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Influence of Fast Global Variations of Solar Magnetic Fields on Space Weather in Cycle 23*

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Abstract It is established that the large-scale and global magnetic fields in the Sun's atmosphere do not change smoothly, and long-lasting periods of gradual variations are superseded by fast structural changes of the global magnetic field. Periods of fast global changes on the Sun are accompanied by anomalous manifestations in the interplanetary space and in the geomagnetic field. There is a regular recurrence of these periods in each cycle of solar activity, and the periods are characterized by enhanced flaring activity that reflects fast changes in magnetic structures. It is demonstrated, that the fast changes have essential influencing on a condition of space weather, as most strong geophysical disturbances are connected to sporadic phenomena on the Sun. An explanation has been offered for the origin of anomalous geomagnetic disturbances that are unidentifiable in traditionally used solar activity indices. It is shown, main physical mechanism that leads to fast variations of the magnetic fields in the Sun's atmosphere is the reconnection process.

Key words Solar magnetic fields, Solar corona, Space weather

1 Introduction

The magnetic field on the Sun changes permanently. The changes of magnetic field during cycle of solar activity are most brightly expressed and have the greatest amplitude. Existing models rather not bad describe the changes of magnetic field in the Sun's convective zone. The changes of magnetic field in solar corona are studied much less. It is connected that the direct measurements of a magnetic field in a solar corona are available only in separate structural areas (protuberances, dense magnetic loop structure). Therefore for research of magnetic field changes in solar corona the results of field calculations, made in potential approximating with a surface of zero potential will be used. The computed coronal magnetic field maps and harmonic coefficients for several altitudes in a solar corona are adduced on Web Site of the Wilcox Solar Observatory.

The coronal magnetic field evolution (calculated in a potential approximation) in the solar activity cycle is analyzed in the paper by Wang and Sheeley^[2]. The model calculation results of magnetic field topol-

ogy changes in the solar corona during a solar cycle are in the paper by Wang and Sheeley^[3]. These calculations are compared with the changes calculated on the base of the observational data. Both in the model, and in calculations on the base of the observational data the case of axial symmetry is esteemed. Besides, it is assumed that the magnetic field in the corona is determined by changes of the subphotosphere magnetic field and spherical surface of a zero potential, and the time scale for the corona to relax to a quasi-potential configuration is much shorter then the time scale for flux to emerge over the solar cycle. Within the framework of their model Wang and Sheeley^[3] have calculated the changes of the magnetic field structure in a solar corona. These changes descend rather smoothly. The different presentation of coronal magnetic field changes, calculated in a potential approximation for the period of April 1973—June 2000 are shown in the paper by Luhmann^[4]. In Fig.4, 5(a), and 5(b) from the paper by Luhmann^[4] there can be seen the availability of rather fast modifications of the magnetic field structures in the solar corona. A rapid transition of the

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polar structures to low-latitude ones is obvious during the growth phase of solar activity and, vice versa, during the decreasing phase.

The authors of Ref.[5] and [6] reported the detection of periods of fast global changes in magnetic fields on the Sun that are characteristic for each 11 year cycle of solar activity and are accompanied by anomalous disturbances in the SW and IMF, cosmic-ray intensity, and geomagnetic activity.

In this paper are studied the fast global variations of large-scale solar magnetic fields, and are investigated the influence of fast global changes of solar magnetic fields on solar wind and interplanetary magnetic field parameters, and on geomagnetic activity.

2 The Changes of Magnetic Field Structure

The long-term variations of the large-scale and global solar magnetic fields have a nonmonotonic character^[7]. Analysis of the dynamics of the global magnetic structure in the corona, based on calculating the coronal magnetic fields within the potential-field approximation for period 1976—2002, shows that, along with slow variations of the global structure of magnetic fields (10—12 solar rotations), there are also rapid changes, spanning approximately two solar rotations. It was found that in each 11 year cycle of solar activity there exist periods of fast global variations on the Sun. These periods recur at regular intervals in every cycle of solar activity and are characterized by enhanced flaring activity, which reflects rapid changes in magnetic structures.

