Solar origins of intense geomagnetic storms in 2002 as seen by the CORONAS-F satellite

O. Panasenco a,*, I.S. Veselovsky a,b, A.V. Dmitriev a,h, A.N. Zhukov a,i, O.S. Yakovchouk a, I.A. Zhitnik c, A.P. Ignat’ev c, S.V. Kuzin c, A.A. Pertsov c, V.A. Slemzin c, S.I. Boldyrev d, E.P. Romashets d, A. Stepanov d, O.I. Bugaenko e, V. Bothmer f, S. Koutchmy g, A. Adjabshirizadeh j,k, Z. Fazel j, S. Sobhanian k

a Skobel’tsyn Institute of Nuclear Physics, Moscow State University, Moscow 119992, Russia
b Space Research Institute, Russian Academy of Sciences, Moscow 117810, Russia
c P.N. Lebedev Physical Institute of RAS, Moscow 119991, Russia
d Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of RAS, 142190, Troitsk, Russia
e Sternberg Astronomical Institute of Moscow State University, Universitetskii prospect 13, Moscow 119899, Russia
f Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau D-37191, Germany
g Institut d’Astrophysique de Paris-CNRS, Paris F-75014, France
h Institute of Space Science, National Central University, Chung-Li 320, Taiwan
i Observatoire Royal de Belgique, Av. Circulaire 3, B-1180, Bruxelles, Belgium
j Tabriz University, Tabriz 51358, Iran
k Research Institute of Fundamental Sciences (RIFS), Tabriz 51358, Iran

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Abstract

We analyze solar origins of intense geomagnetic perturbations recorded during 2002. All of them were related to coronal mass ejections (CMEs). The initiation of CMEs was documented using the SPIRIT instrument (SPectrohelIographic Soft X-Ray Imaging Telescope) onboard the CORONAS-F satellite. Monochromatic full Sun images taken in the Mg XII doublet at 8.418 and 8.423 Å showed the appearance of free energy release sites at altitudes up to 0.4 solar radii. CMEs were initiated at these sites and propagated in interplanetary space under appropriate local conditions including the geometry of the magnetic fields.

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1. Introduction

Intense long-lasting (several hours) southward interplanetary magnetic fields ($B_z < -10$ nT, $\tau > 3$ h) at the Earth’s orbit are sufficient conditions for the generation of large magnetic storms ($D_{st} < -100$ nT), see Tsurutani (2001) for a review and references. Necessary and sufficient conditions on the Sun responsible for producing such heliospheric parameters and hence geomagnetic storms at a given time with a given strength, duration and other characteristics are still elusive to forecast. Many works are devoted to this question. We mention here only a few recent studies where these problems are approached from different points of view (Bothmer and Schwenn, 1998; Papitashvili et al., 2000; Cane et al., 2000; Richardson et al., 2001; Veselovsky et al., 2002; Huttunen et al., 2002; Zhukov, 2005, and references therein). The quantitative criteria on the Sun are not established in this respect, but the qualitative side is becoming clearer after years of studies (Temerin...
and Li, 2002). A review of CME studies near the Sun and in the interplanetary space (ICMEs) has been provided by Cargill (2001).

The study of the initiation of CMEs, i.e., plasma outward bulk motions is an important part of this problem. The task is difficult because of many reasons: (1) the lack of sufficient observational information about the physical properties and the morphology of the upper atmosphere of the Sun; (2) poor understanding of dominant MHD and kinetic processes leading to plasma outbursts with transient electric currents and magnetic fields; (3) reliable theoretical models of these processes have not been constructed yet. The aim of this paper is concentrated around the item (1). We are trying to use the available new measurements for the characterization of the signatures of the CME initiation processes as seen by the SPIRIT instrument onboard the CORONAS-F satellite in combination with other data recorded in space and on the ground.

2. Data and analysis

The CORONAS-F satellite was launched on July 31, 2001 (Oraevsky and Sobelman, 2002). The SPIRIT instrument provides information about plasma structures in the solar corona in wide range of effective excitation temperatures (ten channels between 0.01 and 20 MK) and altitudes (from transition region up to 0.5 solar radii). The most remarkable channel of the instrument for registration of full sun images is that of Mg XII resonance doublet 8.418 and 8.423 Å. The effective excitation temperature of this doublet is 5–20 MK with the maximum at 10 MK.

