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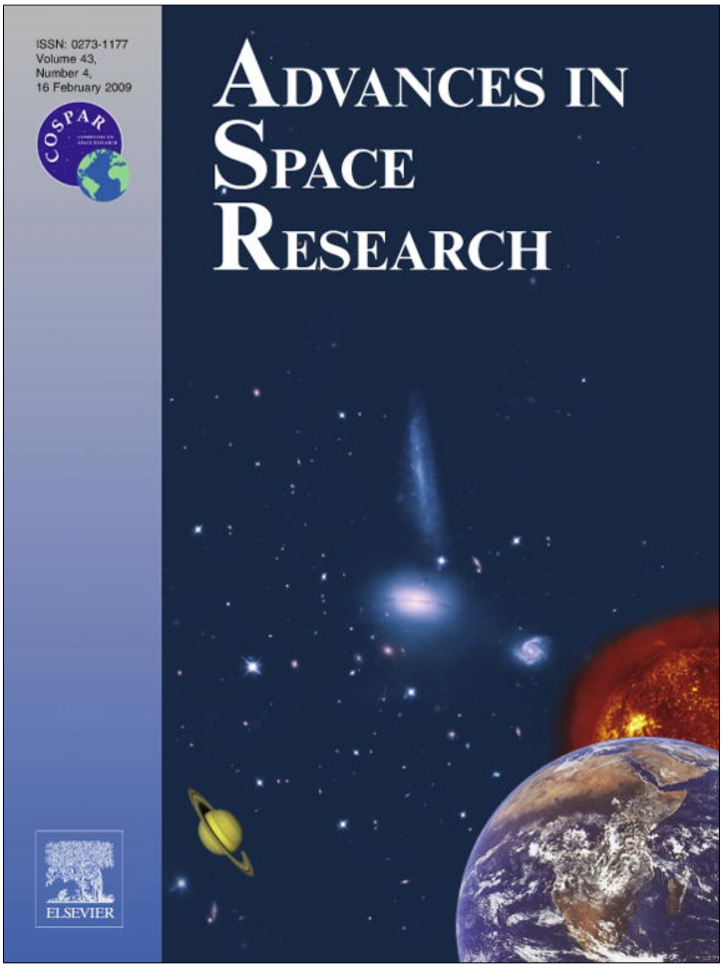

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Strong perturbations on the Sun and in the heliosphere leading to large geomagnetic storms: Similar and individual characteristics

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Abstract

We briefly present the selected results obtained up to now by the Russian scientific groups regarding powerful solar ejections as main causes of large geomagnetic storms in the near-Earth space. Strongest perturbations on the Sun and in the near-Earth space responsible for large geomagnetic storms were well registered and analyzed during the 23rd solar cycle. Open issues and perspectives are discussed.
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1. Introduction

Large geomagnetic storms attract attention of researchers and general public because of scientific interests and practical reasons (see e.g. Bothmer, 2006). Progress in their study and understanding during last dozen years is very impressive due to efforts of many groups and individuals. The important contribution to the new information about physical conditions on the Sun, in the interplanetary space and in magnetosphere–ionosphere system related to large geomagnetic storms during 23rd solar cycle has been obtained in Russia using satellites (4 satellites of INTERBALL project, CORONAS-F, Meteor-3M, Express-A2 and A-3, Universitetskii-Tatyana (Sadovnichy et al., 2007) and others) and ground based measurements. For the study of this information, the Solar Extreme Event (SEE) initiative collaboration headed in Russia by M.I. Panasyuk was established in 2003 during a series of seminars and discussions in SINP MSU just after the famous October–November storms on the Sun, in the heliosphere, magnetosphere, ionosphere, upper atmosphere and on the ground. The International SEE Symposia were held in 2004 (http://www.magnetosphere.ru/see/) in Moscow (Russia), in 2005 in Nor Amberd (Armenia) and in 2007 (http://cosray.phys.uoa.gr/SEE2007/Previous%20SEE.htm) in Athens (Greece). The papers with the first results presented at the SEE-2004 meeting and submitted for publication as the special issue of the Advances in Space Research are still waiting their turn. Preliminary reports can be found in collaborative compilations (Veselovsky et al., 2004; Panasyuk et al., 2004; Yermolaev et al., 2005; Ermolaev et al., 2005) and in original papers published in special issues of Cosmic Research, N 5, 2004 and Geomagnetism and Aeronomy, N 1 and 6, 2005. Proceedings of the SEE-2005 were also published http://crdlx5. yerphi.am/index.php?Page=/On-line_News/CRDSEE/Proceedings/&Title=0. Papers in the national journals are not readily available for the broader community. Nevertheless, these studies contributed additional information to the detailed investigations by other authors (see e.g. papers by Gopalswamy et al. (2005, 2008), Kozyra et al. (2006), Bothmer (2006), Hudson (2007), Fletcher et al. (2007), Zhang et al. (2007)). We are aimed here to bring brief account in telegraphic style and discuss only several selected results obtained up to now mostly focusing on solar flares