Let us look at the properties of the magnetic restructurings in the solar corona using observational data on large-scale magnetic fields.

During the growth phase of solar activity, the rapid changes are characterized by an enhancement of the low-latitude magnetic fields and signal the start of an intense interaction of emerging magnetic fields of the new cycle with pre-existing fields in the solar atmosphere.

This period includes rapid (one-two solar rotations) changes of the global magnetic structure, “destruction” of the unified current system on the Sun

(dipole-like), and the transition to a more complex structure (the change from the two-sector to four-sector structure). In Fig.1 there are shown the maps of coronal magnetic field at $2.5 R_s$ (in potential approximation with a zero potential surface). On the right-hand panels it is visible, that the configuration of a magnetic field has changed essentially during 1664 Carrington rotation, while on the left-hand panels of a magnetic field slowly change during 6 rotations.

The decreasing phase of solar activity exhibits an opposite process: there is taking place an attenuation of the large-scale low-latitude magnetic fields, and the formation of a common current system (the change from the four-sector to two-sector structure).

The Fig.2 illustrates the evolution of the magnetic structure of the solar corona for the period December 1981—May 1982. The maps of the coronal magnetic field at the Source Surface, calculated in potential approximation with a zero potential surface* are shown on the left-hand panels. It is obvious that from Carrington rotation 1717 to 1719 there is a significant change in the magnetic structure, characterized by an attenuation of the magnetic fields, the disappearance of small-scale inclusions, and by the formation of a structure similar to a dipole one. During this period there occurs a significant enhancement of transient processes, and an additional mass and magnetic field ejection by non-stationary solar wind streams. The anomalous character of this period is due to the interaction of large-scale magnetic fields of the northern and southern hemispheres, and to their merging as a consequence of reconnection. Should note, that analogous period was at October 2003, but its influence on heliosphere was more powerful.

The response of geomagnetic activity to these events is also a unique one. Rather strong geomagnetic disturbances were observed nearly continuously from January 30 to March 2, 1982. This is seen from the data on the geomagnetic activity index C9, which are presented in this Figure (right-hand panel). Note that during this period, solar activity remained virtually unchanged in regard to Wolf numbers.

During maximum solar activity, the variations of large-scale magnetic fields are also nonmonotonic

