

Investigation of the cosmic ray ground level enhancements during solar cycle 23

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Abstract

Major solar energetic particle events associated with large solar flares can give rise to cosmic ray ground level enhancements (GLEs). Up to December 2003 during solar activity cycle 23, 13 GLEs (Number from 55 to 67) have been recorded by the worldwide network of neutron monitors. Nine of the 13 GLEs (69%) originated from the southern hemisphere and 11 of the 13 GLEs (85%) originated from the western hemisphere. All GLEs originated from the solar activity region within a latitude strip between S20° and N40° and a longitude west of E10°. Each GLE corresponds to a solar fast coronal mass ejection (CME) which had the potential of producing disturbances to the geospace. The average speed of CMEs is high up to 1762 km s⁻¹. Among the 13 relevant CMEs 9 are responsible for nine major geomagnetic storms (defined by disturbance storm time index ≤ -100 nT). The largest four geomagnetic storms (Dst ≤ -277 nT) correspond to the four GLEs (Nos. 59, 62, 65 and 66) which have the highest proton flux with energy >10 MeV. It seems to imply that the solar proton events (SPEs) having great proton flux are more likely to be associated with major geomagnetic storms. Simultaneous existence of high flux SPEs, high optical flare classification, and fast halo CMEs near the central meridian of the Sun, as well as GLEs may be an effective indicator for predicting the occurrence of a strong geomagnetic storm. © 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Solar proton events; Ground level enhancements; Coronal mass ejections; Geomagnetic storms

1. Introduction

It is known that solar energetic particles with energies above several hundred MeV at the top of the atmosphere can produce secondary particles giving rise to an increase in the cosmic radiation flux as measured on the surface of the Earth. These highest energy solar proton events (SPEs) are called cosmic ray ground level enhancements (GLEs). Since a historical beginning of the first GLE observation in 1942 (Forbush, 1946), 67 GLEs have been recorded mainly by the worldwide network of neutron monitors. Measurements of GLEs have indicated that the Sun can accelerate protons up to GeV energies (Park, 1957; Miroshnichenko, 2001).

It is widely accepted that the majority of solar energetic particles are accelerated by shock waves driven by CMEs through the coronal and interplanetary space. Solar CMEs also drive solar wind disturbances and some can result in major geomagnetic storms. Many early studies indicated that major solar proton fluence events are usually associated with a solar flare and a fast CME (Shea and Smart, 1996; Smart and Shea, 2002). Furthermore, those events emanating from close to the central meridian of the Sun more likely produce major geomagnetic storms at the Earth. Most GLEs correspond to chain events from the Sun to the Earth, including flares, CMEs, SPEs and geomagnetic storms. We will call this a ‘Sun–Earth chain event’. Although studies of major SPEs and GLEs have been made for decades, their characteristics such as particle acceleration and production factors have not been well understood. In

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this paper, we found and studied such Sun–Earth chain events associated with 13 GLE events in the current (23rd) solar cycle.

2. Data and identification of chain events

A significant SPE is defined as one having fluxes ≥ 10 particles $(\text{cm}^2 \text{ s ster})^{-1}$ above 10 MeV, in agreement with the criteria established by the NOAA Space Environment Laboratory. By this criteria our database includes 78 SPEs recorded near the Earth between January 1996 and December 2003. Among them, 13 events (17%) recorded by at least two neutron monitors have been defined as GLE events. First, we find the solar flare and CME event associated with the GLE according to the time of each GLE. The solar sources were obtained from the on-line Solar Geophysical Data (SGD) and observations of CMEs were from the Large Angle and Spectrometric Coronagraph (LASCO) (Brueckner et al., 1995). Second, we find major geomagnetic storms originating from solar CME. There are in general two kinds of solar sources of geomagnetic storms, CMEs and corotating interaction regions. Both CMEs and corotating interaction regions contribute to minor and moderate geomagnetic storms. Nevertheless, major geomagnetic storms are found to be mainly caused by CMEs (Gosling et al., 1990; Tsurutani and Gonzalez, 1997). In this paper a major geomagnetic storm is classified by the Dst index of less than or equal to -100 nT at the peak disturbance. Statistical studies have found that the CME transit time from the Sun to the near-Earth space falls in between 1 and 5 days and coarsely depends on the CMEs initial speed (Gopalswamy et al., 2000; Cane et al., 2000). Using a fixed time window method and looking into solar wind signature, Zhang et al. (2003) have identified solar CME sources for 27 major geomagnetic storms occurring between 1996 and 2000. For a given fast CME, we choose a fixed 30–120 h forward time window to look for a candidate for major geomagnetic storms. Taking into account solar wind signatures, major geomagnetic storms originating from solar CMEs were further confirmed. These values are listed in Table 1.

