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Enhancement of Solar Energetic Particles During a Shock – Magnetic Cloud Interacting Complex Structure

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Abstract The behavior of solar energetic particles (SEPs) in a shock – magnetic cloud interacting complex structure observed by the *Advanced Composition Explorer* (ACE) spacecraft on 5 November 2001 is analyzed. A strong shock causing magnetic field strength and solar wind speed increases of about 41 nT and 300 km s^{-1}, respectively, propagated within a preceding magnetic cloud (MC). It is found that an extraordinary SEP enhancement appeared at the high-energy ($\geq$10 MeV) proton intensities and extended over and only over the entire period of the shock – MC structure passing through the spacecraft. Such SEP behavior is much different from the usual picture that the SEPs are depressed in MCs. The comparison of this event with other top SEP events of solar cycle 23 (2000 Bastille Day and 2003 Halloween events) shows that such an enhancement resulted from the effects of the shock – MC complex structure leading to the highest $\geq$10 MeV proton intensity of solar cycle 23. Our analysis suggests that the relatively isolated magnetic field configuration of MCs combined with an embedded strong shock could significantly enhance the SEP intensity; SEPs are accelerated by the shock and confined into the MC. Further, we find that the SEP enhancement at lower energies happened not only within the shock – MC structure but also after it, probably owing to the presence of a following MC-like structure. This is consistent with the picture that SEP fluxes could be enhanced in the magnetic topology between two MCs, which was proposed based on numerical simulations by Kallenrode and Cliver (*Proc. 27th ICRC* **8**, 3318, 2001b).

Keywords Solar energetic particle · Shock · Magnetic cloud · Particle acceleration

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1. Introduction

Gradual solar energetic particle (SEP) events are believed to be the result of particle acceleration by shocks driven by coronal mass ejections (CMEs). Reames (2000) found that the SEP intensity is correlated with the CME speed but the scatter is large. Such scatter occurs not only because the CME speed does not reflect the real shock strength (Shen *et al.*, 2007) but also because many factors may influence the SEP intensity, including the longitude of the parent solar event with respect to the observer, seed particle populations, the magnetic field configuration around shocks, the interaction between CMEs and other interplanetary structures, and CME brightness and width (*e.g.*, Reames, 1997, 2002; Kahler, 2001; Gopalswamy *et al.*, 2004; Kahler and Vourlidas, 2005). It is also possible that different solar wind streams (fast and slow) (Kahler, 2004) and coronal holes (Shen *et al.*, 2006) could significantly influence the SEP intensity. Here, the term SEP intensity refers to the intensity that is observed near the Earth.

The preceding/preexisting interplanetary large-scale structures, such as interplanetary CMEs (ICMEs), are considered to be an important factor that could significantly influence the SEP intensity (*e.g.*, Richardson, 1997; Kallenrode, 2001; Cane and Lario, 2006). Magnetic clouds (MCs), a subset of ICMEs, can be identified by three definite signatures: enhanced magnetic field strength, long and smooth rotation of the magnetic field vector, and low proton temperature (Burlaga *et al.*, 1981). Many observations showed that the SEP intensity is usually depressed in isolated MCs, particularly in those traveling in the ecliptic plane (Richardson, 1997; Cane and Lario, 2006, and references therein). An explanation proposed by Kallenrode (2001) is that magnetic clouds may act as a barrier for external SEP propagation. Richardson (1997) also suggested that ejecta are predominantly closed magnetic structures, thus avoiding the easy access and exit of particles into or from the ICME.

However, such decreases in particle intensities are only true for simple and/or isolated events. For some complex structures, the behavior of SEPs may be much different.

Interplanetary complex structures are often observed, especially during solar maximum (Burlaga *et al.*, 2001; Burlaga, Plunkett, and St. Cyr, 2002; Wang, Ye, and Wang, 2002, 2003; Wang *et al.*, 2003a, 2003b). They may result from shock – MC, MC – MC, MC – CIR (corotating interaction region) interactions and any other combinations among them. For the shock – MC interacting complex structures, Wang *et al.* (2003a) reported some definite cases and studied their effects on geomagnetic disturbances. It is found that the shock compression of preceding magnetic cloud fields is an important interplanetary cause of large geomagnetic storms. Recently, Xiong (2006a, 2006b) further studied the formation, evolution, and interaction of such complex structures with the aid of 2.5-dimensional MHD simulations. However, investigations regarding SEPs in shock – MC interacting complex structures, another important effect on space weather, are rare. Some interesting events in which the SEP intensities were influenced by complex structures have already been studied (Kallenrode and Cliver, 2001a; Lario and Decker, 2002, and references therein). Here, we will present a clear case, in which the SEP intensity is extraordinarily enhanced.