*<http://wso.stanford.edu/synsource.html>

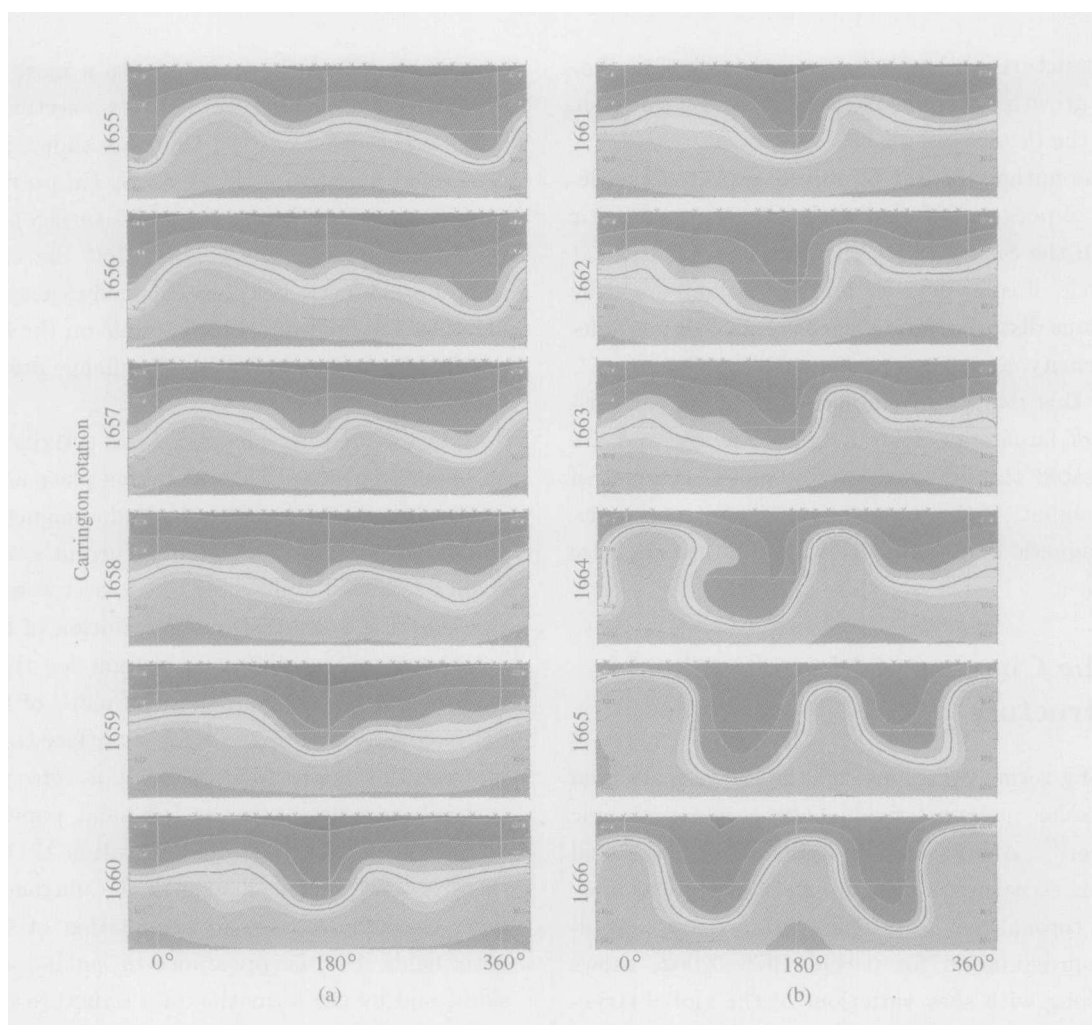


Fig.1 Change in the magnetic structure of the solar corona (Synoptic maps of a magnetic field on $2.5 R_{\odot}$ in a potential approaching with a surface of a zero potential*) for the rising phase of solar activity (Carrington rotations 1655—1666, May 1977 April 1978). (a) slow changes; (b) fast global reconfiguration of magnetic fields in the corona

in character. As regards the period (1972—2002) under consideration, especially noteworthy are the rapid changes in the global magnetic structure of the corona, and their effects in the heliosphere in 1989, 2000, and 2001.

The data in Fig.3(a) show that the stable global structure of magnetic fields in the solar corona changed during one solar rotation (the beginning of April). At this time the large-scale area of positive polarity at Carrington longitudes of 330° — 30° was disrupted and through two rotations there was formed the area of inverse polarity. This resulted in a large number of large-scale powerful Coronal Mass Ejections (CME) observed by the SOHO observatory

(Fig.3, right). In Fig.3 at the right there are shown (as an example) three images of the solar corona obtained on SOHO**. The upper image demonstrates that prior to the beginning of the period of fast rearrangement the CMEs take place only in separate areas, while in the period of rearrangement (other images) they are seen almost simultaneously in different areas that is clearly seen in the analysis of the corona image series obtained on SOHO**. According to flaring activity, this period was unique for the entire current cycle. From March 20 to April 17, 2001 there occurred 51 flares of importance M, and 8 flares of importance X, and on April 15 there was an increase in solar high-energy cosmic-ray intensity,

*<http://wso.stanford.edu/synsource.html>

**<http://sohowww.nascom.nasa.gov>

and a long-lasting geomagnetic storm.

In the paper by Cliver and Leng^[1] there are considered the connection of changes of the open magnetic flux, coronal mass ejections and cosmic ray modulation in the 21st cycle of solar activity. The daily CME rate for period 1979—1990 is presented on Fig.4. As can be seen in Fig.4 the daily CME rate changes during a cycle not continuous. We can see the considerable ascending of this rate in the period of fast rearrangement at a growth phase of solar activity at the end of 1988. At this time there is also a spike in the change of delta open flux for heliolatitudes less 45° , and in intensity galactic cosmic ray in this period the enough strong decreasing is watched^[1]. Should note, that in 1982 the data of daily CME rate are incomplete.

