

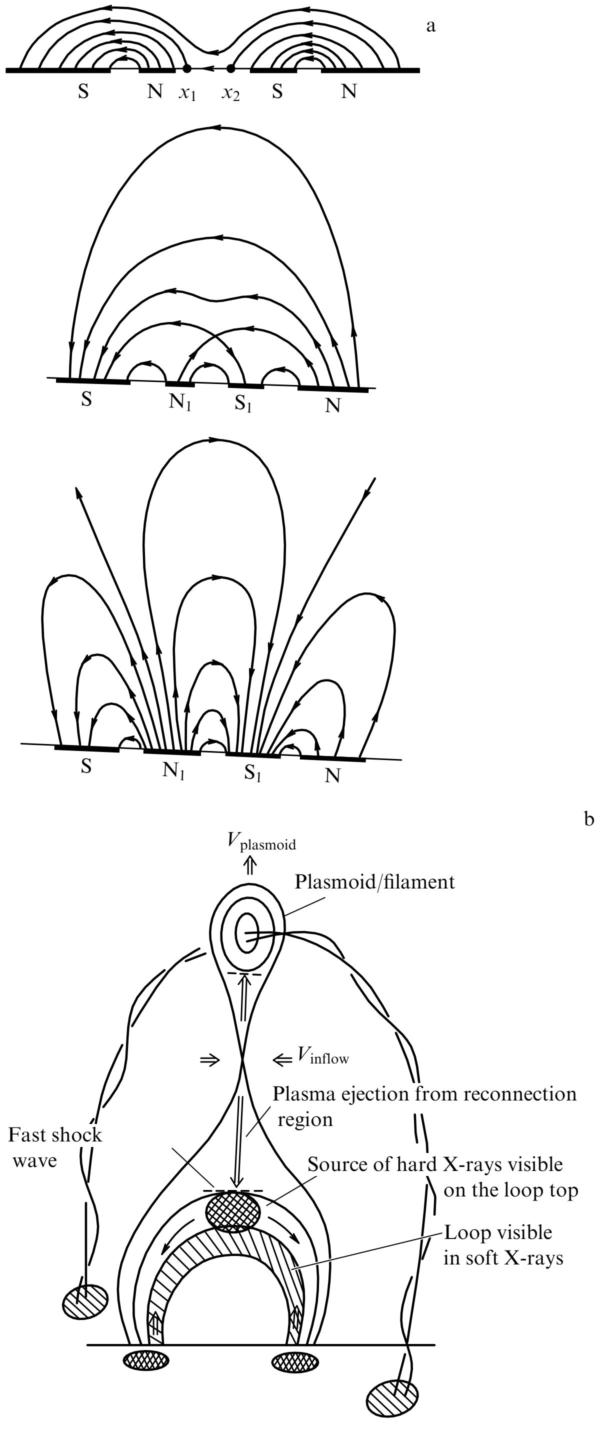

Figure 6. (a) Syrovatskii's ejection model based on an emerging new magnetic flux and its outburst into the corona as a result of magnetic reconnection at the null point [36]; x_1 and x_2 are the positions of the null points on the photosphere, S, S_1, N, and N_1 are the south and north polarities on the photosphere. (b) Development of the ejection model [37] on the basis of current observations (XR denotes X-ray radiation).

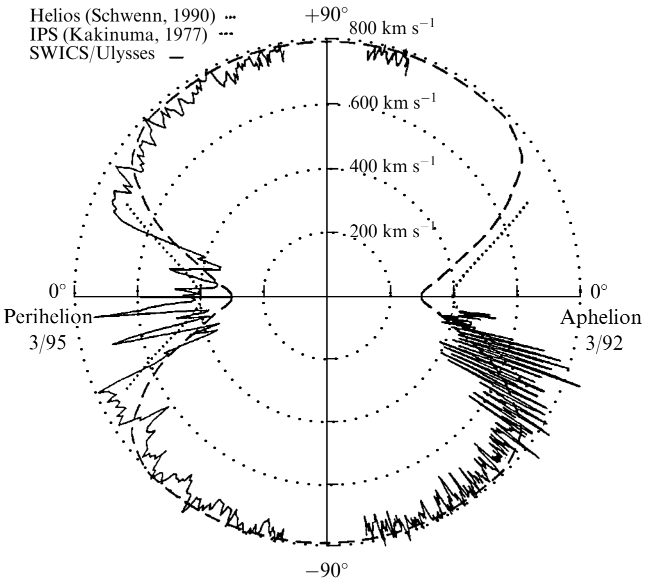

Figure 7. The helio-latitude dependence of the solar wind velocity obtained by the Ulysses spacecraft.