This event was observed by the *Advanced Composition Explorer* (ACE) spacecraft on 5 November 2001. According to the SPE (Solar Proton Events) list compiled by NOAA,[1] it caused the largest SEP event (*i.e.*, the highest proton intensity, 31 700 pfu, where 1 pfu = $1\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{ster}^{-1}$, at an energy $\geq$ 10 MeV) in solar cycle 23. The solar and interplanetary observations of this event are shown in Section 2. In Section 3, by comparing it with other top

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[1] http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt.

SEP events in the same solar cycle, we address the importance of such complex structures in causing large SEP events. Section 4 gives some conclusions and presents a brief discussion of the proposed scenario.

2. Observations of the 5 – 6 November 2001 Event

Figure 1 shows interplanetary magnetic field, solar wind plasma, and energetic proton data from the ACE spacecraft and the proton flux profiles from GOES-8 (the primary GOES spacecraft for protons before 8 April 2003) from 12:00 UT on 5 November to 00:00 UT on 7 November 2001. The first six panels, from top to bottom, show magnetic field strength B, the elevation angle θ, azimuthal angle ϕ in the Geocentric Solar Ecliptic (GSE) coordinate system, the bulk flow speed V, the proton number density N_{p}, and the proton temperature T_{p}. All solar wind data have 64-second resolution except V, N_{p}, and T_{p} after about 01:24 UT on 6 November, which were collected in the search suprathermal ion (STI) mode with a resolution of about 32 minutes by the ACE/SWEPAM instrument (McComas *et al.*, 1998; Skoug *et al.*, 2004). The STI mode data are used because the normal high-resolution data cannot be collected during extremely large SEP intensities. The two bottom panels show the proton intensities at low energies observed by ACE/EPAM and at high energies observed by GOES, respectively. Between 19:30 UT on 5 November and 05:30 UT on 6 November, the magnetic field strength was high, showing a long and smooth rotation, whereas the proton temperature was relatively low except for the region after 01:24 UT on 6 November when a shock arrived at ACE (solid vertical line in Figure 1). These signatures strongly suggest an MC (hereafter referred to as MC-I) with an embedded shock during that period. This MC was first identified and reported by Wang *et al.* (2003a) and also included in the list compiled by Zhang *et al.* (2007). At the shock, the magnetic field and speed significantly increased by $\approx$ 41 nT and $\approx$ 300 km s^{-1}, respectively. Both indicate a strong compression, which distorted the low-temperature signature of MCs and produced the extraordinarily high proton temperature observed after the shock passage. The front boundary of MC-I is clearly determined according to the sharp decrease in proton temperature and the start of the smooth magnetic field (indicated by the first dotted vertical line). The rear boundary is determined by the end of the smooth rotation of the magnetic field vector, where θ suddenly decreased (the second dotted vertical line). This MC is the interplanetary counterpart of a slow halo CME first observed by the C2 camera of the Large Angle Spectrometric Coronagraph (LASCO; Brueckner *et al.*, 1995) onboard the *Solar and Heliospheric Observatory* (SOHO) at 19:20 UT on 3 November, which moved out with a projected speed of 457 km s^{-1} and took $\approx$ 48 hours to arrive at 1 AU.

The shock propagating within MC-I is probably driven by a following MC-like structure (hereafter called MC-II), as shown in Figure 1. Based on the ACE observations, this MC-like structure began at 13:00 UT on 6 November and ended at 19:12 UT, during which time the signatures of enhanced magnetic field and long and smooth rotation are significant. By searching in the CME catalog[2] compiled at NASA's Goddard Space Flight Center (GSFC), we found an extremely fast halo CME, first observed by LASCO/C2 at 16:35 UT on 4 November as a possible origin of MC-II. There are other (partial) halo CMEs on 3 and 4 November, but they are too slow to drive such a large shock. The CME at 16:35 UT on 4 November originated from the NOAA active region 9684 with a projected speed of

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[2] http://cdaw.gsfc.nasa.gov/CME_list.

