Highlights of the October - November 2003 Extreme Events

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Abstract
There was a high concentration of coronal mass ejections (CMEs), X-class soft X-ray flares, solar energetic particle (SEP) events, and interplanetary shocks observed during the episode the late October and early November 2003 period. The CMEs were very energetic and the consequences were also unusually intense. These extreme properties were commensurate with the size and energy of the associated active regions. This study suggests that the speed of CMEs may not be much higher than ~3000 km/s, consistent with the large free energy available in the associated active regions. The observations indicate that the CMEs may not have speeds much higher than ~ 3000 km/s implying that the Sun-Earth travel times of CME-driven shocks may not be less than ~0.5 day. Some of the CMEs were both geoeffective and SEPeffective, which are the most important from a space weather point of view.

1. Introduction

An extreme event is considered to be profoundly unique either in its occurrence or in its consequences. The October - November 2003 solar eruptive events (also known as the Halloween storms) qualify as extreme events on both counts: source properties at the Sun and their heliospheric consequences. Several aspects of theses events including active region size and potential energy flare occurrence rate and peak intensity, coronal mass ejection (CME) speed and energy, shock occurrence rate, SEP occurrence rate and peak intensity, and the geomagnetic storm intensity displayed extreme behavior. This period witnessed a high concentration of energetic eruptions including two CMEs that attained the level of a handful of historical events with an extremely short (less than a day) Sun-Earth shock transit time. The plasma, particle and electromagnetic consequences of the Halloween eruptions were observed not only in geospace but also at various locations in the heliosphere, thanks to the distributed array of space and ground based observatories that were available for observation. It was possible to compare the Halloween events with the rest of the events observed over the whole solar cycle to assess the severity of solar eruptions one should expect. For example, the Sun-Earth travel time of CME-driven shocks may not be less than about half a day. This paper highlights some of the key results obtained by analyzing the October-November 2003 CMEs originating from three solar active regions.

2. Overview

The October-November 2003 eruptions originated from three active regions, with NOAA numbers 484, 486, and 488. The white light image obtained on 2003 October 27 shows the relative locations of these events (see Fig.1). AR 484 and 488 were in the northern hemisphere, while AR 488 was in the southern hemisphere. The three regions produced a set of 143 well-observed flares (54 from AR 484; 60 from AR 486; 29 from AR 488). There were at least 80 CMEs during the two week period, most of them originating from the three active regions. AR 486 was the most prolific producer of CMEs, with the eruptions starting when it was behind the east limb. It continued to produce eruptions during disk passage and even behind the west limb. AR 488 emerged during the study period. The flares from AR 484 were observed between 18 and 26 October and returned as AR 501 to produce more energetic eruptions. The active regions were very big, with areas among the highest during solar cycle 23. The flare recurrence times were only a few hours (~4 h), while the CME recurrence time was a bit longer (~10 h).

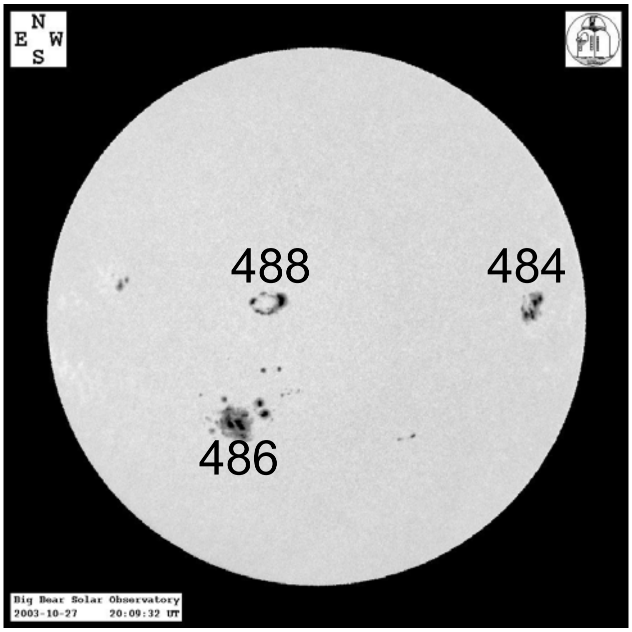

Figure1. White-light image of the Sun showing the three active regions of interest (AR484, 488, and 486) taken on 2003 October 27 at 20:09 UT at the Big Bear Solar Observatory.