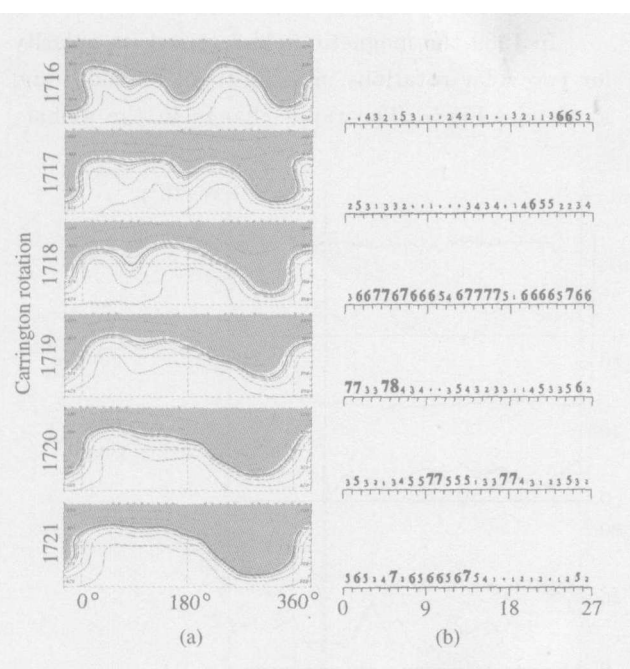


Fig.2 (a) change in the magnetic structure of the solar corona (Synoptic maps of a magnetic field on $2.5R_s$ in a potential approaching with a surface of a zero potential*) for the decreasing phase of solar activity (Carrington rotations 1715—1721, January April 1982); (b) geomagnetic activity index C9

On the basis of the observational data analyzing, in paper Zherebtsov *et al*^[7] was formulated a unifying concept, and was suggested the scenario for fast variations, and also was declared that, the key physical processes of interaction of magnetic fields in the Sun's atmosphere are the reconnection process.

*<http://wso.stanford.edu/synsource.html>

As the magnetic field emerges from the convection zone, because of the high plasma conductivity in the solar atmosphere there is taking place a relatively

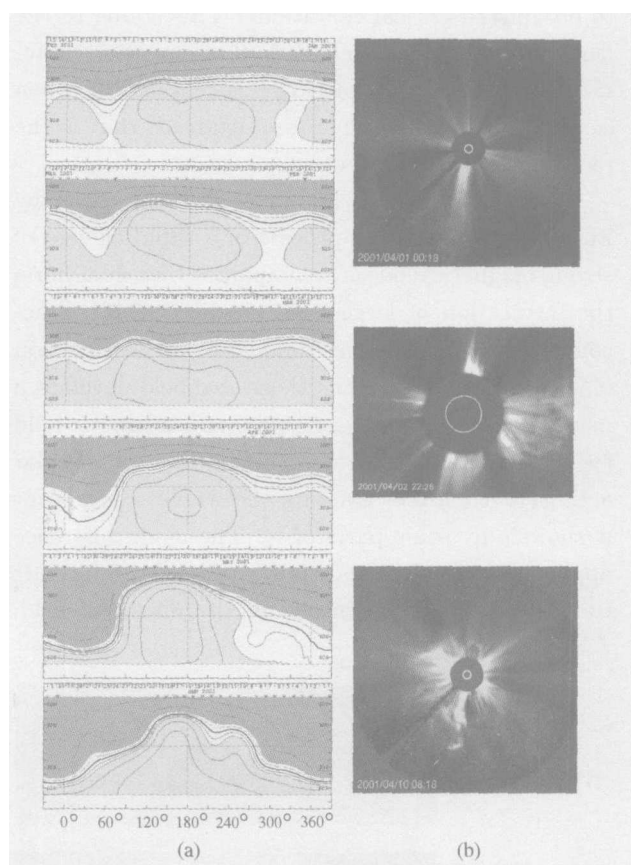


Fig.3 (a) change in the magnetic structure of the solar corona (Synoptic maps of a magnetic field on $2.5R_s$ in a potential approaching with a surface of a zero potential*) (Carrington rotations 1773—1776, February May 2001); (b) corona images at the heights of $2.5R_s$ and $5R_s$ taken by LASCO on SOHO