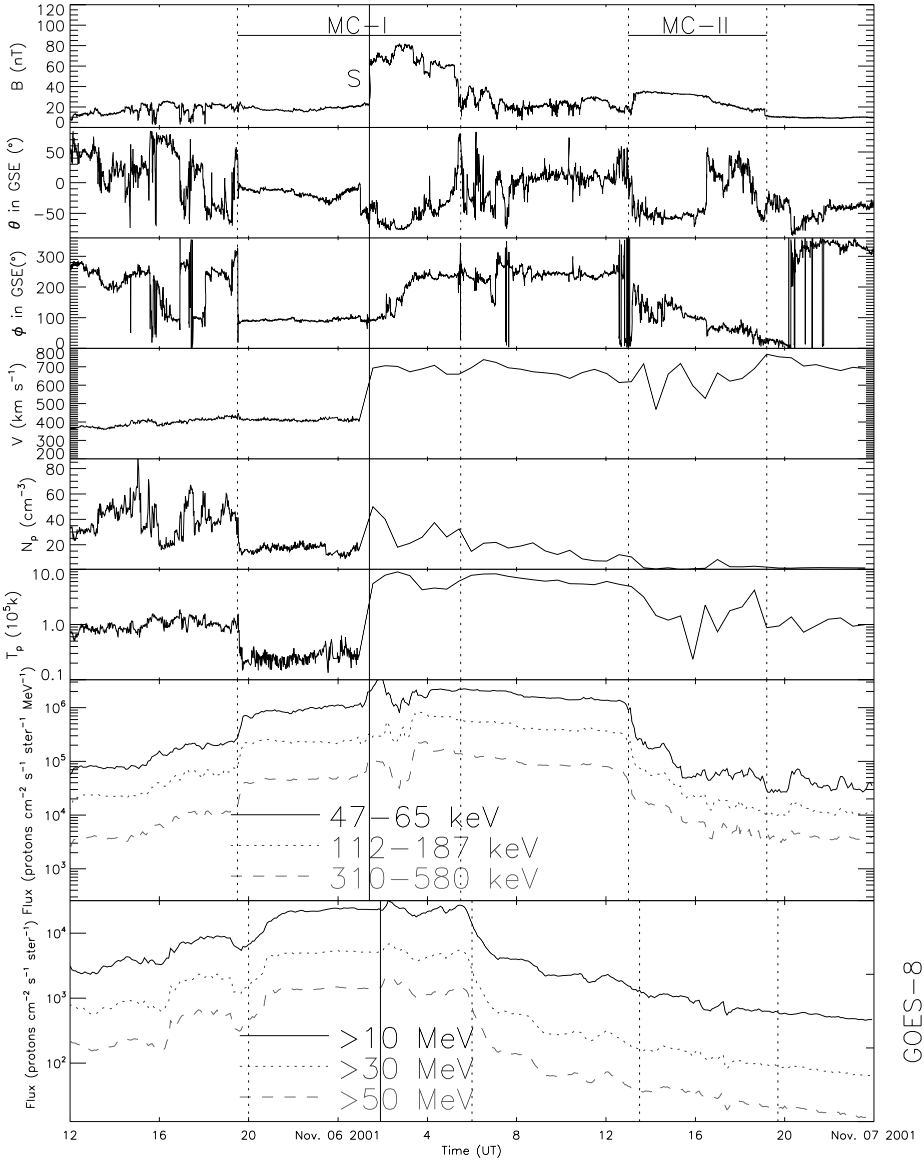

Figure 1 Observations by the ACE (top seven panels) and the GOES-8 (bottom panel) spacecraft from 12:00 UT on 5 November to 00:00 UT on 7 November 2001.

1810 km s^{-1} and was associated with an X1.0 class flare at N06°W18° almost facing the Earth. The *Wind*/WAVES observations show that it produced a long-lasting decameter–hectometer (DH) type II radio burst,[3] as shown in Figure 2. The DH type II radio burst started at a frequency of 14 MHz, the upper limit of the frequency range of *Wind*/WAVES,

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[3] Refer to the list of type II bursts at http://lep694.gsfc.nasa.gov/waves/waves.html.