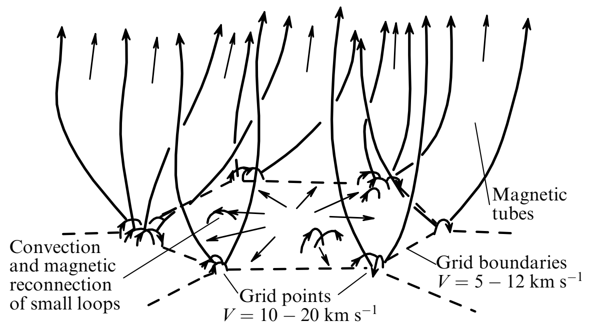

Figure 8. Magnetic network as a possible formation source of solar wind flows [41, 42].

question regarding the true picture of solar wind sources on the Sun.

7. Space weather and its terrestrial effects

The Sun is the main source of space weather formation. Flares, mass ejections, and solar wind flows disturb the heliosphere and near-Earth space, causing magnetic storms and the accompanying phenomena [43]. In the STEREO project, two spacecraft rotate around the Sun in the terrestrial orbit, one of them ahead of Earth and the other at the same distance behind it, such that they can see a noticeable part of the Sun's back side and predict what activity we can expect on the visible side of the Sun. The overlapping of visual fields from these two spacecraft allowed creating stereo images and stereo films of the Sun, providing a 3D picture (Fig. 9). On the STEREO spacecraft, observations of mass ejections propagating from the Sun through the heliosphere were realized for the first time by using a heliospheric telescope [44]. These observations have allowed following the forefront motion of the ejection up to significantly larger distances compared to those provided by ordinary coronographs. The aim of these observations is to control the forefront collision with Earth's magnetosphere; this allows predicting the beginning of a geomagnetic storm and the related effects more accurately compared to current predictions.

Investigation of numerous space weather effects in the near-Earth space is related to practical applications of solar studies and solar–terrestrial physics. The space weather factors (ionospheric and geomagnetic field disturbances, enhanced fluxes of energetic particles and radiations, and so on) affect satellites, their electronics and drag, and ground-based technical systems (transmission lines and energy

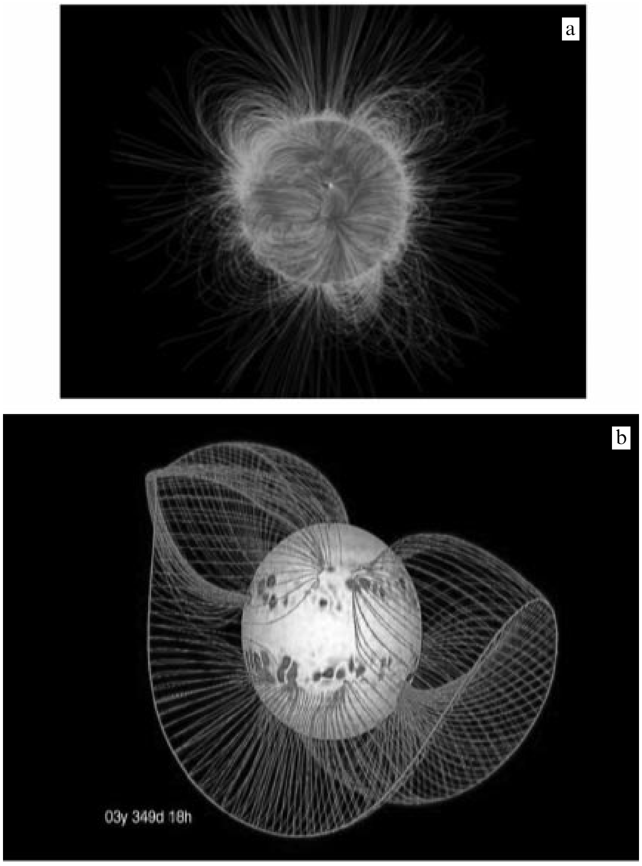

Figure 9. Three-dimensional magnetic fields (a) on the Sun and (b) in the heliosphere (heliospheric current layer) (modeling results by the SOHO scientific group).

infrastructure, pipelines, and so on). Space weather now is a vast research area [45].

