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Prompt Solar Energetic Particles with Large-Scale Cross-Disk Coronal Disturbance

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Abstract. By using the observations of the Extreme-UV Imaging Telescope (EIT), we studied three major solar eruptions from the same super active region NOAA 10486 during the interval of October 26 to November 04, 2003. The three eruptions took place when the active region located on the eastern hemisphere, near the central meridian and on the western limb, respectively. In the first event (Oct 26 event), the coronal disturbance (indicated as an EIT wave) in EUV images was limited east to the central meridian, and there were no solar energetic particles (SEPs) detected. The second event (Oct 28 event) accompanied a nearly entire disk disturbance and very large and prompt SEP enhancements. For the last event (Nov 04 event), there was no obvious coronal disturbance on the disk, and the SEP enhancements were much more gradual. From these observational features, we suggest that different coronal disturbances correspond to different acceleration and propagation histories. A large-scale, cross-disk coronal disturbance may open quite a lot of magnetic field lines in the low corona, facilitating the direct access of flare accelerated SEPs to the Sun-Earth connected interplanetary magnetic field lines. Subsequently the SEP intensity will exhibit a very prompt enhancement.

Keywords. Sun: corona, coronal mass ejections (CMEs), magnetic fields, particle emission

1. Introduction

It is generally accepted that solar energetic particles (SEPs) can be produced on different timescales and at different site. They can be rapidly accelerated during a flare, or by coronal mass ejection-driven shocks traveling in the interplanetary space in several days (Lee & Fisk 1982; Jones & Ellison 1991; Reames, Kahler & Ng 1997). So two distinct classes of SEP events, impulsive events and gradual ones, have been defined (Reames 1999; Tylka 2001). The former ones have the origin in flares, while the latter ones are associated with CMEs.

However, there are more and more observations that impulsive and gradual component can both exist in one single SEP event. Kahler, Reames & Sheeley (2001) reported a clear connection between a narrow CME and an impulsive event. They attributed the narrow CME to flare ejecta rather than the traditionally considered CME. Mason, Mazur & Dwyer (1999) measured ^{3}He abundance from ∼0.5 to 2 MeV nucleon^{-1} in 12 large SEP events and found in some of these events the ^{3}He/^{4}He ratios are substantially larger than the solar wind value. In studying the very large 2000 July 14 event, Tylka *et al.* (2001) found the energy spectra of Fe are strikingly different from those of lighter species but can be well modeled with a small (∼5%) admixture of flare component. These authors suggested that remnant suprathermal ions which result from previous impulsive events can be a source population available for further acceleration by interplanetary CME-driven shocks that accompany large SEP events, leading to some characteristics of impulsive events.

Recently, there are arguments that mixed acceleration processes can exist in one single flare/CME event, and the impulsive characteristic SEPs may originate from the current flare, not the suprathermal ions from the previous events. This leads to the concept of hybrid SEP events (Clive 1996). In such cases, more attention should be paid to the early phase of the solar eruptions, because the disturbances in the corona would link different SEP populations to form a very complex pattern. Torsti *et al.*(1999) found the fast enhancement of $\geqslant$ 10 MeV protons in association with an EIT wave. In their opinion, the EIT wave was the signature of a quasi-perpendicular shock that gave rise to the $\geqslant$ 10 MeV protons, and the transform from the quasi-perpendicular shock acceleration to the quasi-parallel shock acceleration explained the spectral softening at the maximum intensity time. However, when comparing to the perfect double power law spectrum at the maximum time, we find at the rapid rise phase, the spectrum has a considerable deviation from a power law pattern. This clearly indicates the existence of multiple acceleration processes during the coronal disturbance, and shock should not be the only acceleration agent.

In October to November 2003, the Sun became wild again. Three super active regions appeared and a lot of major solar eruptions took place from these active regions. In this paper, we choose three eruptions with distinctly different SEP behaviors to see the relationship between coronal disturbance and SEP acceleration process. In §2 we describe the observations. Discussion and summary are given in §3.