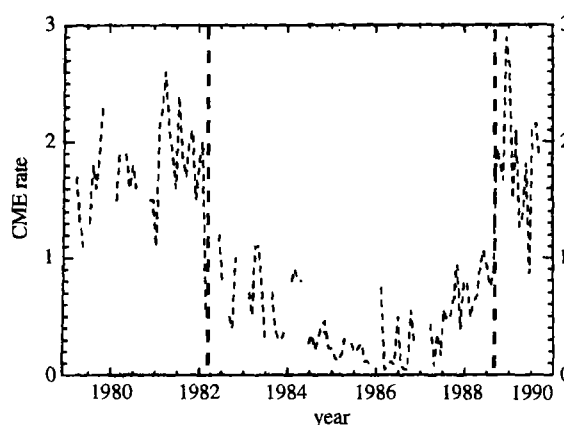


Fig.4 The daily CME rate for period 1979—1990^[1]

slow mutual deformation of the emerging and pre-existing magnetic fields, in other words a new current system is formed, which decays rapidly when to obtain the critical conditions. This is due to the fact that, as the new magnetic flux emerges, an active interaction of magnetic fields sets in only when certain critical parameters are attained, that is the reconnection process sets in.

According to unifying concept of the paper by Zhrebtsov *et al*^[7] the process of a rapid change of strong magnetic fields is accompanied by a solar flare; the interaction of large-scale magnetic fields is accompanied by a mass ejection and by an acceleration of solar cosmic rays, while the global field develops a new structure, and triggers mass and magnetic field ejections. In accordance with this concept, a solar activity cycle either exhibits the whole scenario, or it shows only some parts of it. The main difference applies to the space-and-time scales of the interaction process, the magnitude of the magnetic field,

and, accordingly, the distinctive features of the manifestation of the scenario in the solar atmosphere, heliosphere, and on the ground.

Let us consider influence fast reconstruction periods on the cosmic weather.

3 The Influence of Fast Global Changes on Cosmic Weather

Let us consider as the fast reconstruction periods of solar magnetic fields are manifested in cosmic ray variations. It is known that in cosmic-ray intensity variations there exist (along with long-term variations associated with an 11-year cycle of solar activity) sporadic variations such as solar cosmic-ray bursts and Forbush-decreases.

In 1989 the magnetic field reversed its polarity for two solar rotations, at almost all latitudes and longitudes Fig.5. The rapid change in the global

