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SOLAR SOURCES OF INTENSIVE GEOMAGNETIC STORMS DURING THE 23rd SOLAR ACTIVITY CYCLE

N.M. Rudneva[1], L.A. Dremukhina[2], P.M. Svidsky[1], A.F. Kharchiladze[2]

[1]*Fedorov Institute of Applied Geophysics, Moscow, Russia*
[2]*Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation RAS, Moscow, e-mail: dremukh@izmiran.ru*

Abstract. The analysis of the solar sources of 66 intensive (- 200 nT ≤ Dst < -100 nT) and 16 very intensive (extreme) (Dst < -200 nT) magnetic storms and their localization on synoptic maps of large-scale solar magnetic field during the 23rd solar cycle (1996-2009) was performed. Coronal mass ejections (CME), coronal holes and filaments were considered as solar sources of geomagnetic storms. The study confirmed the existing opinion that extreme Dst-decrease is mainly associated with coronal mass ejections (CME) of type "halo". It was shown that effective solar flares (accompanied by CME) are localized at the boundaries of open magnetic field lines (sector's and subsector's boundaries). During the 23rd solar cycle, as in the past cycles, extreme storms occurred near the maximum of solar activity and its decay phase, and were caused by "halo"-type CMEs, accompanied by flares and filament's disappearances. Geoeffective CME were located mainly near the Sun's central meridian, and their solar wind had a speed more than 700 km/s. Very intense magnetic storms always associated either with strong or weak flares. Disappearances of filaments, not accompanied by flares, don't cause of intensive magnetic storms, in about 90% of events. All flares and the filament's disappearances, followed by a development of intensive or very intensive magnetic storms, occurred on the boundaries of sub-sectors (OR-regions) or near projection of the heliospheric current sheet. In the reviewed period also coronal holes led to the development of intensive magnetic storms only in every seventh case.

Introduction

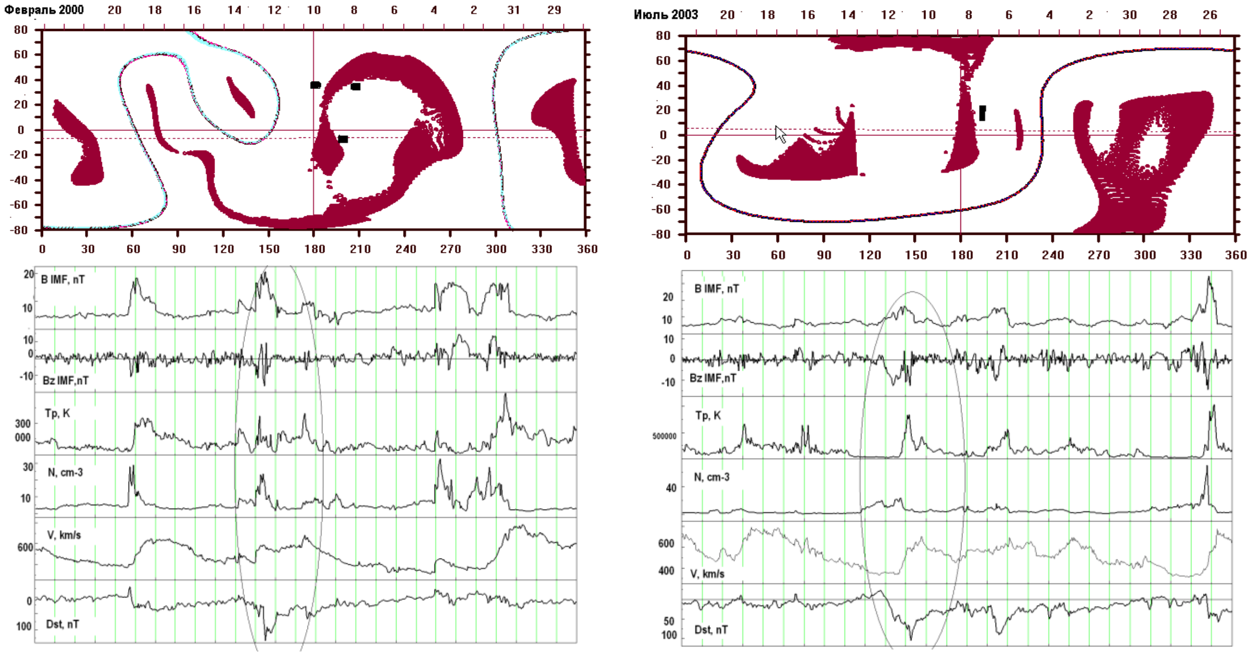
Since ancient times geomagnetic storms were divided into two types: the sporadic and recurrent. Sporadic disturbances with sudden onset are associated mainly with solar flares. As sources of recurrent disturbances, repeating every 27 days, deemed "coronal holes" - areas on the Sun with a low radiation in the ultraviolet range and with radially directed magnetic field lines, which were discovered by "SKYLAB" [*Hundhausen*, 1980]. Their connection with high-speed solar wind streams was later shown [*Svalgaard*, 1977; *Sheely and Harvey*, 1981].

