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Statistical properties of the most powerful solar and heliospheric disturbances

O.S. Yakovchouk [a,*], I.S. Veselovsky [a,b], K. Mursula [c]

[a] Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow 119992, Russia
[b] Space Research Institute (IKI), Russian Academy of Sciences, Moscow 119992, Russia
[c] Department of Physical Sciences, University of Oulu, 90014, Finland

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Abstract

We present and discuss here the first version of a data base of extreme solar and heliospheric events. The data base contains now 87 extreme events mostly since 1940. An event is classified as extreme if one of the three critical parameters passed a lower limit. The critical parameters were the X-ray flux (parameter R), solar proton flux (parameter S) and geomagnetic disturbance level (parameter G). We find that the five strongest extreme events based on four variables (X-rays SEP, Dst, Ap) are completely separate except for the October 2003 event which is one the five most extreme events according to SEP, Dst and Ap. This underlines the special character of the October 2003 event, making it unique within 35 years. We also find that the events based on R and G are rather separate, indicating that the location of even extreme flares on the solar disk is important for geomagnetic effects. We also find that $S = 3$ events are not extreme in the same sense as $R > 3$ and $G > 3$ events, while $S = 5$ events are missing so far. This suggests that it might be useful to rescale the classification of SEP fluxes.

Keywords: Sun; Heliosphere; Extreme solar events; X-ray flares; Solar proton events; Magnetic storms

1. Introduction

The study of space weather and solar-terrestrial relations remains topical and important both from scientific and practical point of view (Cole, 2003; Schwenn, 2006). While the basic concepts of solar-terrestrial physics are well established, many detailed questions and, e.g., the possibility of forecasting needs further investigation (Crooker, 2000; Gopalswamy et al., 2001; Daglis et al., 2003; Gonzalez et al., 2004). Moreover, the unexpected and extreme solar events during solar cycle 23 have raised questions about their causes and properties (Veselovsky et al., 2004; Panasyuk et al., 2003; Yermolaev et al., 2005a; Gopalswamy et al., 2005; Kane and Echer, 2007).

Geomagnetic storm development can be predicted fairly well based on the solar wind and interplanetary magnetic field measurements upstream from the Earth. Measurements in the L1 libration point allow to do this rather reliably about 10–40 min in advance, depending on the solar wind velocity. Also, less certain predictions for much longer lead times exist, based on solar observations (Schwenn et al., 2005).

Many properties of extreme solar and heliospheric events are still poorly known (Ishkov, 2005; Yermolaev et al., 2007). Their study is difficult because they are rare and sometimes out of the range of measurement capability. Also, reliable theoretical models are still lacking. Nevertheless, one can note on a few interesting properties. Extreme solar flares and active regions demonstrate a complicated multi-scale structure and time behavior characterized by

* Corresponding author.
E-mail addresses: olesya@ dec1.sinp.msu.ru (O.S. Yakovchouk), veselov@dec1.sinp.msu.ru (I.S. Veselovsky), Kalevi.Mursula@oulu.fi (K. Mursula).

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dimensionless scaling parameters (Conlon et al., 2008; Sen, 2007). Strongest solar and heliospheric events, e.g., major flares and coronal mass ejections have a nonlinear and non-local character from smallest to largest scales. The coupling between the scales, which is still not well understood, often leads to a non-uniform time behavior with multiple energy releases which may be concentrated around one or several active regions, prominences or coronal holes, and have an asymmetric hemispheric or longitudinal distribution (Veselovsky et al., 2005; Mursula, 2007).

The aim of this paper is to present and investigate an empirical data base of the most powerful solar and heliospheric disturbances.