8. Future solar space projects

The strategy of future solar space missions is to carry out observations with a higher spatial and temporal resolution, to conduct local measurements in the nearest solar environment, to obtain spectroscopic images from higher helio-latitudes, to make observations outside the Sun–Earth line, and to obtain 3D solar images. All these observation types are designed to improve our understanding of the phenomena occurring on the Sun and to explain unsolved problems of the Sun's physics such as solar coronal heating and solar wind acceleration, the nature of solar wind sources on the Sun's surface, trigger mechanisms of flares and mass ejections, the solar dynamo, and solar cycle mechanisms. Solving these problems will open the way to understanding the Sun's workings and the mechanism of solar–terrestrial connections, and will facilitate improvement of space weather forecasts and reduce the dependence of terrestrial civilization on space weather factors.

The time frames of space projects are important in the context of the phase of the 11-year solar activity cycle. The 23rd solar cycle finished in December 2008, and the 24th cycle is unpredictably long delayed. Such a long minimum solar cycle phase, which has already lasted for more than three years, was not predicted by experts. This tells us that we still understand the Sun and its cyclicity insufficiently well. The new cycle, with the maximum expected in 2012–2014, is predicted to not be high, and this prognosis will serve as an estimate of how correct our views of the Sun's workings are.

In the Russian Interhelioprobe Project [7, 46], which is currently being developed in the framework of the Federal Space Program, spacecraft will approach the Sun as a result of multiple gravitational maneuvering near Venus. Reaching of the corotation point is possible, when spacecraft will hover shortly above the Sun without relative motion. The near-Venus gravitational maneuvers will allow inclining the orbit plane with respect to the ecliptic plane, and performing out-of-ecliptic solar observations. The spacecraft approach to the Sun along the heliocentric orbit will make it possible to observe scales on the Sun smaller than those accessible from near-Earth orbits, which have only been used until now for space solar observations. This is necessary, for example, for investigating the fine structure and dynamics of the solar atmosphere: magnetic network, magnetic elements, and turbulence, as well as for observations of solar wind sources and phenomena such as microreconnection. The corotation regime observations will allow establishing relations between solar and heliospheric phenomena. Local measurements near the Sun, at distances of 40–60 solar radii, will allow investigating plasma processes in detail.

Looking further ahead, the Polar–Ecliptic Patrol (PEP) project is being worked out [7]; in this framework, two spacecraft at heliocentric inclined orbits around the Sun will proceed with a global solar survey and continuous observations of the Sun–Earth line from an out-of-ecliptic position, which should provide better understanding of the 3D picture of solar activity and near-solar space, and the most effective control of space weather.

9. Conclusion

In celebrating Syrovatskii's fruitful contribution to particular areas of solar physics, we stress that many of his ideas regarding the current sheet theory and the solar flare mechanism were confirmed by the results of solar space observations, which were in fact planned under the influence of Syrovatskii's work. The theory of current sheets and magnetic reconnection was significantly developed and observationally confirmed on the Sun, as well as in Earth's magnetosphere [47, 48]. In 2000, the first book on magnetic reconnection was published [47], which was then was translated into Russian. National solar space projects CORONAS-I, CORONAS-F, and CORONAS-FOTON have been realized. The CORONAS-F project work was honored with the Russian Federation Government Award (2008); the project results are presented in book [49]. Noticeable advances are being made in laboratory and numerical modeling of magnetic reconnection [50, 51]. Promising new national projects such as Interhelioprobe and Polar–Ecliptic Patrol are being developed. Continuing solar observations from space under the SOHO, TRACE, RHESSI, Hinode, STEREO, and SDO projects will provide a large amount of more detailed information on solar phenomena at the initial phase of the new cycle and improve understanding of processes occurring in our star.

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Magnetic reconnection in solar flares

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1. Introduction

I was privileged to work under the supervision of Sergei Ivanovich Syrovatskii from 1966 to 1979, first as a graduate and postgraduate student, and then as a scientist at the Theoretical Department of the Lebedev Physics Institute. During those years, which quickly flew by, Syrovatskii was mostly interested in the solar flare problem.

The essence of the problem, its scientific and applied value, is determined by two facts. First, solar flares are a nonstationary electromagnetic phenomenon, typical for space plasmas but accessible to the most detailed investigations, in contrast to other stellar flares and bursts of objects in the Universe. Second, solar flares strongly influence interplanetary and near-Earth space, Earth's atmosphere, and even the biosphere. It is no coincidence that solar flares are interesting for not only astronomers and physicists but also specialists in cosmonautics/astronautics and power engineering, as well as biologists and medics. Syrovatskii made a fundamental contribution to establishing and successfully developing theoretical and experimental solar flare science in our country and abroad. In this communication, I touch upon only one key issue of this science, the role of the

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