Figure 2 provides an overview of flares, CMEs, SEP intensity, solar wind speed, and Dst index over an one-month interval in October and November 2003. The flare activity was very intense with the background intensity in GOES soft X-rays exceeding C1.0 level. The soft X-ray flux dropped dramatically when AR 486 rotated behind the west limb during early November 2003. The high concentration of CMEs is revealed by the height-time plots from the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO). There were a large number of halo CMEs (indicated by the solid lines in the height-time plots). The SEP intensity is plotted from GOES data in the >10 MeV channel. The intensity remained above the storm level (10 particle flux units) for about two weeks, representing a long interval of radiation hazard in the near-Earth space environment. The solar wind speed measured by the ACE spacecraft shows that the solar wind speed was close to an unprecedented 2000 km/s (see also Skoug et al., 2004). The Dst index shows three super-intense storms, the first two occurring around the time of very high solar wind speed and the third one occurring on November 20, 2003. The last storm happens to be the largest storm of the cycle, associated with AR 501 (see Gopalswamy et al. 2005a for details).

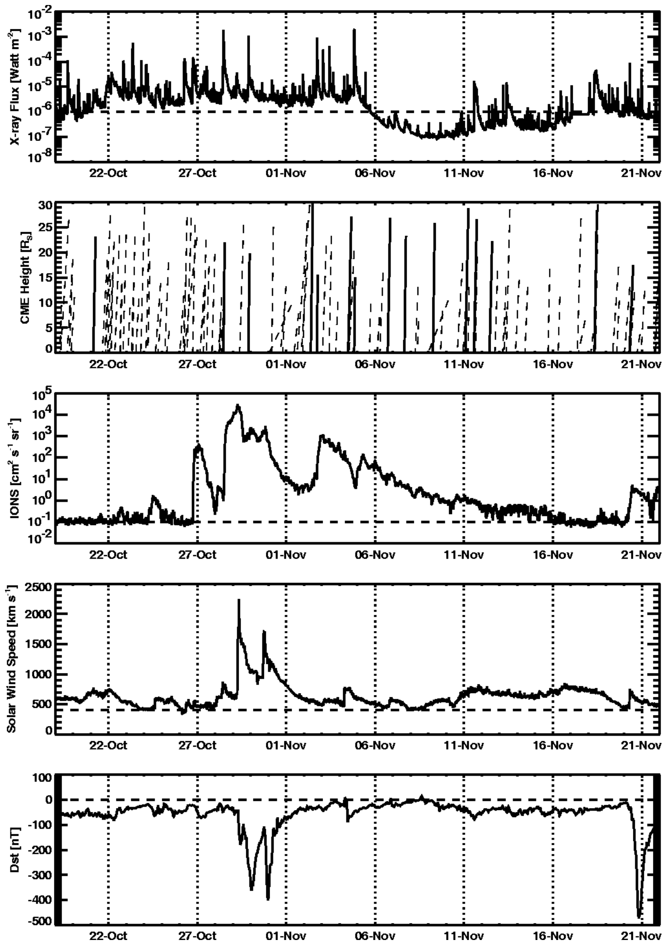

Figure 2. Overview plots (from top to bottom) of solar activity (GOES X-ray flares; CME height-time plots) and the heliospheric consequences (SEP intensity, solar wind speed, and Dst index). The horizontal dashed lines in each plot refer to approximate quiet conditions (GOES X-ray plot shows the C1.0 level; 0.1 pfu in the SEP plot; 400 km/s in solar wind speed; 0 nT in Dst index). The solid and dashed lines in the CME height-time plots represent halo and non-halo CMEs, respectively (from Gopalswamy et al., 2005b). The largest geomagnetic storm of the cycle occurred when AR 484 returned as AR 501 (see Gopalswamy et al. 2005a for details).

The intensity of SEPs was so high that instruments on board the SOHO such as CDS (Coronal Diagnostic Spectrometer) and UVCS (UltraViolet Coronagraph Spectrometer) had to stop making observations and turn off the high voltage supply. Both instruments returned to normal observations two days later. The onslaught of SEPs resulted in severe degradation of white light and EUV images (the so-called "snowstorm"), making it difficult to detect new CMEs. The SEP event on October 28, 2003 resulted in significant ozone depletion between 50 and 80 km from the ground (Jackman et al. 2005). Awareness of the storms prompted safety measures to be taken for most of the space assets. About 59% of the reporting spacecraft and about 18% of the onboard instrument groups were affected by the Halloween SEP events (Barbieri and Mahmot, 2004). Electronic upsets, housekeeping and science noise, proton degradation to solar arrays, changes to orbit dynamics, high levels of accumulated radiation, and proton heating were observed. Most earth-orbiting spacecraft were put into safe mode to protect from the particle radiation.