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and coronal mass ejections (CMEs) as immediate physical causes of the strongest storms in the near space.

2. Observations and selected results

INTERBALL mission (Galeev et al., 1996; Zelenyi et al., 1996) consisted of four satellites for solar, interplanetary space and magnetospheric studies and operated from 1995 to 2000. One of the first interesting and strong events observed by INTERBALL in the solar cycle 23 was interaction of magnetic clouds with the Earth on 10 January, 1997 [see, for instance, Yermolaev et al. (1998) and other papers by INTERBALL team in the same GRL special issue]. In particular, several important consequences of this interaction were: (1) observations of the magnetopause position 6RE nearer to the Earth than on average; (2) a huge increase in the magnetosheath plasma density and temperature; and (3) oscillation of magnetospheric tail structures past the satellite. Correlations of strong magnetosphere disturbances during 1995–2000 with interplanetary perturbations have been discussed by Yermolaev (2001). Solar sources of magnetospheric disturbances were studied with AKR-2X radiometer and DOK-2 spectrometer of energetic particles on the INTERBALL-1 satellite (Kuril'chik et al., 2006).

CORONAS-F mission (Oraevskii et al., 2002.) operated from July 31, 2001 to December 6, 2005. The most important results obtained with the CORONAS-F satellite in 2001–2004 are published in the Solar System Research special issue (Kuznetsov, 2005). They are related to global oscillations of the Sun, active regions and solar flares, the lower corona, ultraviolet and X-ray solar radiation, and solar cosmic rays. We refer to this review for references to original papers. A part of them was published in the same issue as well as in other journals.

Nearly total polarization of the hard X-ray emission observed during the flare of October 29, 2003 by the spectral polarimeter CORONAS-F/SPR-N was tentatively associated with the horizontal part of the effective electric current loop where acceleration of electrons took place. Absence of strong polarization in other cases could be understood as a consequence of a more complicated and tangled geometry (Veselovsky et al., 2004). This interpretation does not contradict telescopic observations onboard RHESSI satellite. Accelerated protons and nuclei in solar cosmic rays were investigated directly in populations arriving to the Earth's orbit and indirectly by their gamma radiation in the source regions on the Sun. Nuclear processes in solar flares leaded to the gamma-line radiation and neutron emissions. Positron annihilation and pi-meson formation processes were documented and investigated with the CORONAS-F/SONG data. The hardest gamma-ray spectra and tooth-like X-ray oscillations were measured in solar flares with CORONAS-F/GELIKON and CORONAS-F/IRIS. Atlas of spectral lines of solar flares in X-ray region was compiled based on CORONAS-F/RESIK. Doppler shifts in X-ray lines were measured during August 25, 2001 solar flare by CORONAS-F/DIOGENNES. Soft EUV emissions during this flare preceded X-ray emissions for several minutes according to CORONAS-F/VUSS-L data. This delay is indicative of the flare development from the chromosphere upwards. New lines found and identified in several experiments during flares. Impacts on the terrestrial atmosphere density, composition and satellite orbits documented and analyzed.