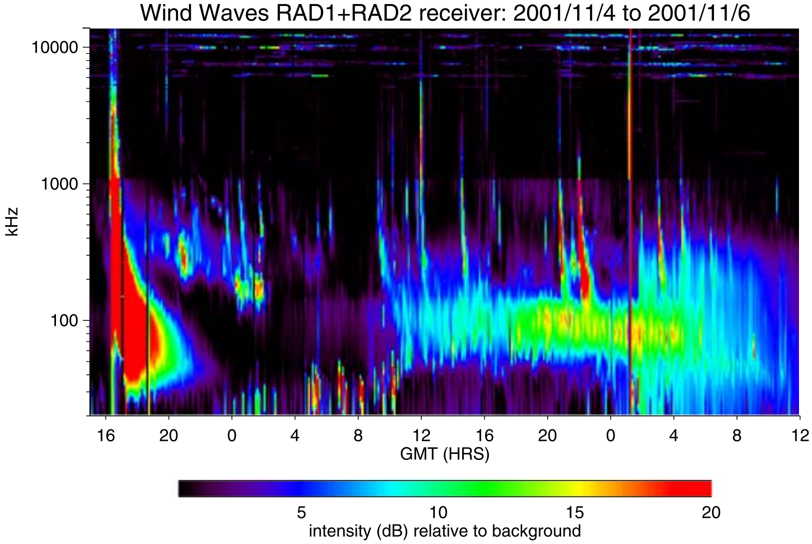

Figure 2 *Wind*/WAVES observations of the 4 November 2001 event.

at 16:30 UT on 4 November, and lasted about two days until 11:00 UT on 6 November at a frequency of 70 kHz. Both the site of the CME source region and the radio observations suggest that the CME and the driven shock should be observed near Earth, and MC-II and the shock inside MC-I are the only candidates for their interplanetary counterparts. Particularly, the long-lasting DH type II emission implies that the CME was powerful, driving a strong shock from the altitude near the solar surface to beyond 1 AU, and the shock continuously accelerated electrons, even in MC-I.

This event caused the highest $\geq$ 10 MeV proton intensity since solar cycle 23. The peak intensity of the GOES integral proton flux at energy $\geq$ 10 MeV was 31 700 pfu. The bottom panel of Figure 1 gives the GOES-8 integral proton fluxes at energies $\geq$ 10, $\geq$ 30, and $\geq$ 50 MeV. The MC boundaries and the shock arrival are also marked by the dotted and solid vertical lines with a small backward shift of 30 minutes in this panel. This shift is based on the consideration of the distance between the ACE and GOES spacecraft and the CME transit speed of $\approx$ 868 km s^{-1}. The GOES data exhibit obvious increases in the integral proton fluxes at these high energies near the front boundary of MC-I. The enhancement is about a factor of 4 for the $\geq$ 10 MeV proton flux. Neither the CME catalog[4] compiled at GSFC nor the list of solar event report[5] generated by NOAA/SEC indicates a solar eruption around that time. So the increases of proton fluxes near the front boundary of MC-I should be attributed to the arrival of the MC itself. After the increase, the intensities remained at high levels until approximately the rear boundary of MC-I, where the integral proton fluxes decreased by about one order of magnitude. Such an increase at the front boundary of the MC and a decrease at the rear boundary provide the evident enhancement of SEP intensity during the entire period of MC-I. This signature is totally different from the common picture that the SEP intensity is low in isolated MCs.

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[4] http://cdaw.gsfc.nasa.gov/CME_list.

[5] http://www.sec.noaa.gov/ftpdir/warehouse/.

3. Comparison with Other Top SEP Events in the Same Solar Cycle

To analyze the signature of such an enhancement and its role in making the highest $\geq$ 10 MeV proton intensity in solar cycle 23, this event is compared with other two well-studied great events, the 14 July 2000 event (Bastille Day event; *e.g.*, Lepping *et al.*, 2001) and the 28 October 2003 event (Halloween event; *e.g.*, Wang *et al.*, 2005). The proton data of the last event come from GOES-11 because GOES-11 served as the primary GOES satellite for protons after 18 June 2003.[6]

These three events are ranked the top three SEP events in terms of the proton intensity at energy $\geq$ 10 MeV in that solar cycle. Table 1 lists the main solar and interplanetary parameters of these events. For the first event, the MC in the table refers to the MC overtaken by the listed shock, which is responsible for the SEP event; for the other two, the MCs refer to the interplanetary counterparts of the CMEs driving the listed shocks, which are responsible for the respective SEP events. All these SEP events were caused by a shock driven by an extremely fast CME originating near the solar central meridian. All the corresponding CMEs were associated with an X-class flare and produced a long-lasting DH type II radio burst, which indicates that they were very powerful and the driven shocks were energetic and strong.