2. Observation

In this study, we use the observations of the Extreme-UV Imaging Telescope (EIT; Delaboudinière *et al.* 1995) on board the *SOHO* spacecraft to track the EUV evolutions of the solar eruptions. SEP data are obtained from *GOES* which gives the intensities of energetic protons in several energy channels.

The three solar eruptions originated from the same active region NOAA 10486 south to the equator. They occur on 2003 October 26, October 28 and November 04, respectively. The corresponding locations of the active region are on the eastern hemisphere, near the central meridian and on the western limb. All of these three solar eruptions accompany X class flares and fast CMEs. But their associated SEP behaviors and coronal disturbances are quite different.

On 2003 October 26, the position of the active region was roughly S15E44. At 05:57 UT, a flare from this active region started, and it peaked at 06:54 UT, attaining the class of X1.2. A fast CME associated with the flare first appeared in LASCO C2 at 06:54 UT, nearly the same time as the flare maximum. Linear fit for the CME's trajectory reveals a speed of 1375 km/s. The EUV evolution of the event is shown in the right panel of Figure 1. This eruption induced an EIT wave. The EIT wave traveled northwestward from the active region. But before it faded out, the wave was still limited on the eastern hemisphere. Although this flare/CME event was quite large, no SEPs associated with this event were detected. The rapid rise of SEPs shown in the left panel of Figure 1 was due to another eruption from another active region.

The second event occurred on 2003 October 28 when the active region rotated to the position of S19E15. LASCO observed a full halo CME . The CME was first observed in C2 at 10:54 UT as a bright loop front over the W limb; by 11:30 UT the front had developed into a full halo CME, very bright all around the occulting disk. The CME was associated with an X17.2 flare. GOES records this flare from AR 0486 between 09:51 - 11:24 UT with peak emission at 11:10 UT. An extremely large EUV disturbance was observed (shown in Figure 2): the large-scale cross-disk coronal brightening developed nearly simultaneously followed by a full-disk dimming. This event caused very strong geoeffects. In Figure 2, SEPs in all channels exhibited prompt enhancements during the

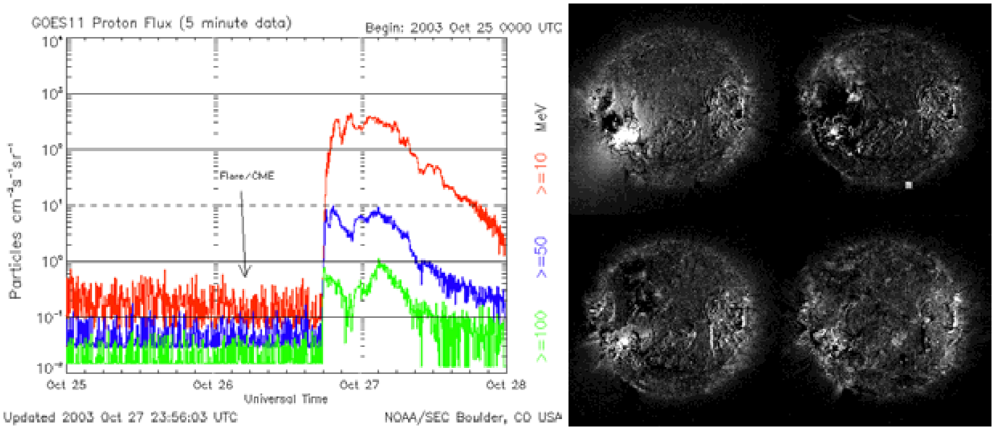

Figure 1. SEP behavior and coronal disturbance for the 2003 October 26 event. Left panel: GOES proton Flux for three energy channels. Right panel: running difference images of the EIT at 195 Å.