Low noise CORONAS-F/SPIRIT XUV and X-ray telescopic experiment allowed a good quality of images (Grechnev et al., 2005). Hemispheric asymmetry in the solar activity distribution was clearly documented during October 2003 eruptions on the Sun. The activity complex consisting of three active regions with erupting trans-equatorial loops was involved in this case in the multiple interacting CMEs generation and series of repeated flares development on the visible side of the Sun. This resulted in a very strong and complicated long lasting geomagnetic perturbation with all its attributes. Interesting results were obtained regarding localization and fast propagation of strongest perturbations on the Earth at all levels of the magnetosphere, ionosphere, atmosphere, and on the ground (Panasyuk et al., 2004). In other cases of extreme events even solitary active region perturbations on the visible side of the Sun not too far from the disk center can produce comparable geomagnetic storms under favorable magnetic field orientation inside and around the propagating ejection. It was not the case, for example, for the powerful solar event of November 4, 2003.

The global asymmetry of the solar activity has important consequences in electromagnetic fields and emissions of the Sun, in the interplanetary magnetic fields and the solar wind flows (Veselovsky et al., 2004). Global CMEs were identified in several instances when observing huge dimmings encompassing more than 180 degrees in the low corona on the Sun (Zhukov and Veselovsky, 2007). These observations substantiate ideas about CME initiation by enhanced convection processes coupled with electromagnetic fields, currents and charges in the solar interior and atmosphere.

Strong CMEs and solar flares never happen just as a spontaneous instability of the stored magnetic energy in the corona apart of driving photospheric causes. We believe that powerful subphotospheric electric currents, potential and inductive fields play important role in these connections. Changes of photospheric magnetic fields leading to CMEs were documented in several instances (Bothmer and Tripathi, 2006). Fast development of sufficiently strong magnetic fluxes measured by photospheric magnetogram patrol can be monitored and practically used for successful warnings (Ishkov, 2003). Necessary conditions are clear and quantified in many instances. Sufficient conditions are more delicate and need further studies.

Enhanced horizontal and vertical convective motions with velocities of the order of 1 km/s at the photospheric level precede strongest active region appearance and eruptions on the Sun. We believe that sometimes horizontal

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motions can dominate (cyclone and tornado type behavior), but in other cases vertical flows (developing like thunderstorm clouds on the Earth) are more readily seen and documented (Grigor'ev et al., 2007). The formation of cyclone type motion was well documented recently for 'colliding sunspots' in December 2006 by Hinode spacecraft observations. Like in the planetary atmospheres, dynamical vortices on the Sun can have vertical, inclined or horizontal main axes. The aspect ratio of large and small radii is variable from case to case for such toroidal and spiraling motions, which are ubiquitous in the atmosphere, but sometimes especially strong.

Strongest CMEs and flares accompany each to other. They represent manifestations of two different energy channels in the free energy release, which is shared between the plasma motion and radiation respectively. Any cause-consequence chain between them in this sense does not exist, contrary to flare and anti-flare myths discussed in the literature. The useful quantitative delimitation between flare-like and CME-like behavior can be provided by the dimensionless parameter V_e (Veselovsky, 2007). It is the ratio between electromagnetic emission and kinetic power, which is larger in first type of events and relatively small in another. The unifying term 'eruption' is often used for solar flares and CMEs.

World-wide neutron monitor network was used jointly with spacecraft data to investigate the galactic (GCR) and solar (SCR) cosmic ray variations during extreme events. Universitetskii-Tatyana small satellite launched in January 2005 registered SCR penetrating in polar caps of the magnetosphere as well as radiation belt transformations during SEE in 2005–2006. Very detailed information was obtained (http://cosmos.msu.ru/). Radiation conditions were also simultaneously monitored onboard ISS, Meteor and GLONAS satellites. Among new findings one can mark detailed information about large transient anisotropy of SCR and GCR, direct propagation of enhanced SCR fluxes, neutrons in SCR. This information can be used for the development of the methods of the now cast and short term forecasts. It is also used in MSU for educational purposes.