The first monochromatic full-Sun heliograms recorded in the Mg XII resonance line 8.42 Å onboard CORONAS-F spacecraft revealed sporadic condensations (relatively small regions of increased brightness) in the absence of impulsive flares in vicinities of active regions with high flux variability during several hours (Sobelman et al., 1996). The heliograms have a high contrast because such hot plasma in the corona is confined in small regions. The most attractive candidates for CME sources seen in the Mg XII line are arches and spider-like structures (Zhitnik et al., 2003a) which are associated with Long Duration Events in the GOES data.

The description of the SPIRIT instrumentation is given by Zhitnik et al. (2003b), the data are presented at the web site http://www.xras.lebedev.ru. Mg XII movies are available at http://spirit.xras.lebedev.ru. The additional information about the experiments and available data can be found at the CORONAS-F web site (http://coronas.izmiran.rssi.ru). We are using the list of geomagnetic perturbations with the Ap index more than 20 registered in 2002 according to the APEV database (http://dbserv.sinp.msu.ru/apev/).

We use standard definitions for the identification of interplanetary shock waves, heliospheric current sheet and sector boundaries. A magnetic cloud is defined as a heliospheric domain with $\beta \ll 1$. Here, $\beta$ is the plasma parameter, i.e., the ratio of the proton gas thermal pressure to the magnetic pressure. We include here reservations for more precise and developed classification of situations taking into account the electron and helium components, not included in the data sets. The magnetic cloud can be considered laminar if $\Delta B/B < 1$. It is turbulent if $\Delta B/B \sim 1$ (here $\Delta B$ and $B$ are the fluctuations and the averages of the magnetic field). We do not specify the definition of “fluctuations” and “averages” quantitatively. Hence, the categorization “laminar” or “turbulent” in this context reflects only our qualitative or visual inspection. It is not absolute, but only relative. We should remark in this respect that the notions “laminar” and “turbulent” are not Gallilean invariants, but are dependent on the frame of reference at least. Nevertheless, these notions are useful for a qualitative description of one-scale and multi-scale situations in space and time. The categorization CH (“coronal hole”) means high speed solar wind streams from coronal holes. The CH flows are dominated by the Alfvén waves and characterized by the rather tenuous plasma, increased temperature. Sometimes, the categorization of the slow wind flow is not certain or represented as a mixture (or “soup”).

Fig. 1 shows the daily averaged $A_p$ index of the geomagnetic activity during 2002. Some regular and irregular features are present. It is well known that the geomagnetic perturbations usually show peaks in spring and in autumn. It is because of the inclination of the Earth’s rotation and magnetic axes against the solar sources of perturbations. Geomagnetic storms appear more or less sporadically, but some of them are clustered. This reflects the activity conditions on the Sun. The partial recurrence patterns are due to the solar rotation. The recurrent clusters are asymmetric with steeper leading fronts because of nonlinear evolution of corotating interaction regions in the solar wind. Weak recurrent storms usually occur during the high speed solar wind stream passages. Enhanced Alfvénic fluctuations are the immanent ingredients of such streams. The magnetosphere acts as a rectifier and integrates the negative $B_z$ contribution to form the ring current particle population supported by the balance of drifts and losses during several or many hours.

In this paper, we consider only several strongest events that are also manifested in the $D_{st}$ index of geomagnetic activity shown in Fig. 2. Both indexes are rather well correlated. The approximate empirical linear regression $A_p \sim 0.8 D_{st}$ is valid for the most of the events within an accuracy of 10%. The deviations from this regression are observed both for extremely weak events around the noise level and for extremely strong events. These deviations are essentially due to the physical diversity of geomagnetic perturbations, which are not global but space and time variable in the magnetosphere. As an example of the deviation in the relation between $A_p$ and $D_{st}$, we can indicate the event on May 23, which was associated with an enormously high solar wind speed.
Table 1 shows the list of selected geomagnetic storms in 2002. Column 1 contains the event number, column 2 – the event number in the APEV database (http://dbserv.sinp.msu.ru/apev/), column 3 is the day of the geomagnetic storm, column 4 is the maximal $A_p$ index (in nT), column 5 is the maximal $D_st$ index (in nT), in column 6 plus signs mark the presence of an interplanetary shock, column 7 is the peak velocity $v$ (km/s) of the geoeffective solar wind stream, column 8 is the average solar wind density $n$ (cm$^{-3}$), column 9 is the $B_z$ magnetic field component (the minimal value, nT), column 10 is the duration of the negative $B_z$ (h), column 11 is the date of the event on the Sun, column 12 is the GOES signature: LDE is a long-duration event, “-” means no

![Fig. 1. Daily averaged $A_p$ index of geomagnetic activity during 2002 (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/).](image1)

![Fig. 2. Daily averaged $D_st$ index of geomagnetic activity during 2002 (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/DST/).](image2)
registered signatures ("problem storm"), column 13 are the CORONAS-F SPIRIT Mg XII observations: plus sign means that the data are available and identification is possible, plus/minus means partial data coverage, column 14 is the NOAA active region number of the CME source region.