A lot of works is dedicated to study of the solar sources of geomagnetic disturbances. Authors of [*Joselin and McIntosh*, 1981; *Joselin*, 1986], on the base of analysis of 65 geomagnetic storms with maximum values of the Ap index ≥30 for the period from June 1976 to June 1979, have established the following frequency of occurrence of solar events previous 2-4 days intensive storms: solar flares - 40%, coronal holes - 52%, filament's disappearances - 65%, and 8% storm's sources were not identified. Most of the storms were caused by a combination of two or three sources. Satellite observations on the space station "SOHO" allowed to detect of coronal mass ejections (CME) [*Yahiro et al*., 2004], that turned out to be directly responsible for the develop of geomagnetic storms. Statistical studies [*Webb et al*., 2000; *Wang et al.*, 2000; *Zhao and Webb,* 2003; *Srivastava and Venkatakrishnan*, 2005; *Kim et al*., 2005] have shown that the majority of CMEs are accompanied by solar flares or disappearance of filaments, and that not every CME causes a geomagnetic disturbance. Authors [*Srivastava and Venkatakrishnan*, 2005] have shown that 82% of extreme storms during 1996-2002 were related to CME s "halo"-type or "partial halo"-type). The intensity of magnetic disturbances depends on the value of the South component (Bs) of the interplanetary magnetic field (IMF). An intensity and duration Bs, related with CME, is determined by the configuration of CME, as well as by its size and orientation relative to the Earth [*Tsurutani et al*., 1988; *Lepping et al.*, 1990]. Study of solar structures, responsible for generating CME, was conducted in [*Zhao and Webb*, 2003]. The authors determined that 40 geoeffective CME in 1998-2000 were located predominantly in the areas over the bipolar coronal streamers between coronal holes with opposite polarities. It is also known that the complexes of solar activity tend to be on sector boundaries – the boundaries between areas of large-scale solar magnetic field. Areas that characterizing by open lines of force of photospheric magnetic field (sub-sectors or OR-regions) were investigated in [*Ivanov and Kharshiladze*, 2002; *Ivanov et al*., 2005]. In these studies it was been shown that the series extrastorms in the summer of 2000 were caused by active dynamics of OR-regions. The study of magnetic fields on the Sun in the periods of individual storms also allowed to conclude that active education, responsible for flares and CME, tend to be located at boundaries OR- regions [*Ivanov and Kharshiladze,* 2002]. In this paper we analyzed the solar sources of intensive and very intensive storms, registered in the period 1995-2009. In contrast to [*Srivastava and Venkatakrishnan*, 2005] we looked at not only CMEs as sources of magnetic storms but also coronal holes and filaments and their localization on synoptic maps of the large-scale magnetic field of the Sun.