Table 1 The top three great SEP events in solar cycle 23.

		1	2	3
CME	Time (UT)[a]	2001/11/4 16:35	2000/7/14 10:54	2003/10/28 11:30
	Location[b]	N06°W18°	N22°W07°	S15°E10°
	Speed (km s^{-1})[c]	1810	1674	2459
Flare	Class	X1.0	X5.7	X17.2
Shock	Arrival[d] (UT)	11/06 01:24	07/15 14:15	10/29 06:00
	V_T^e (km s^{-1})	1270	1523	2252
MC[f]	Begin (UT)	11/05 19:30	07/15 19:00	10/29 11:00
	End (UT)	11/06 05:30	07/16 10:00	10/30 02:30
LDT II[g]	Duration (hours)	42.5	28	37
SEP	Intensity (pfu)[h]	31 700	24 000	29 500

[a] The time of the first appearance of the CME in LASCO/C2.

[b] The location of the CME source region identified from the SOHO/EIT observations.

[c] The projected speed of the CME observed by SOHO/LASCO.

[d] The time of the shock arrive at ACE.

[e] The mean transit speed of the shock from the Sun to 1 AU.

[f] For the first event, this refers to the MC overtaken by the listed shock. For other two, this refers to the MC driving the shock.

[g] Long-lasting DH type II radio burst.

[h] The intensity of proton flux with energy $\geq$ 10 MeV observed by GOES.

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[6] http://www.swpc.noaa.gov/ftpdir/lists/xray/README.

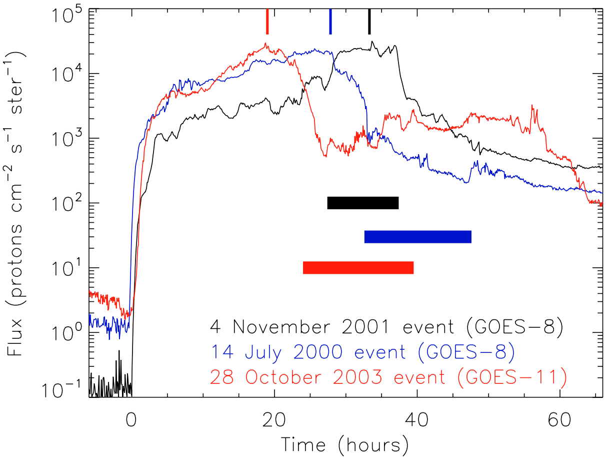


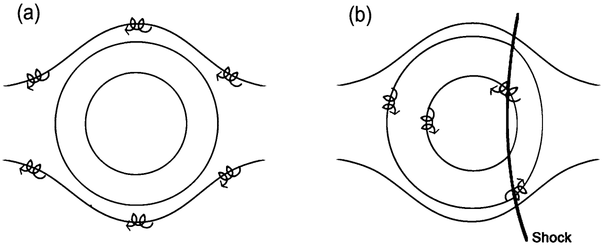
Figure 3 Comparison of the proton flux profiles at proton energy ≥ 10 MeV of the top three SEP events in solar cycle 23. The black, blue, and red lines indicate the 4 November 2001, 14 July 2000, and 28 October 2003 events, respectively. The x-axis scales the time line after the first appearances of the corresponding CMEs observed by LASCO/C2. The solid vertical lines at the top denote the arrivals of the shocks at the ACE spacecraft. The thick horizontal bars mark the periods of these MCs passing through the ACE.