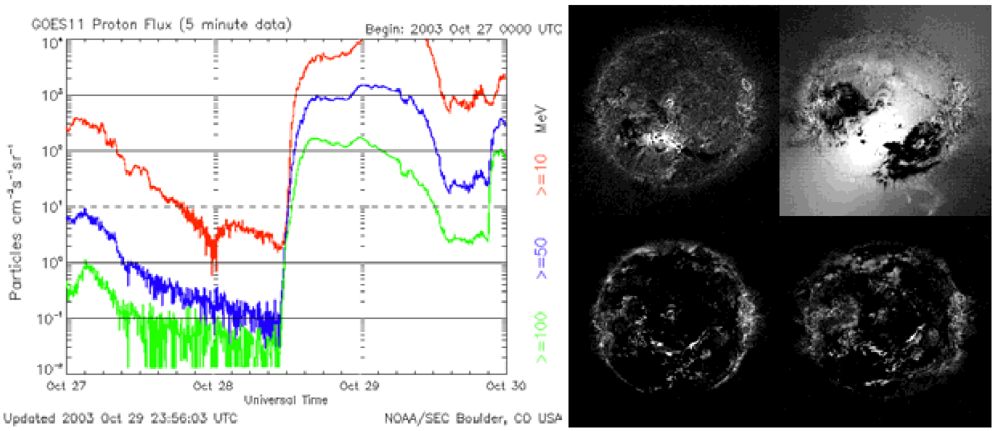

Figure 2. SEP behavior and coronal disturbance for the 2003 October 28 event.

solar eruption. After the rapid enhancement phase, the SEPs began to rise more gradually when the CMEs propagated into the interplanetary space.

The 2003 November 04 event was a limb event. Qiu *et al.* (in this proceeding) have studied the low corona signature of the event and found the disappearance of two loops which initially extended out from the active region. This interesting findings in the EIT fixed difference images (in Qiu *et al.*) are two dimmings corresponding to the footpoints of the two loops after the eruption. And in the running difference images shown in Figure 3, it seems that there was no obvious coronal disturbance on the disk. The X28 flare between 19:29 - 20:06 UT holds the record of the largest flare. The associated CME also has an unusually high speed of about 2300 km/s. But in comparison with the October 28 event, this event was in association with more gradual enhancements of the SEPs. Furthermore the peak flux of this SEP event was much smaller than that of the former one.

3. Discussion and Summary

The distinctly different SEP behaviors mentioned above imply different acceleration histories in different solar eruptions. Shock acceleration is often proposed to account for

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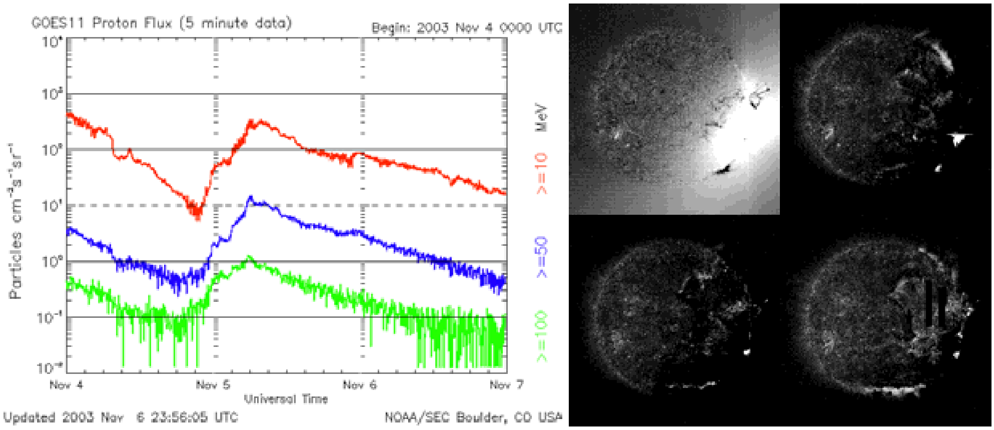