Data, method of analysis and results

Geomagnetic storms were selected at the Dst values published on the website: *http://omniweb.gsfc.nasa.gov/*. Between 1998 and 2005 there were 16 of very intensive storms with a maximum Dst< -200 nT, (in the years close to solar activity minimum,1995-1997 and 2006-2009, of such storms was not observed) and 66 intensive storms with a maximum value of - 200 nT ≤ Dst < -100 nT. To determine the solar source of the geomagnetic disturbance and its solar coordinates, we used the following observational data: catalog of coronal mass ejections (CME) (*http://cdaw.gsfc.nasa.gov/CME_list/*); daily reports of solar and geomagnetic activity prediction center in Boulder (SWPC) website (*http://www.swpc.noaa.gov/ftpmenu/warehouse.html*); the data about the disappearance of filaments and prominences on the website "Edited Solar Events Lists" (*http://www.ngdc.noaa.gov/stp/stp.html*); catalog of coronal holes on the website (*http://www/dxlc/com/solar/coronal_holes.html*); image of coronal holes in UV and x-ray ranges (http:www.spaceweather.com/; maps large-scale magnetic field of the Sun. The magnetic field of the Sun was calculated on the source surface (2.5 radiuses of the Sun) with the help of the program "ISOPAK" [*Harshiladze and Ivanov*, 1994]. The large-scale magnetic field of the Sun was calculated on the source surface (2.5 of radiuses of the Sun) with the help of the program "ISOPAK" [*Harshiladze and Ivanov*, 1994]. Calculated open (radial) lines of force of magnetic field, and the HCS was projected on the surface of the photosphere. Areas on the photosphere, where the projection of the open field lines from the source surface coincide with the bases of power lines on the photosphere were called by OR-regions. The examples of calculated synoptic maps with indicating of the projections of HCS and OR-regions and location of solar flares previous of CME are shown in Fig.1. Synoptic maps are centered on the dates 10.02.2000 and 08.07.2003. Near the central meridian the locations of flares (at left, 02.2000) and filament (at right, 07.2003) are shown. After these solar events it was registered geomagnetic storms: 12.02.2000 (max Dst = -133 nT) and 12.07.2003 (max Dst=-110 nT). On the bottom panel of the figure shows the parameters of the solar wind of registered CME, and the geomagnetic storm that followed after him.

It is known that most of geomagnetic disturbances is the consequence of a whole complex of events on the Sun. Several flares, CME or the disappearances of filaments as well as coronal holes can be observed consecutively or simultaneously [*Joselin*, 1986; *Harshiladze and Ivanov*, 1994]. We were looking for the source of the storm that causes it most likely.



a 12.02.2000 **b** 12.07.2003

Figure 1. Top: synoptic maps, centered on 10.02.2000 (**a**) and 08.07.2003 (**b**): solid line is a projection of the HCS on the source surface; painted regions are OR-regions; flares are indicated by squares, DSF - by rectangle. Bottom: solar wind parameters near the Earth's orbit - IMF module, Bz IMF, plasma temperature Tp, density N, velocity V, Dst-index.

Solar sources of very intensive and extreme storms

Analysis of observational data for the period from 1 to 5 days prior to the storm, showed that extremely intense storms, in selected period, were observed after "halo"-type CME (and only in one case - after "partial halo") accompanied by solar flares. The amount of storms corresponding to the certain selected characteristics of solar activity are shown at the Table 1. As can be seen from the Table 1, very intensive storms were caused by "halo"-type CME, 13 of which occurred near the central meridian and only 3 - in the western hemisphere of the Sun. All of CME had a velocity in the corona > 700 km/s. Three of CME were accompanied by weak flares (Class C), and 13 – by strong (class X and M).

Table 1. The distribution of very intensive and extreme storms on the parameters of the solar activity

Solar sourse	**Number of storms**
X-class flare	7
M-class flare	6
C-class flare	3
HelioLongitude E < 18 º W < 40 º	13
HelioLongitude W >40 º	3
HelioLatitude < 22 º	16
"halo" availability	16
"halo" velocity 700 км/с <V< 1000 km/s	4
"halo" velocity > 1000 km/s	7
"halo" velocity > 2000 km/s	3

Solar sources of intensive magnetic storms (-200 nT ≤ Dst < -100 nT)