3. Dimensionless scaling approach to the theory of extreme events

What defines an extreme event? The theory of extreme events on the Sun is not well developed. It can be based on statistical or dynamical considerations. Statistics is rather poor. Extreme events are rare by definition. One can define 'extreme event' on purely statistical basis as unique phenomenon according to some selected quantitative criterion or several objective criteria. Otherwise, one can use dimensionless parameters for scaling. Dynamical approaches based on dissipative MHD or kinetic models assume given boundary and initial conditions as well as other input information about parameters, which are often not known a priori because of lack of needed measurements. The situation resembles a strong turbulence with many degrees of freedom. It is complicated, multi-scale in its nature, not homogeneous, non-stationary, intermittent in space and in time. Any universal geometry scenario does not exist. Because of this, morphological classifications using dimensionless scaling are suggested and appear to be useful for the qualitative and semi-quantitative representation of observed realizations. Dimensionless scaling is useful in this situation to clarify and fix the relative importance of physical processes under consideration. For example, such a classification of CMEs according to their velocities relative to the background solar wind flow leads to binary and ternary types quantitatively depicting different fast/slow or fast/intermediate/slow situations (Veselovsky, 2007).

Let us consider now shortly the set of dimensionless parameters in Table 1. The Knudsen number is the natural measure of the length scale of the problem. It compares this length with the corresponding mean free path lengths. As usually, the Knudsen number delimits microscopic (kinetic) and macroscopic (fluid) regimes. The Faraday number represents the natural measure of importance (or non-importance) of Coulomb potential electric fields due to electric charges versus inductive (Faraday's) electric fields due to time variable magnetic fields. It is easy to see that this number is large for slow time variations and small space scales. The a priori neglect of electric charges in plasmas can lead to serious physical errors. Non-compensated electric charges in plasma exist every time. They could be 'small' and not essential only under special boundary conditions, which need investigations. Plasma quasi-neutrality does not mean total absence of electric charging and potential electric fields in the commoving 'plasma reference frame' or 'frozen coordinate systems'. It is not possible indicate such a global coordinate system in the inhomogeneous plasma in most interesting cases, contrary to opposite statements in papers and some textbooks (see e.g. E.N. Parker, The alternative paradigm for magnetospheric physics, J. Geophys. Res., Vol. 101, pp. 10587–10625, 1996; Priest, E. and Forbes, T., Magnetic Reconnection: Magnetohydrodynamic Theory and Applications, Cambridge Univ., Press, 2000). Hence, electric fields can be not completely reduced to velocity and magnetic field considerations, as assumed by these authors based on extrapolations of the frozenness conception beyond its very restricted validity domain.

Table 1
Dimensionless parameters and their physical role (Veselovsky, 2007)

Name	Description	Role
Strouhal	Time/Flight times	Time scales
Knudsen	Mean free path/Length	Length scales
Velocity-emission	Kinetic energy/EM emission	Plasma density
Mach	Bulk speed/Thermal speed	Temperature
Magnetic Mach	Bulk speed/Alfvén speed	Magnetic field
Froude	Bulk speed/Free escape speed	Gravity
Faraday	Potential fields/Inductive fields	Electric field
Trieste numbers	Inflows (outflows)/Inner flows	Openness degrees

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A priori neglect of electrostatic fields appeared a very serious limitation for the thermonuclear fusion using magnetic plasma confinement. It is easy to see from estimates of the Faraday parameter, that long-term asymptotic behavior of the plasma in general determined not by inductive, but by Coulomb fields. Quasi-steady confinement is difficult to attain with the 'frozen degree of freedom' (potential electric fields due to charging assumed to be irrelevant). This assumption appears to be misleading in practical laboratory devices. This degree of freedom plays crucial role also in the solar atmosphere especially during flares and CMEs.