Figure 3. SEP behavior and coronal disturbance for the 2003 November 04 event.

large SEP events and power-law spectra are expected theoretically for shock acceleration below $\sim$ 30 MeV amu^{-1} (Ellision & Ramaty 1985). In higher energies, the power-law spectra will be multiplied by exponential rollovers. This means efficiency for acceleration of high-energy ions ($>$ 30 MeV amu^{-1}) by shocks will decrease more rapidly than those at low energies. Recently, Tsurutani *et al.* (2003) numerically studied the formation and propagation of a CME-induced shock. They found the shock formation will be sufficiently high in altitude and late in time. Even the CMEs in this paper may be fast enough to drive shocks in the low corona (Tang & Dai 2003), the low Mach numbers of the induced shocks will strongly affect the acceleration efficiency in high energies. So the prompt enhancements of the SEPs, especially for the high energy SEPs in the 2003 October 28 event, can not be mainly due to shock acceleration. Reconnection acceleration which can easily energize particles to several hundreds MeV amu^{-1} in very short timescale, must be included into the consideration.

The reconnection accelerated particles are produced quite low in the corona. So open magnetic field lines are necessary from the acceleration site to the root of interplanetary field for these SEPs to be observed quickly. In the 2003 October event, the large scale brightening and dimming in EIT images indicate the ejection of large amount of material from the low corona. At the same time, sufficient magnetic field lines are opened. This process changes the globe magnetic structure, facilitating the direct access of flare accelerated SEPs to the Sun-Earth connected interplanetary magnetic field lines.

For the other two events, the coronal disturbances are not large enough to ensure the direct access of flare accelerated SEPs. Therefore we can't see the prompt pattern of the SEPs. The 2003 November event accompanied more moderate SEP enhancements. Shock acceleration on a long timescale should be a reasonable explanation. Finally, why the 2003 October 26 event didn't produce any SEP? We notice the CMEs of 2003 October 28 and November 04 are both full halo CMEs, and the 2003 October 26 CME is the exception, whose width is 207 °. Although very board in comparison with typical CMEs, its width may be still not sufficient to produce SEPs. This is consistent with the result of Kahler & Reames (2003) that broad widths are necessary for CMEs to be associated with SEP events.

In summary, we suggest that in a large SEP event, multiple acceleration processes accelerate particles in different phases, and large-scale cross-disk coronal disturbances will link the different SEP populations to form a hybrid pattern. And in the interplanetary space, the width of CME is also an important factor in producing SEPs.

Acknowledgements

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Discussion

Bothmer: Paper by Bothmer *et al.* 1998 for April 7, 1997 event shows that particles arrived before EIT wave had reached the W-hemisphere. Send me e-mail so I can send you the paper.

Dai: You can e-mail to yhtang@nju.edu.cn. I will read the paper carefully.

Ruffolo: You have interpreted your data in terms of an EIT wave. Another interpretation would be in terms of magnetic connection. The solar wind speed was unusually fast, so the best connected longitude was near central meridian. This could explain why the Oct. 28 event had the fastest onset.

Dai: When the eruption takes place, the speed of the solar wind was not very high. I think the solar wind B accelerated by the CME. So we think the eruption site was still away from the well-connected regions.

Grechnev: One day before yesterday I warned against artifacts, both instrumental and methodical, in handling EIT images. The Bastille Day event and October 28, 2003 event are similar in that they both show large areas subjected to the scattered light. October 26, 2003 was shown by V. Slemzin on Monday, and the coronal wave in that event was in the NE section. So please be consider EIT images carefully, otherwise you can obtain incorrect results.

Dai: The results of the Oct. 26 event we showed are consistent with that of Dr. Slemzin. And in the Oct. 28 event we just want to show a large-scale coronal disturbance. And we will reexamine the EIT images carefully.