2. Compilation of extreme event data base

We are using the five-scale NOAA classification of space weather disturbances: minor (1), moderate (2), strong (3), severe (4), and extreme (5) (www.sec.noaa.gov/NOAAscales; Ishkov, 2005). Table 1 shows the five X-ray flare classes (R1–R5) ordered by the maximum intensity of soft X-rays in the energy range 1–12.5 keV (0.1–0.8 nm) observed at the Earth's orbit. It is worth to mention that X-ray flares can lead to sudden ionospheric disturbances and cause radio communication problems also called radio blackouts (which is why X-ray classification is indicated by R). We have considered extreme and, thereby, included in our data base all those events in the NOAA data base that have been classified as R4 or R5 (http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarflares.html).

Solar proton events (SEP classes S1–S5) are given in units of pfu (proton flux unit), which is the number of protons at the Earth's orbit per cm^2 per steradian per second with energy higher than 10 MeV. Solar proton events appear as a result of particle acceleration in solar flares and in heliospheric shocks. Events with SEP classes S3–S4 are included as extreme events in our data base. Note that no S5 class event has been observed yet (Shea and Smart, 1990; Miroshnichenko, 2003; http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt).

Geomagnetic storms (classes G1–G5) result from the impact of the disturbed solar wind and interplanetary magnetic field upon the magnetosphere of the Earth. The key controlling factor of the intensity and duration of the storm is the southward component of the interplanetary magnetic field. Index G is based on the planetary geomagnetic 3-h Kp index, which is produced from measurements at 12 ground-based magnetic observatories at mid-latitudes. Geomagnetic storms of index G4 and G5 are included as extreme events in the data base (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/, http://swdcwww.kugi.kyoto-u.ac.jp/kp/index.html).

Table 2 presents our data base of extreme events based on the three parameters (R, S, G) so that if either the R value or the G value of the event was 4 or 5, the event was considered extreme and included in the data base. Also, if the S value was 3 or 4, the event was included in the data base. The columns in Table 2 indicate (1) the event number; (2) the year; (3) date and (4) UT time of the event in the Sun; (5) the coordinates and (6) NOAA classification number of the solar active region; (7) the X-ray and/or optical flare classes; (8) the speed (in km/s) of the possibly related coronal mass ejection according to the SOHO LASCO CME catalogue (http://cdaw.gsfc.nasa.gov/CME_list/); (9) the solar energetic proton flux (in pfu); (10) the duration (in hours) of the geomagnetic storm, (11) the maximum Ap index; (12) the minimum Dst index; the related five-scale NOAA classes for (13) R , (14) S, and (15) G. Blank entries in the table indicate gaps in data or irrelevance.

From early 1970s onward, the data base is more or less complete and homogeneous with all three selection parameters (R, S, G) having measured values. In earlier times, since 1932, the event selection was only based on the G value or, from 1942 onwards, partially on both G and S (Miroshnichenko, 2003). As additional information on flare activity, we have also included the flare classes based on white-light (optical) observations. From about 1940 to 1966, the flares observed in white light were classified in three classes (1–3), with 3+ indicating the largest flares. Thereafter they were classified in four main classes (1–4), with subdivisions indicated by letters (see, e.g., Dodson and Hedeman, 1975).

Note that the data base can be extended even further back in time using the long-term geomagnetic indices like the Aa* index (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/). In the future we will extend the data base by using the relation between the Ap/Kp indices known since 1932 with the aa index (Mayaud, 1980), the recent Ah index (Mursula and Martini, 2007) and with the extended and corrected Dst/Dcx index (Mursula and Karinen, 2005).

Table 1
NOAA classification of space weather perturbations (www.sec.noaa.gov/NOAAscales; Ishkov, 2005).

NOAA scale	R radio blackouts (X-ray flux)	S SEP (flux of $E > 10$ MeV particles)	G geomagnetic storm (Kp value)
5 – Extreme	>X20 (2×10^{-3} W m^{-2})	>100,000 pfu	9
4 – Severe	>X10 (10^{-3} W m^{-2})	>10,000 pfu	8 and 9
3 – Strong	>X1 (10^{-4} W m^{-2})	>1000 pfu	7
2 – Moderate	>M5 (5×10^{-5} W m^{-2})	>100 pfu	6
1 – Minor	>M1 (10^{-5} W m^{-2})	>10 pfu	5