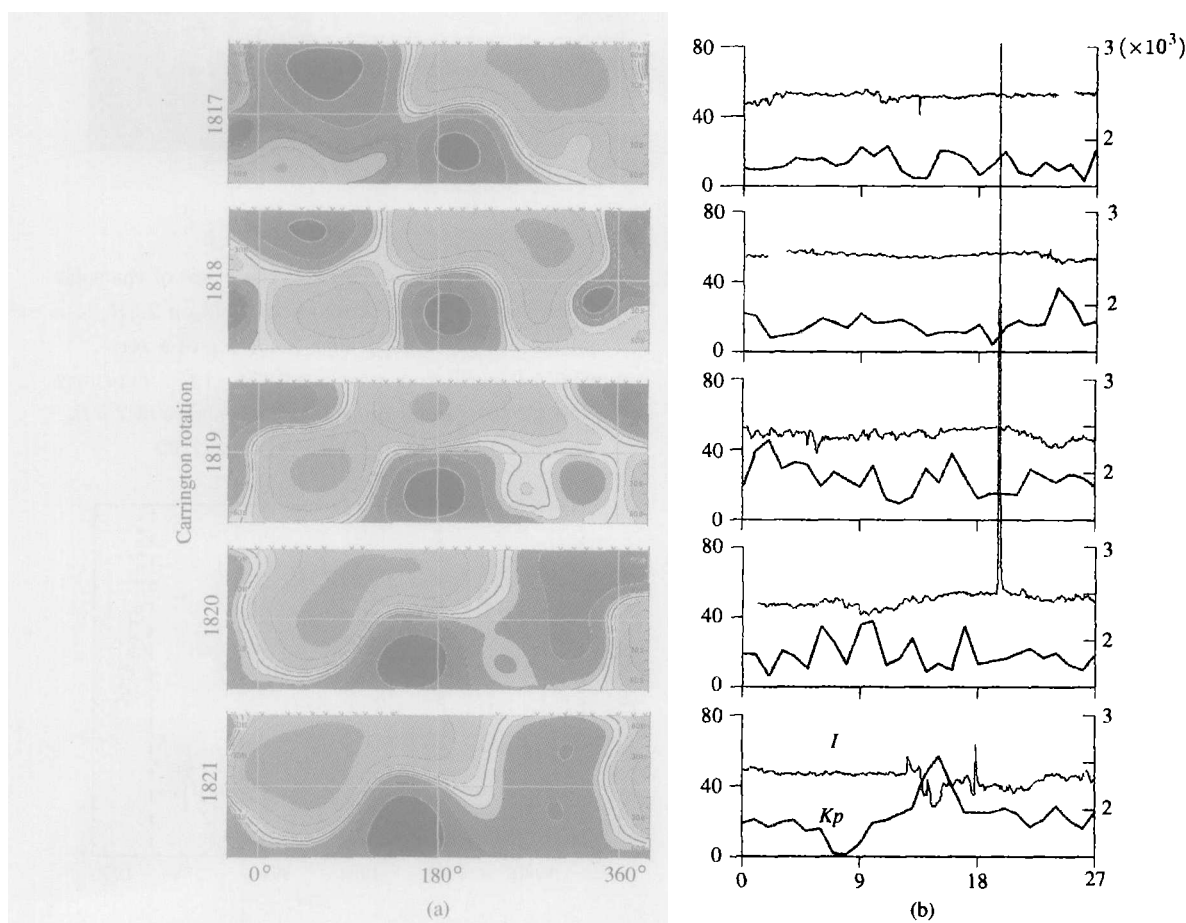


Fig.5 Fast variations of the global magnetic structure at maximum solar activity (1989). (a) fast magnetic restructuring of the solar corona; (b) cosmic-ray intensity and geomagnetic activity index Kp