Figure 3 shows the comparison of the proton flux profiles at energy ≥ 10 MeV between these great SEP events. The first appearances of these CMEs in LASCO/C2 are all toggled to zero time. It is clear that the proton flux increased rapidly soon after the CME onset for all the events, which formed the impulsive phase. The magnitude of the enhancement in the impulsive phase for events 2 and 3 is much bigger than that for event 1. This is probably because *i*) the background proton flux in events 2 and 3 is higher than that in event 1, as shown in Figure 3, *ii*) the flare in events 2 and 3 is larger in intensity than that in event 1, *iii*) the shock in events 2 and 3 is probably stronger than that in event 1, as implied by the mean transit speeds of shocks listed in Table 1, and *iv*) the CME speed in event 3 is much higher than that in event 1. But the CME speed in event 2 is similar to that in event 1, and this may result from the fact that the CME speed observed by SOHO/LASCO was influenced by projection effects and the CME source region in event 2 was closer to solar center than the source region of the CME in event 3. After the impulsive phase, the proton fluxes increased slowly and remained at high levels for all the events, then reached peak values near the arrivals of the shocks. This is the typical profile of SEP events caused by a shock driven by a CME originating near the solar central meridian (Reames, 1999; Lario, 2005, and references therein). The interesting point is that ahead of the front boundary of the MC in event 1, the proton flux is much smaller than thats in event 2 and 3, but the extraordinary enhancement of SEPs (from ≈ 6000 pfu to ≈ 25 000 pfu) inside the shock – MC complex structure of event 1 brings it up to the highest ≥ 10 MeV proton intensity in that solar cycle. This result suggests that the shock – MC complex structure played an important role in causing this great SEP event.

4. Conclusion and Discussion

We report an extraordinary enhancement of SEP intensity in a shock – MC interacting complex structure observed by the ACE spacecraft on 5 November 2001, in which a strong shock that caused a significantly sudden increase in B and V propagated in a preceding MC. The SEP enhancement appeared at the ≥ 10 MeV proton intensities and extended over and only over the entire period of the MC passing through the spacecraft. Such SEP behavior is quite different from the usual picture that the SEP intensity at high energies is depressed in MCs. The comparison of this event with other top SEP events of solar cycle 23 (2000 Bastille Day

Figure 4 Schematic picture of the cross sections of (a) an isolated MC with an SEP event and (b) a shock – MC complex structure. The arrows indicate that the motion of particles is almost frozen into the magnetic field lines.



event and 2003 Halloween event) shows that such an enhancement resulted from the effects that the complex shock – MC structure had on the SEPs, leading to the highest $\geq$ 10 MeV proton intensity of solar cycle 23. These observational facts imply that a shock inside a magnetic cloud significantly increases the efficiency of shock-accelerated particles.

It has been suggested that MCs are looplike structures with two ends anchored to the solar surface (*e.g.*, Richardson and Cane, 1996; Larson *et al.*, 1997). Figure 4 shows the cross section of an MC in the interplanetary medium without and with an embedded shock. Theoretical studies suggest that the cross-field diffusion is small, and the ratio $\kappa_\perp/\kappa_\parallel$ of perpendicular to parallel diffusion coefficient is roughly in the range of 0.005 – 0.05 (*e.g.*, Jokipii *et al.*, 1995; Giacalone and Jokipii, 1999; Zank *et al.*, 2004; Bieber *et al.*, 2004). Kallenrode (2001) found that MCs may serve as a confining barrier to the SEPs. These results describe a picture in which MCs are more likely independent objects in the interplanetary medium, and the energetic particles accelerated in the solar wind will move along the interplanetary magnetic field lines and be hard to propagate into MCs, as shown in Figure 4(a). Thus, it is easy to explain why SEP intensities are usually depressed in MCs in observations. But in the special case presented in this paper, a strong shock was propagating in an MC. Naturally, the shock would accelerate the particles carried by the MC, and based on the confining barrier picture, most of these accelerated particles should be restricted in the MC, as shown in Figure 4(b). Since MCs may still be rooted at the Sun, a new injection of SEPs from the Sun into MCs is a valid source of the seed population for the embedded shock to produce high-energy particles.