Major impact also occurred on the society: about 50,000 people in southern Sweden (Malmoe) experienced a blackout, where the oil in a transformer heated up by 10 degrees. Surge currents were also observed in Swedish pipelines. Several occurrences of degradation and outage of GPS systems were reported. Interference in high-frequency radio communications were felt by several teams on Mount Everest. When the storms arrived at Mars, the MARIE instrument on board Mars Odyssey succumbed to the onslaught of radiation. The storms continued to the orbits of Jupiter and Saturn as detected by Ulysses and Cassini, respectively. Finally, the disturbances reached Voyager 2 after about 180 days, piled up together as a single merged interaction region (MIR), which led a large depression in cosmic ray intensity, lasting more than 70 days (Burlaga et al. 2005).

Because of the large armada of observing facilities available on ground and in space, a wealth of data has been accumulated on the October-November 2003 events. A first set of more than 70 scientific papers have already appeared in Journal of Geophysical Research (Space Physics), Geophysical Research Letters and Space Weather (see Gopalswamy et al. 2005a for a list of these papers). Further analysis is needed for obtaining a complete picture of the Halloween events. In the following we discuss mainly issues related to CMEs in the inner heliosphere.

3. CMEs

Figure 3 shows the daily CME rate and mean speed averaged over Carrington rotation periods from 1996 to the end of 2005. The CME rate had fallen to ~2 per day just before the Halloween CMEs and then increased to ~3.7 per day. Such local activity maxima are due to the passage of some very active ARs with copious production of CMEs. The Halloween spike in the CME rate is not spectacular compared to the two later spikes, but the corresponding peak in the CME mean speed is the largest one, thus distinguishing it as an extreme event.