3. Brief description of the selected events

3.1. Event 259 (Figs. 3–5)

This is rather a weak storm with a sudden commencement (SC) associated with the arrival of an interplanetary shock (Fig. 3). The initial phase (IP) lasted during about a day on February 28. The main phase (MP) started only with the arrival of sufficiently strong negative $B_z$ (up to $-15$ nT) that was followed by a classical recovery phase (RP). The immediate heliospheric driver of the main phase can be related to the NS magnetic flux rope passage. The orientation of the axis of the corresponding heliospheric electrojet was not optimal, the magnetic field strength not too big, 10–15 nT. The most probable event on the Sun occurred about 4 days before. We looked in this and all other cases at GOES, SOHO/EIT, SOHO/LASCO and CORONAS_SPIRIT data, as well as solar synoptic maps (see Fig. 4) and a number of signatures near the central meridian: calculated heliospheric current sheet (HCS) position, evolving coronal holes, disappearing filaments, solar flares, coronal mass ejections. A long-lasting event like a ribbon brightening started on February 23 around 13:00 UT in the SPIRIT Mg XII channel. Fig. 5 shows the corresponding images before, during and after the event. This event was associated only with a small (C level) signal in the GOES 8 data.

3.2. Event 261

This is a typical compound event. The parent situation on the Sun and in the heliosphere is complicated. A turbulent SN magnetic cloud (flux rope) near the HCS was the driver of the event, which appears to be partially sporadic and partially corotating with the event described above (event 259). The storm started immediately after the shock arrival without a delay because of the favorable SN geometry. Strong negative $B_y$ determined the overall orientation of the axis and also contributed to the storm development. Multiple onsets are clearly seen and could be unambiguously associated with the internal structure of the heliospheric driver fields and plasma parameters. The first shock arrived at the Earth on March 23, the second one on March 25. They were superimposed on the flux rope event (electrojet), which passed the Earth from March 23 to March 26. It is interesting to note that only the part of the magnetic flux rope with the southward (S) field intensified the development of the storm main phase. The subsequent part with the northern (N) field and the second shock arrival were not effective in this sense and even accelerated the recovery phase. Multiple eruptive sources near the center of the Sun show characteristics similar to the previous case.

3.3. Events 262–264

Events 262–264 are a strong compound heliospheric perturbation consisting of several shocks and magnetic flux ropes. The corresponding multiple onsets and partially recovery phases are seen in this series of stormy days during the April 17–April 20. The amplitude of the storm is not extremely high because of a moderate IMF strength.
The storm is mainly sporadic, but partially belongs to a corotating family. The empirical rule $A_p \sim D_{st} \sim (5–10) B_z$ is valid for maximal values in many instances and also in this case. The overall time profiles of $A_p$ and $D_{st}$ indices are not monotonous and more or less reproduce the $B_z$ variation (as usual) with a delay of one or several hours needed for the plasma drift in the magnetosphere to form the partial/symmetric ring current. This compound storm also occurred near the heliospheric current sheet nominal position and could be considered as a subsequent member of the corotating series after two previous events (March, February). The situation in the source region on the Sun is very complicated, but the reasonable localization, identification and timing of parent solar process is still possible even in this case using CORONAS-F images.

3.4. Event 269

This event continues the series of (April, March, February) recurrent storms described above with a strong sporadic component: a narrow but very high speed solar wind stream ($\sim 1000$ km/s) from the coronal region adjacent to the cold eruptive prominences, coronal holes and HCS. The shock initiation could be associated with a
powerful solar event seen at 23:00 UT on May 21 as documented by Mg XII SPIRIT movie (http://spirit.xras.lebedev.ru). Two shocks and two strong negative $B_z$ domains behind them correspond to two steps in the development of the magnetic storm with first and second “sudden commencements” (SC). The second SC happened when the storm has already developed.