Analysis of solar sources was carried out for 66 intensive storms. The number of storms caused by type "halo"-type CME is 49 (8 of them are "partial halo"-type). The number of storms caused by coronal holes is 9. Sources of the remaining 8 storms are defined less precisely, and, presumably, they were caused by active and disappearing filaments unaccompanied by CME. So intensive storms are caused most by CME associated with the flare or DSF. CME were accompanied by flares of high class, in some cases - by weak flares of class C. Often, before a magnetic storm it was observed not one CME, but several, one after another. In a series, CME could be accompanied by a number of flares of different classes and DSF. It could be that a significant reduction of Dst-index is related with not the most energetic ejection. About a quarter of flares were long living. Coordinates of flares mostly close to the central meridian, but, in some cases, they removed to the western limb (more) or to the eastern one (less). In 6 of cases, CME were caused by sudden DSF in the absence of flares. The most frequently observed rate of CME was ~ (600 -700) km/s, but there were also low (~ 300 km/s c) and very high (> 2000 km/s) values of V. It should be noted: solar flares not only of high class, but also weak flares can cause CME related to great geomagnetic storm; long living flares play significant role in the development of geomagnetic disturbances; in the period under consideration, phenomenons of filament's disappearance, unaccompanied by flares, rarely (<10%) led to a strong geomagnetic disturbances; coronal holes caused of intensive magnetic storms rarely.

Location of solar power intensive and very intensive magnetic storms on solar large-scale magnetic field maps

Flares and DSF, previous of CME, and follow magnetic storms occurred mostly near the HCS, on the boundaries of the OR-regions or the boundaries between the HCS and OR, if OR and the HCS slightly (20-25 degrees) away from each other. Storms number corresponding to possible localizations are shown in the Table 2.

The Table 2 shows that the flares and DSF, previous to intensive and extreme magnetic storms, occur on the boundaries of sub-sectors (OR-regions) or near the HCS. This result confirms the conclutions of [*Ivanov and Kharshiladze*, 2002], and is an additional argument in favor of the view that activity complex are localized near sector and sub-sector boundaries.

Table 2. Distribution storms relatively solar regions

Location	Extreme storms	Intensive storms	Total number
HCS	6	6	12
OR	6	42	48
HCS-OR	4	10	14
Total number	16	58	74

On coronal holes as sources of geomagnetic perturbations

It has been noted that the source of a geomagnetic storm is not some separate manifestation of activity on the Sun [*Joselin and McIntosh*, 1981]. it is known that the "pure" solar wind flows from coronal holes do not exist, and, as a rule, they are distorted by interaction with adjacent streams from another coronal hole or from filaments or flares. Our analysis of streamers from coronal holes confirmed this conclusion. In the Fig 1 (at right) the parameters of solar wind near the Earth's orbit are shown for the stream that flowed from the filament's area and coronal hole in July, 2003. OR-region and location of filament are shown at the top of the Fig.1. The filament disappeared by portions, while CME was not noted. Reduction of Bz IMF that leaded to Dst -110 nT was, most likely, related with a cold, dense and low-velocity flow from the filament than with a high-speed stream of coronal hole.

The tendency of activity complexes located on boundaries of OR-regions (often coinciding with coronal holes), which was discussed above, explains the absence of "pure" solar wind streams from coronal holes.

Conclusions

1. During the 23rd solar cycle (1996-2009) as in the previous ones, very intensive storms were observed near the maximum of solar activity and its decay phase. They were caused by CME "halo"-type, accompanied by solar flares and disappearances of filaments. The geoeffective CME were located mainly near the central meridian of the Sun and had the solar wind velocity over 700 km/s.
2. In addition to the analysis of solar sources for the period 1976-1979 [*Joselin*, 1986] it was found: a) not only high-class flares, but also weak flares can cause very intensive magnetic storm; b) long living flares play a significant role in the development of geomagnetic disturbances; c) in the period under consideration, phenomenon of disappearance of filaments, unaccompanied flares, rarely (<10% of storms) led to intensive magnetic disturbances. In solar cycle 23, we found that only 14% of large magnetic storms are related to coronal holes. In the previous cycle, according to [*Joselin*, 1986] coronal holes preceded 52% of intensive storms.
3. All the flares and filament’s disappearances, followed by intensive or extreme magnetic storms, were located on the boundaries of sub-sectors (OR-regions) or in the vicinity of the HCS projection.

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