Kallenrode and Cliver (2001a, 2001b) observationally and numerically studied some great SEP events, whose unusually large SEP intensities have led them to be called “Rogue events.” They found that the physical mechanisms leading to a rogue event were *i*) a barrier (most likely the magnetic cloud) upstream of the particle event and shock and *ii*) a continuous (strong) injection of particles from the shock belonging to the particle event. Lario and Decker (2002) studied the 20 October 1989 event, the largest SEP event in solar cycle 22, in which the maximum $\geq$ 10 MeV proton intensity observed by GOES was 40 000 pfu. They found that the high-energy particle population in that event was not a locally shock-accelerated population but rather a population of particles confined to a plasma structure. Similar to that event, the high-energy particle population in the largest SEP event in solar cycle 23 studied in this paper is confined in an MC. These results suggest that the interplanetary factors, such as complex structure of MCs and other plasma structures in front of the shock, are very important in causing SEP events, especially great ones.

The seventh panel of Figure 1 shows the ACE/EPAM data of proton fluxes of the 5 November 2001 event at lower energy ranges. It is found that at the end of MC-I the SEP flux at lower energies did not significantly decrease as does the flux at higher energies. The high flux continued until the arrival of MC-II. This is because the SEP enhancement at lower energy ranges occurs not only within MC-I but also in the region between MC-I and MC-II. This probably is the first observational report of such SEP enhancements between two MCs,

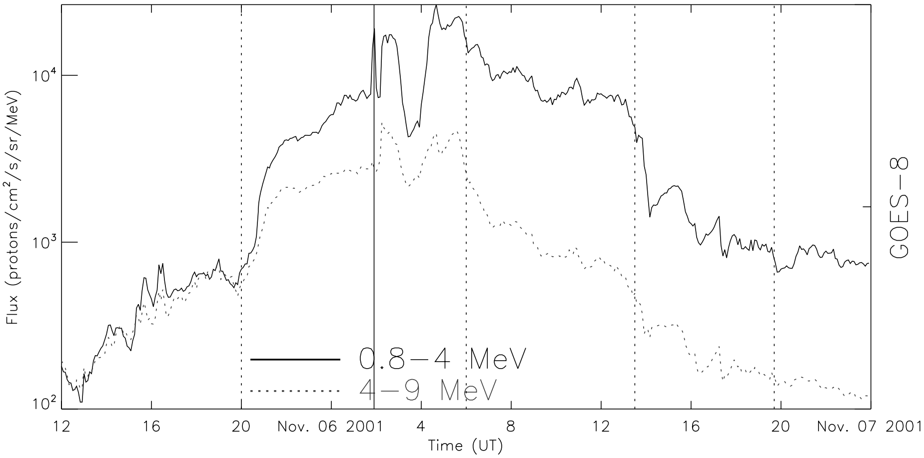


Figure 5 The GOES-8 observations at different energy ranges.

which matches the numerical study by Kallenrode and Cliver (2001b). In their simulations, they found that there should be a strong enhancement in intensity by about one order of magnitude between two MCs. Further, such an enhancement appearing only at lower energy implies that the magnetic topology between two MCs might not be strong enough to confine particles at higher energy, whereas the regular and relatively closed magnetic topology inside magnetic clouds may act as a better container to confine energetic particles even if the energy of particles is higher than 50 MeV.

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Appendix: Saturation Effects in GOES and ACE/EPAM Data

The observations of high energy particles by GOES and ACE/EPAM shown in this paper may be affected by saturation effects, especially for the lower energy channels during large SEP events (D.K. Haggerty, private communication, 2008). In this study, the saturation effect is not significant for $\geq$10 MeV protons, because there are evident fluctuations, as seen in Figure 3. Moreover, even if there is a saturation effect, it will not affect our conclusion here that the high-energy proton flux is enhanced within the shock – MC structure, which usually did not occur in isolated MCs. For the lower energy protons, as shown in the seventh panel of Figure 1, the high intensities reached in this event indicate that saturation is possible. However, it also does not affect our conclusion that the enhancement of lower energy protons occurs not only within the shock – MC structure but also between the two MCs. As a supplement, Figure 5 shows the proton fluxes at lower energies from the GOES-8 satellite for the 5 November 2001 event, in which the saturation effect is much smaller as the fluctuation is significant. A difference between the GOES-8 and ACE/EPAM lower energy proton observation is that the proton intensity did not continuously evolve through the rear edge of MC-I but decreased slightly. Even though there was a decrease at the rear boundary of MC-I, the proton intensity is still very high compared to those measured in the period before MC-I and after the arrival of MC-II.

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