Finally, we should comment on Trieste numbers in Table 1. The set of these numbers is defined as ratios of energy, momentum and mass flows inside considered volumes, outside of them and through their boundaries. The set of corresponding numbers defines the openness degree of the considered physical object against energy, momentum and mass flows. The system is adiabatically closed if corresponding Trieste numbers are small, $T << 1$. Otherwise, it is essentially open in the sense of the exchanges with the surrounding medium. One example: the standard paradigms of quiescent prominences as 'plasma equilibrium in magnetic fields with normal and abnormal configurations' is practically not tenable. It is because of permanent plasma motions through the boundaries of loop systems considered as main structuring elements of prominences. Quiescent prominences during their life time replenish their material many times. In other words, prominences are not isolated systems, but open ones. Inflows and outflows through the legs, red-and blue- shifts are big enough. Eruptive prominences with a loop-like shape are directly driven by non-local electric fields and electric currents supplied from below the photosphere. The main mechanism of motion – plasma drifts in crossed electric and magnetic fields.

4. Open questions and perspectives

Results obtained up to now allow us to formulate several open physical questions, which remain to be investigated in future, and possible ways of their solution for better understanding of the solar extreme events:

(1) We know from available measurements very little about potential electric fields and corresponding electric charges involved in flares and CMEs. This important 'degree of freedom' is usually supposed to be frozen in most theories and interpretations of solar phenomena. Similar neglect led to failure of initial simplistic concepts of 'magnetic confinement' in the controlled thermonuclear fusion problem (Veselovsky, 2007). Stark effect measurements could be helpful, but they are not easy to perform and to interpret.

(2) We have not sufficient data about the real quantitative role of the white light emissions in the energy balance of eruptive processes on the Sun. The problem is difficult because of the low contrast of perturbations, which are underestimated. Existing data is too scarce and based on telescopic measurements with a not sufficient sensitivity, resolution and signal/noise ratio. More accurate spectral and telescopically resolved measurements from space are possible similar to, but surpassing the SORCE mission capabilities (Veselovsky and Koutchmy, 2005).

(3) Reliable deterministic predictions of extreme solar events are impossible without knowledge and monitoring of subphotospheric processes which govern solar flares and CMEs. Helioseismology methods and signals seen on the surface could be helpful, but there is a principal question if they appear sufficient. Monitoring of photospheric magnetic fluxes and inferred electric currents in the solar atmosphere with a good space-time resolution is very promising as a first step.

(4) Possible limits on amplitudes, probabilities and predictability horizons of the uppermost attainable perturbations on the Sun and in the heliosphere are difficult to establish based on first physical principles. Statistics of their observations is scarce. Long term coordinated programs in observations and in theory are needed for the progress in this respect because such extreme events are very rare.

(5) Geomagnetic observatories registered global and local perturbations even before the space era. Modeling efforts developed for all solar-terrestrial manifestations allow partial reconstruction of parent solar and heliospheric extreme events in the past based on geomagnetic and other archives.

5. Conclusions

Ongoing space research and ground based measurements shed new light on physical processes involved in large geomagnetic storms and clarified some important fragments in the complicated dynamical picture of the non-linear solar-terrestrial relations originating in the interiors of the Sun. Principally, one can expect and even predict perturbations on the Sun, in the solar atmosphere, heliosphere and magnetosphere leading to geomagnetic storms within some confidence levels for their parameters, but not schedule them in a manner of any calendars or time tables. We would like to remind the words and opinions expressed long ago by W.N. Hess (1964) regarding solar flares: 1) "Satellites have contributed significantly to our knowledge of flare phenomena." 2) "The visible flare may well be a secondary effect, and the real flare process invisible by our present observational techniques." These words still actual even in a broader context of solar-terrestrial relations and stimulate our further studies.

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based observatories. We are grateful to our colleagues in the Russian and international SEE community for discussions and sharing information before publication. This study was supported by the RFBR Grants 07-02-00147, 06-05-64500, 07-02-00042, NSh -1255.2008.2, INTAS 03-51-6202 and MSU Interdisciplinary Scientific Project. It is also fulfilled as a part of the Programs of the Russian Academy of Sciences: “Origin and evolution of stars and galaxies” (P-04), “Solar activity and physical processes in the Sun–Earth system” (P-16, Part 3) and “Plasma processes in the Solar system (OFN-16).

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