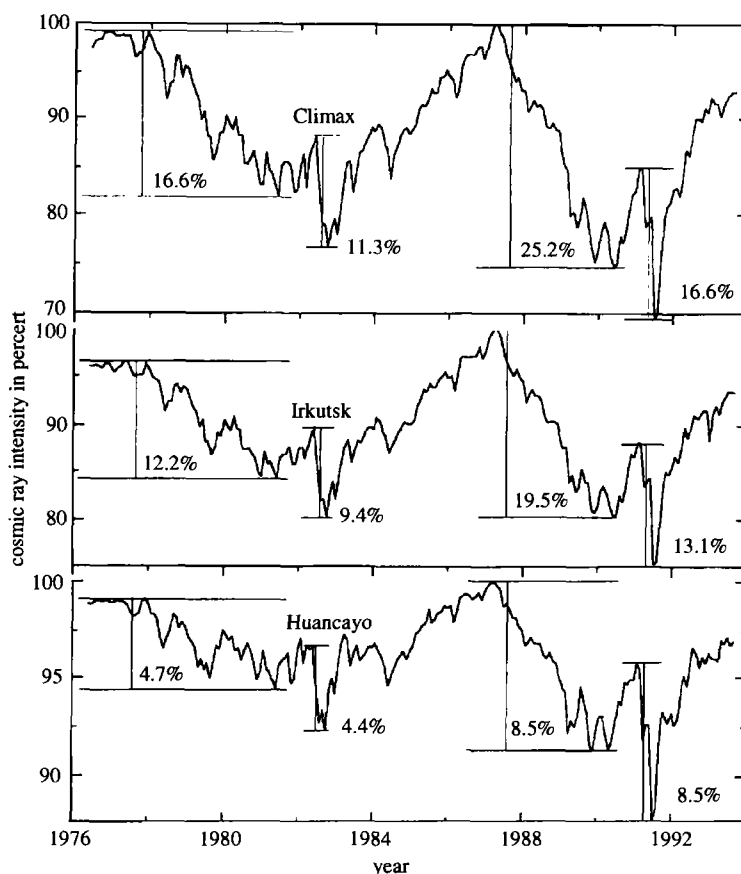


Fig.6 Variations of monthly mean values of the intensity of the cosmic-ray neutron component for stations with different cutoff rigidity: Climax –2 GV, Irkutsk –4 GV and Huancayo –13 GV for the period 1968–2002

magnetic structure in the corona coincides with the September 29, 1989 anomalous event in cosmic rays. A characteristic feature is not only the large value of the particle flux but also the value of the maximum particle energy (several tens of GeV). According to ground-based observations, this increase was the largest for the last three cycles of solar activity. Only a unique solar cosmic-ray flare of February 23, 1956 is comparable. It seems likely that the rapid changes of the electromagnetic structure in the corona at large scales for strong solar magnetic fields create “favorable” conditions for an effective acceleration of solar high-energy cosmic rays. An analysis of the changes in the global magnetic structure using synoptic maps of the Sun in the $H\alpha$ -line for the period of the February 23, 1956 solar cosmic-ray outburst lends support to this conclusion. Similar phenomena, yet in significantly smaller-scale regions, were also observed in 2001.

Galactic cosmic-ray intensity variations are a

sensitive indicator of global changes of the heliosphere. Fig.6 presents the monthly mean intensity values of the neutron component of cosmic rays for stations with different cutoff rigidity: Climax –1 GeV, Irkutsk –4 GeV, and Huancayo –13 GeV, all for the period 1968–2002. The period of fast global variations of solar magnetic fields is more conspicuous and characteristic in long-term cosmic-ray intensity variations during the decreasing phase of each cycle of solar activity (1982, 1991). The incipient recovery of the cosmic-ray intensity, associated with an 11 year cycle of solar activity, is interrupted by an anomalously abrupt decrease, which is characterized by an unusually hard spectrum, of the variations. Fig.6 also gives for each station the values of 11 year variation amplitudes and the amplitude of the decrease, associated with fast global variations of solar magnetic fields. In this case the following important feature is obvious: the amplitude of the anomalous decrease for station Huancayo

($R \approx 13 \text{ GeV}$) is equal to the 11-year variation amplitude in each cycle, while for Irkutsk and Climax the amplitude of the decrease in these periods is significantly lower compared with the 11-year variation amplitude.

A decrease in variation amplitude ratios at stations Climax and Irkutsk against Huancayo means that with a simplification of the corona's global magnetic structure, there is a predominant enhancement of the IMF inhomogeneity on larger scales.

This means that the anomalous decreases in 1982 and 1991 were brought about by variations of the large-scale or even global magnetic structure on the Sun and, accordingly, in the heliosphere.

It is our opinion that an anomalous decrease arises from a global "release" of the solar corona mass, which goes on during 1 or 2 solar rotations. This "release" occurs in the form of a series of solar plasma and magnetic flux ejections, with a pronounced enhancement of the large-scale component of the interplanetary magnetic field. It is latter that determines the hardness spectrum of cosmic-ray intensity variations during that period.

The changes of the global magnetic structure on the Sun and, accordingly, in the heliosphere, as we showed earlier, are responsible for the anomalous decreases during these periods.

The properties of the heliosphere (space-time distribution of the solar wind velocity, particle flux, and interplanetary magnetic field) are governed by large-scale solar magnetic fields and their dynamics. Of special interest is the origin of the large-scale inhomogeneities in the solar wind.