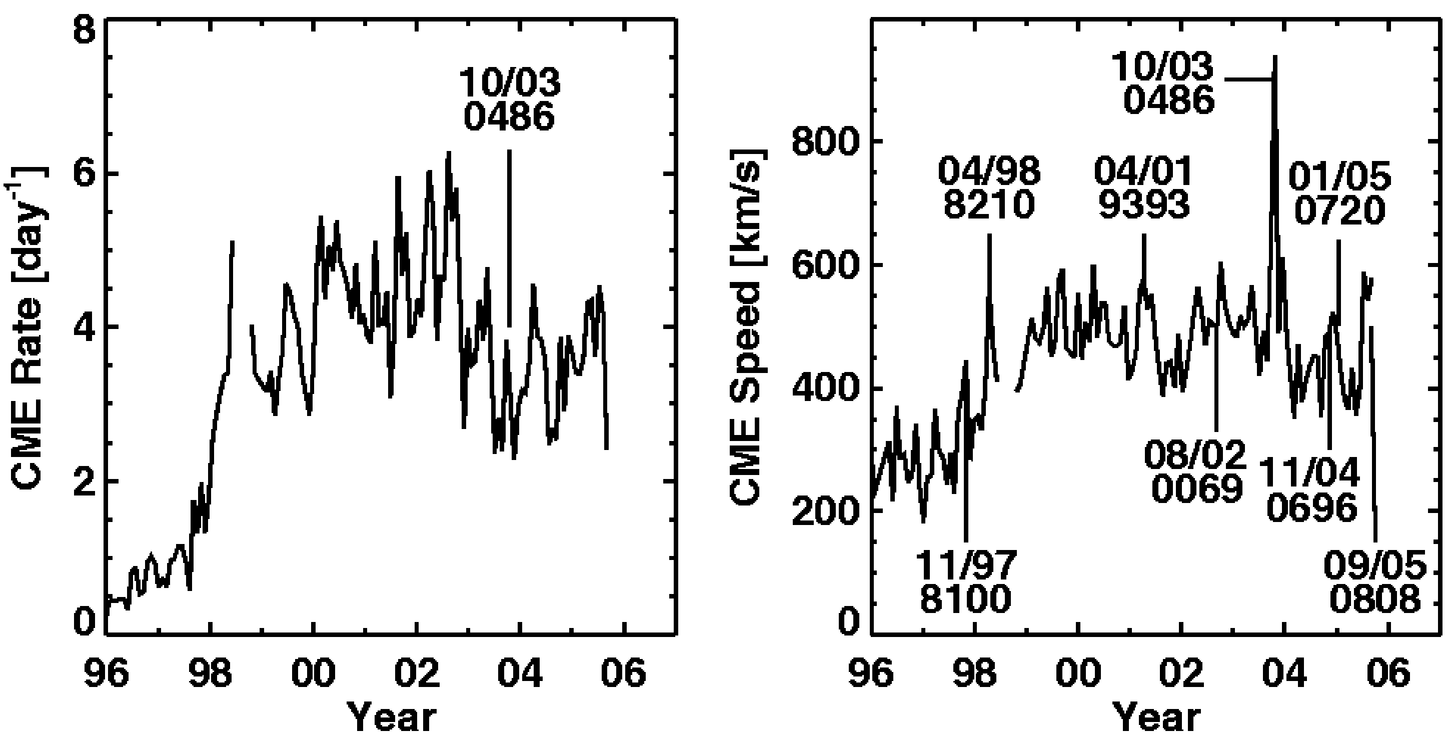

Figure 3. The daily CME rate (left) and CME mean speed (right) averaged over Carrington rotation periods from 1996 to the end of 2005. The peak in CME rate corresponding to the Halloween events is indicated by an arrow. The month and NOAA numbers of some CME-productive active regions are marked in the speed plot. The October 2003 period stands out, mainly contributed by AR 486.

There were 80 CMEs during Halloween period. This is much smaller than the 143 flares observed during the same interval. The actual number of CMEs is expected to be larger because some narrow CMEs originating from close to the disk center are not likely to be observed by the coronagraphs (see Gopalswamy et al., 2001a; Yashiro et al., 2005). Most of the CMEs originated from the three active regions (ARs 484, 486, and 488). The Halloween CMEs clearly stand out when compared with the general population. Table 1 compares the properties of the general and Halloween populations. The Halloween CMEs were fast and wide on the average and hence were very energetic. There were 8 ultra-fast CMEs (speed ≥ 2000 km/s) during the Halloween period, compared to 37 over the entire cycle 23. The rate of full-halo CMEs was nearly four times the average rate during cycle 23. At least 19 shocks were observed near the Sun, while eight of them were intercepted by spacecraft along the Sun-Earth line. The Halloween CMEs were highly geoeffective: the resulting geomagnetic storms were among the most intense of cycle 23. The CMEs were associated with very large SEP events, including the largest event of cycle 23.

The Halloween CMEs contained a large fraction (12%) of full halo CMEs compared to the general population (3%). About half (48%) of the Oct/Nov 03 CMEs were wide events (width > 60^o), while only 37% of the general population were so wide. The masses were also accordingly higher, with a median value of $2.4x10^{15}$ g. This is more than 3 times larger than the median mass of the general population. The average kinetic energy of the Halloween CMEs was $4.5x10^{30}$ erg, which is an order of magnitude higher than the corresponding value ($5.2x10^{29}$ erg) for the general population. Thirteen CMEs had kinetic energy exceeding 10^{32} erg: 10 from AR 486, two from AR 484 and one from AR 488.

Table 1. Comparison between the 2003 October November extreme events with the general population of CMEs observed until the end of 2003.

CME Property	Halloween CMEs	All CMEs
Average speed (km/s)	878	480
Average width (deg.)	50	47
Average mass ($x10^{14}$ g)	15	6.7
Average kinetic energy ($x10^{29}$ erg)	44	5.4
Fraction of wide CMEs (%)	48	37
Fraction of full halos (%)	12	3
Fraction > 900 km/s CMEs (%)	36	7
Fraction of >2000 km/s CMEs (%)	9	0.3
Fraction of fast and wide CMEs (%)	25	4
Fraction of CMEs with SEPs (%)	8	0.7
Fraction SEP events with GLEs (%)	50	25
Fraction of CMEs with DH type II	16	2.5
Fraction of CMEs with metric type II	21	10
Fraction of CMEs with mkm type II	8	0.8

4. Shocks and SEPs

The abundance of fast and wide CMEs during the Halloween 2003 period (see Table 1) resulted in a large number of type II radio bursts in the corona and IP medium. Coronal and interplanetary shocks are inferred from type II bursts in the metric, decameter-hectometric (DH), and kilometric (km) wavelength domains. Shocks are also identified from in situ observations. During the October November 2003 period, 17 metric and 13 DH type II bursts were reported, with 11 of the DH bursts having metric counterparts. This represents an unusually large fraction (11/17 = 69%) of metric type II bursts having longer wavelength counterparts, compared to just 36% for the 1996-2002 period (Gopalswamy et al. 2004b). The type II association rate of Halloween CMEs was much higher than that of the general population: 21% vs. 10% for metric and 16% vs. 2.5% for DH type II bursts (see Table 1). Not all shocks observed near the Sun are observed at 1 AU, because weaker shocks decay before reaching 1 AU. Eight shocks were observed at 1 AU (roughly half of the shocks observed near the Sun)., which represent a higher concentration during the Halloween period.