From left to right in Table 1, the columns divided into five parts, GLE, SPE peak flux in unit pfu ($1 \text{ pfu} = 1 \text{ proton } (\text{cm}^2 \text{ s ster})^{-1}$) with energies above 10 MeV from the GOES observations, X-ray flare, CME and geomagnetic storm. GLE column represents the GLE number, date of GLE. X-ray flare column represents time of the 1–8 Å X-ray flare peak flux, heliocentric coordinates of flare, NOAA active region number, and optical flare class. CME column designates solar CME time, CME position angle (PA), CME angular width (AW) and CME velocity. Geomagnetic storm column designates the Dst peak time, Dst index value and

Table 1
Parameters of SPEs, X-ray flares, CMEs and geomagnetic storms related to GLEs

GLE No.	Date	SPE Flux (pfu ^a)	X-ray flare			CME				Geomagnetic storm			
			Time (UT)	Location	Region	Bright	Time (UT)	PA (deg.)	AW (deg.)	Velocity (km s ⁻¹)	Date (m.d.UT)	Dst (nT)	Kp
55	1997.11.06	490	11:55	S18W63	8100	X9/2B	12:10	halo	360	1556	11.07 04:00	-104	7
56	1998.05.02	150	13:42	S15W15	8210	X1/3B	14:06	halo	360	938	05.04 05:00	-216	9-
57	1998.05.06	210	08:09	S11W65	8210	X2/1N	08:29	309	190	1099	-	-	-
58	1998.08.24	670	22:12	N35E09	8307	X1/3B	-	-	-	-	08.27 12:00	-188	8
59	2000.07.14	24000	10:24	N22W07	9077	X5.7/3B	10:54	halo	360	1674	07.15 21:00	-300	>9
60	2001.04.15	951	13:50	S20W85	9415	X14/2B	14:06	245	167	1199	04.18 07:00	-101	7+
61	2001.04.18	321	02:14	S20W1mb	9415	C2/2B	02:30	halo	360	2465	04.22 16:00	-103	6+
62	2001.11.04	31700	16:20	S06W18	9684	X1/3B	16:35	halo	360	1810	11.06 06:00	-277	9
63	2001.12.26	779	05:40	S08W54	9742	M7/1B	05:30	281	>212	1446	-	-	-
64	2002.08.24	317	01:12	S02W81	10069	X3/1F	01:27	halo	360	1878	-	-	-
65	2003.10.28	29500	11:10	S16E08	10486	X17/4B	11:30	halo	360	2459	10.29 24:00	-345	9
66	2003.10.29	3300	20:49	S15W02	10486	X10/2B	20:54	halo	360	2029	10.30 23:00	-401	9
67	2003.11.02	1570	17:25	S14W56	10486	X8.3/2B	17:30	halo	360	2598	-	-	-

^a 1 pfu = 1 proton $(\text{cm}^2 \text{ s ster})^{-1}$.

K_p index value. Some parameters are absent in several lines because no major geomagnetic storms were found in the five-day time window. We also study the moderate ($10 \text{ pfu} < I_p < 100 \text{ pfu}$) SPE events and correlated CMEs for the purpose of comparisons. In the same period we selected 30 events that were required to have a simultaneous existence of both flare and CME.

3. Results and discussion

GLE events refer to the most powerful signature of solar activity. Table 1 shows that 11 (85%) of 13 flares are class X level and SPE fluxes are more than several hundreds. It indicates that high solar proton flux is more likely to create GLEs. It is commonly believed that strong flare activity is not only the foundation for ejecting seed particles from the Sun into interplanetary space but also a common factor to large CMEs that drive shock wave to accelerate particles to higher energies. We think there are multiple factors working on production of major SPE and GLE together such as the helio-

spheric magnetic field structures, the CME in association with solar flare of class X, as well as the magnetic activities on the Sun during the production of major SPEs and GLE events.