3.5. Events 272–273 (Figs. 6–8)

These are compound events as well. They are similar but weaker in comparison with the events 262–264 described above. It is primarily because of the seasonal effect. Shocks and flux ropes are clearly seen again. We notice an interesting feature in Fig. 6: the absence of the storm on July 29 after the comparable shock arrival, but without negative $B_z$. Only small intensifications (of the order of the noise level) in the geomagnetic activity can be marked during July 29–31 in the delayed response to the negative $B_z$ turnings. We were able to investigate in part the origins of this event on the Sun with the SPIRIT data which did not cover the interval between 19:00 UT on July 28 and 17:00 UT on July 29. The LDE started on July 29 around 20:10 UT. The situation on the Sun and in the heliosphere is dynamical and complicated. Multiple onsets of the magnetic storm are clearly documented in association with negative $B_z$ turnings.

3.6. Event 279

This is a member of another vast recurrent series of geomagnetic storms observed during many solar rotations in the second half of 2002 and the spring of 2003. The corotating series is obviously associated also with coronal mass ejections and processes in the southern coronal hole. Such a North–South asymmetry can be ascribed to the quadrupole magnetic field component of the Sun. The storm started around the time of the heliospheric current sheet (sector boundary) crossing. The slow development of the storm and its main phase correspond to negative $B_z$ values.
3.7. Event 280

This event started during the recovery phase of the previous storm on September 4 (Event 279). Evolving coronal structures seen with flares and eruptions are documented by the SPIRIT (CORONAS-F). They indicate the LDE near the center of the disk, which started around 12:40 UT on September 5 and could be associated with the halo CME seen by SOHO/LASCO at that time. The initial acceleration of this CME was about 40 km/s², the final speed in the plane of the sky was 1600 km/s. This coronal process initiated the interplanetary shock propagation responsible for this magnetic storm.

The temporary termination of the storm development is due to the positive Bz arrival in the flux rope behind the shock. The magnetic storm started slowly and before the shock arrival in response to the Bz turning to the South ahead of the shock.

3.8. Event 284

A NS magnetic flux rope was preceded by the shock wave, which was the main driver of this magnetic storm via the compressed magnetic field in the sheath between the ICME and its bow shock. Several eruptions on September 25 were documented.
The coronal hole region and disappearing filaments were also located near the central meridian of the Sun.

The situation on the Sun and in the heliosphere was complicated with several nearly simultaneous disturbances originating in different regions. This is a typical case when the attempt to localize a single point-like “source” is often misleading.

3.9. Event 293

The storm was rather weak. It is not aggravated by the sporadic activity on the Sun and also belongs to the series of recurrent perturbations associated with coronal holes. No association with Mg XII signatures was found in this case.

4. Discussion

The EUV heliograms provide information about possible sources of CMEs in the solar corona – from the transition region to a few tenths of the solar radius. The observations of the solar corona with high spatial resolution in resolved spectral lines give more detailed information about physical properties of plasma. But these
observations need a special imaging spectroscopy technique because of multitude of lines in the EUV region of the solar spectra.

The first monochromatic full-Sun images recorded in the Mg XII resonance line 8.42 Å onboard the CORONAS-F satellite revealed sporadic condensations in the absence of impulsive flares in vicinities of active regions with high flux variability during several hours (Sobelman et al., 1996). Results of more detailed studies of the transient phenomena in the same line by the SPIRIT instrument on board CORONAS-F satellite were reported by Zhitnik et al. (2002). In the present paper, we have suggested that most of these events are associated with CMEs that propagate in the heliosphere as ICMEs and hit the Earth.

The observations of dynamic coronal processes in the Mg XII resonance line onboard the CORONAS-F satellite has some advantages (better contrast and localization) in comparison with several other methods and instruments that are being used currently or were used in the past. We refer to details of this comparison to the paper by Zhitnik et al. (2003c) and mention only that the image composition time is 9–100 s for the SPIRIT (CORONAS-F) instrument and ~300 s/slit ~10^7 × 10^8 for the CDS (SOHO) spectrometer.

5. Conclusions

1. Strong geomagnetic perturbations (D_st > 100) observed in 2002 and investigated in this paper can be related to heliospheric disturbances originating on the Sun.
2. The sensitivity of the SPIRIT instrument is sufficient to observe the brightest parts of the CME energy releases. It is possible to identify in this way the solar sources of geomagnetic storms.
3. The continuous monitoring of the solar images in the Mg XII 8.42 Å doublet with a sufficiently high sensitivity, space resolution of arc seconds and time cadence of minutes could be a useful diagnostic tool for “space weather” applications.
4. The traditional “event analysis” on the Sun and in the heliosphere should be replaced by a “situation analysis” in many cases because of non-local but global character of a source perturbation on the Sun.

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References