These inhomogeneities are the manifestation of the solar variability in interplanetary space, as well as the chief cause of geomagnetic field disturbances. The main sources of the inhomogeneities are coronal holes, solar flares, and coronal mass ejections.

Analysis of the long-term variations of solar activity indices, such as the Wolf number or the solar radio flux (10.7 cm), and geomagnetic activity, reveals that their variations not infrequently show differences. In some periods when solar activity is high, geomagnetic activity is very low. On the other hand, there are periods of anomalously high geomagnetic disturbance, corresponding to low solar activity during the growth and decreasing phases of an 11-year

solar cycle. This brings up the question: What is the origin of these anomalies? that are accompanied by anomalous manifestations in the heliosphere and geomagnetic field.

Fig.7 presents the data on long-term variations of the helio-geophysical parameters for the period from 1968 to 2002: solar activity, Wolf number (R_z), A_p index of geomagnetic activity, solar wind particle flux, for a low speed solar wind the velocity is less than 400 km/s , mean values of the modulus of the B_z component of the interplanetary magnetic field, for a high speed solar wind the velocity is larger than 500 km/s .

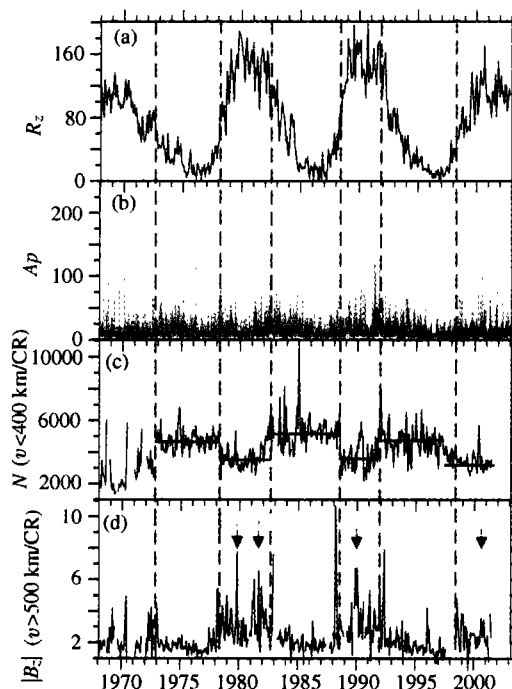


Fig.7 Monthly mean values. (a) Wolf number; (b) A_p -index of geomagnetic activity (daily values); (c) low-speed SW particle flux; (d) modulus of the IMF B_z component for a high-speed SW. Vertical dashed lines represent the periods of fast restructurings of the global magnetic field of the Sun, and the arrows correspond to large-scale magnetic fields restructurings

Changes in the global structures are quite well distinguished in particle flux density of a low speed solar wind (with velocities below 400 km/s), and in the B_z component of the interplanetary magnetic field.

Indeed, an examination of the solar wind parti-

cle flux variations using the data presented in Fig.7 reveals their main regularities that reflect global changes of the magnetic structure of the corona. In addition to fluctuations, there are rapid (spanning 1—2 solar rotations) changes of the solar wind particle flux, decreases during the growth phase of solar activity, and increases during the decreasing phase, which are caused by a global reconfiguration of the magnetic field in the corona. These changes are accompanied by significant increases of the B_z component of the interplanetary magnetic field for a high speed solar wind, which reflect the effects of transient processes in the solar corona. During the aforementioned periods the global structure of the corona undergoes a restructuring from the minimum and maximum type, and vice versa.

4 Results

The main results of this paper are:

(1) Rapid changes in the global magnetic structure on the Sun are accompanied by considerable amplification of nonstationary processes on the Sun (coronal mass ejections, acceleration of solar cosmic rays, solar flares), which largely determine space weather.

(2) Periods of anomalous geomagnetic disturbances and regularities of their manifestations over

an 11-year cycle of solar activity have been revealed, which are caused by rapid changes in the global magnetic structure on the Sun.

(3) An explanation has been offered for the origin of anomalous geomagnetic disturbances that are unidentifiable in ordinary used solar activity indices.

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