Table 1 also shows that nine GLEs (69%) originated from the southern hemisphere and 11 GLEs (85%) originated from the western hemisphere. In Fig. 1 we plot the heliocentric coordinates of the solar surface source region of the related solar flare. We can see the latitude distribution of the solar flare source region is similar for GLE-flares (Fig. 1(a)) and moderate SPE-flares (Fig. 1(b)), within a latitude strip of $\pm 40^\circ$. However, the longitude distribution are different. GLE-flares are west of $E10^\circ$ while moderate SPE-flares seem to occur in more eastern solar longitude. The most probable longitude for both flares are between $W60^\circ$ and $W70^\circ$. There is a strong tendency for the solar active region responsible for a GLE to be located at westward solar longitudes. This is consistent with early results (McDonald, 1963; Shea and Smart, 1990).

Fig. 2 shows the speed distribution of GLE-CMEs (Fig. 2(a)) and moderate SPE-CMEs (Fig. 2(b)). The

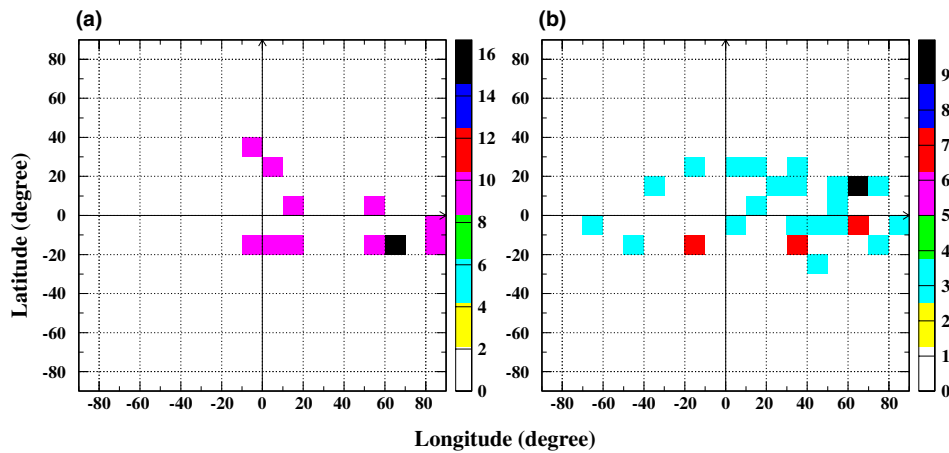


Fig. 1. Distribution of heliocentric coordinates of the solar surface source region of the flare: (a) associated with GLEs; (b) associated with moderate SPEs. The numbers on the grey scale indicate percentage of appearance probability (for example, 16 means 16%). Black represents the most probable region.

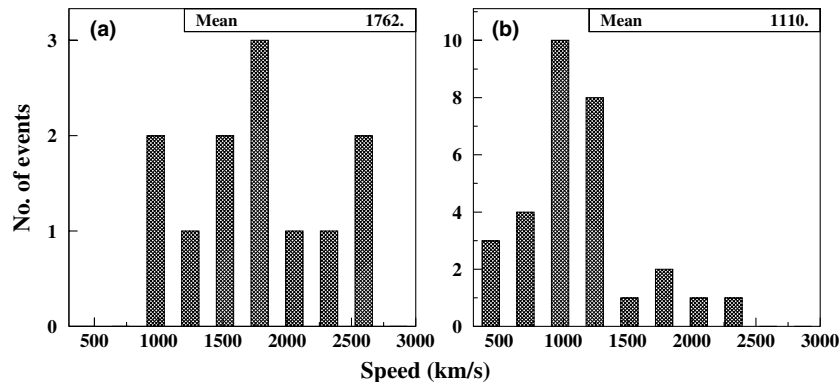


Fig. 2. Distribution of CME speed: (a) associated with GLEs; (b) associated with moderate SPEs.

speed of the GLE–CMEs is the fastest (average speed $\sim 1762 \text{ km s}^{-1}$), while that of the moderate SPE–CMEs is slightly slower (average speed $\sim 1110 \text{ km s}^{-1}$). All CMEs have speed exceeding the average speed ($\sim 450 \text{ km s}^{-1}$) therefore belong to fast CME. There are no obvious correlation between CME speed and Dst peak time of geomagnetic storm. Except for CME initial speed, transit time from Sun to near-Earth space are determined by solar wind signatures and the interplanetary shock wave. We note from Table 1 that all CMEs are halo CMEs, which include nine (75%) full-halo CMEs and three (25%) partial-halo CMEs (defined by angular width exceeding 140°).

The largest four major geomagnetic storms which have Dst index of less than -277 nT and Kp index of nine correspond four significant SPEs with the highest fluxes in Table 1. They are all associated with front-side halo CMEs with speeds above 1800 km s^{-1} . It is suggested that the ejection of high solar proton fluxes accelerated by a shock driven by a fast halo CME and resulting in a GLE event are essential requirements for creating an extremely strong geomagnetic storm. We found there were another 64 major geomagnetic storms without GLEs in the same period. Two of the largest ones, 2001 March 31 and 2003 November 20 events, have Dst index of less than -300 nT . The former corresponds a X class flare (in N20W19)/fast halo CME (with speed 942 km s^{-1}), but solar proton flux is only 35 pfu. The later is an exception. There are no SPEs and large flares before it. So these factors are only as a sufficient condition not a necessary condition. We can at least use these factors of forecasting extremely major geomagnetic storms.

4. Conclusion

Based on the GOES, LASCO and SGD data, We have identified the Sun–Earth chain events (flare, CME, SPE and geomagnetic storm) of 13 GLE events occurring between 1996 and 2003. We found 11 (85%) of the flares are class X and all SPE fluxes are more than several hundreds. These powerful solar activities took place within the longitude range between $E10^\circ$ and $W90^\circ$ and the latitude range between $S20^\circ$ and $N40^\circ$. Nine GLEs (69%) originated from the southern hemisphere and 11 GLEs (85%) originated from the western hemisphere. All CMEs are fast halo CMEs (75% full-halo and 25% partial-halo) with a average speed of $\sim 1762 \text{ km s}^{-1}$ and a average angle width of 317° .

Nine major geomagnetic storms with Dst index less than -100 nT were originated from fast halo CMEs.

We noted four largest geomagnetic storms (three $\text{Dst} \leq -300 \text{ nT}$ and one $\text{Dst} = -277 \text{ nT}$) are from solar source of halo CMEs and correspond simultaneously to the powerful SPEs of great flux of over thousands or ten thousands pfu. It may be possible to predict the largest geomagnetic storms by making use of the simultaneous existence of solar flares with a high optical flare classification, fast halo CMEs near the central meridian of the Sun, and a powerful SPE and GLE.

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References

- Brueckner, G.E., Howard, R.A., Koomen, M.J., et al. The large angle spectroscopic coronagraph (LASCO). *Sol. Phys.* 162, 357–402, 1995.
- Cane, H.V., Richardson, I.G., St. Cyr, O.C. Coronal mass ejections, interplanetary ejecta and geomagnetic storms. *Geophys. Res. Lett.* 27, 3591–3594, 2000.
- Forbush, S.E. Three unusual cosmic-ray intensity increases due to charged particles from the Sun. *Phys. Rev.* 70, 771–772, 1946.
- Gopalswamy, N., Lara, A., Lepping, R.P., et al. Interplanetary acceleration of coronal mass ejections. *Geophys. Res. Lett.* 27, 145–148, 2000.
- Gosling, J.T., Bame, S.J., McComas, D.J., et al. Coronal mass ejections and large geomagnetic storms. *Geophys. Res. Lett.* 17, 901–904, 1990.
- McDonald, F.B. Solar proton manual, NASA, Technical Report TR R-169, Washington, DC, September, 1963.
- Miroshnichenko, L.I. *Solar Cosmic Rays*. Kluwer Academic Publishers, 2001.
- Park, P.N. Acceleration of cosmic rays in solar flares. *Phys. Rev.* 107, 830–836, 1957.
- Shea, M.A., Smart, D.F. A summary of major solar proton events. *Sol. Phys.* 127, 297–320, 1990.
- Shea, M.A., Smart, D.F. Solar proton fluxes as a function of the observation location with respect to the parent solar activity. *Adv. Space Res.* 17 (4/5), 225, 1996.
- Smart, D.F., Shea, M.A. Comment on estimating the solar proton environment that may affect Mars missions. *Adv. Space Res.* 31, 45–50, 2002.
- Tsurutani, B.T., Gonzalez, W.D. The principal interplanetary causes of magnetic storms. In: Tsurutani, B.T., Gonzalez, W.D., Kamide, Y., Arballo, J. (Eds.), *Magnetic Storms*, vol. 98. AGU, Washington, DC, pp. 77–89, 1997.
- Zhang, J., Dere, K.P., Howard, R.A., et al. Identification of solar sources of major geomagnetic storms between 1996 and 2000. *APJ* 582, 520–533, 2003.