One of the interesting aspects of the shocks observed during the Halloween period is their extreme transit times. There were only 15 shocks with a Sun-Earth transit time < 1 day since the time of the Carrington flare in 1859.

The transit times were typically inferred from the flare onset to the sudden commencement (see Cliver and Svalgaard, 2004). Two of the 15 shocks were from the Halloween 2003 period with transit times of 18.9 (October 28, 2003 CME) and 19.7 h (October 29, 2003 CME). The historical events are shown in Fig. 4 along with two other SOHO events (not historical) for comparison: the 26 October 2003 event with a transit time of 31.8 h and the famous Bastille Day event (14 July 2000) with a transit time of 27 h. The solid curve is the empirical shock arrival (ESA) model (Gopalswamy et al. 2005c,e), which gives the shock transit time (T) in terms of the initial speed (V) of the driving CME: $T = ab^V + c$, where a = 151.002, b = 0.998625, and c = 11.5981. The ESA model curve suggests that a 3000 km/s CME would drive a shock that is expected to have a transit time of about 13.5 hours. A CME has to be launched with a speed of ~4300 km/s in order for its shock to have a transit time of ~12 h. The fastest CME observed by SOHO had a near-Sun speed of ~3387 km/s. There was only one other CME with speed exceeding 3000 km/s (2005 January 20 event, see Gopalswamy et al., 2005f). These results suggest that CMEs may not have speeds far greater than ~3000 km/s, which implies that CME-driven shocks take at least about half a day to reach Earth. The CME speed is ultimately linked to the amount of free energy available in active regions. AR486, which produced all the extreme events, had a maximum free energy of 4.6×10^{33} erg. One of the CMEs from AR 486 (the October 28 CME at 11:30 UT with a speed of ~2500 km/s) had a kinetic energy of 1.2×10^{33} erg, which represents ~ 26% of the free energy in the active region. It must be pointed out that active regions with spot areas twice as large as that of for the Carrington event (or AR 486) have been observed. This, along with the fact that only a small fraction of AR energy goes into the CME suggests that we may have yet to see the worst that the Sun has to offer. However, the limiting magnetic field in sunspots (~4500 G) suggests that the half-a-day transit time is a good limit for CME-driven shocks.

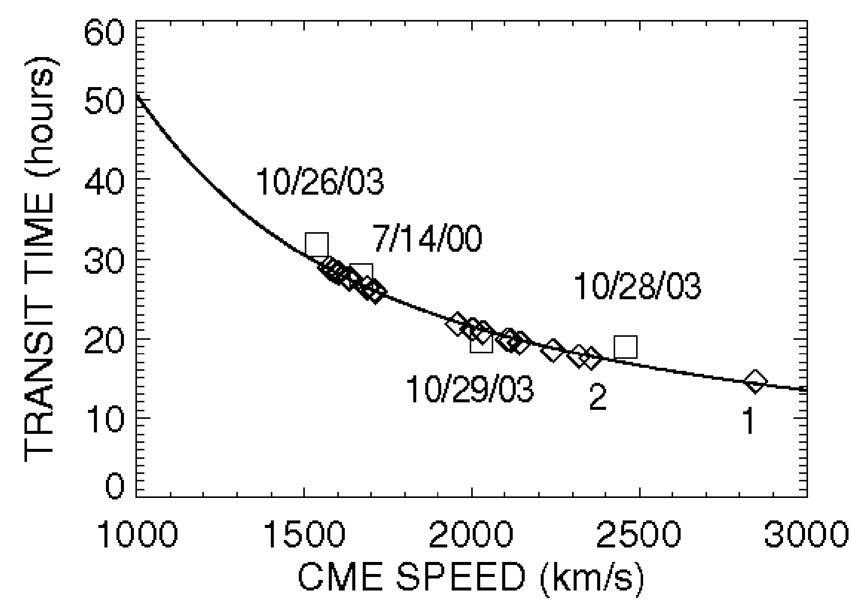

Figure 4. A plot of the Sun-Earth transit time (T) of shocks as a function of CME speeds (V) observed near the Sun. The solid curve is the empirical shock arrival (ESA) model: $T = ab^V + c$ with a = 151.002, b = 0.998625, and c = 11.5981). The travel times of historical events plotted as diamonds. The CME speeds of the historical events were inferred from the ESA model. For the three 2003 October events (10/26/03, 10/28/03, 10/29/03) and the Bastille Day event (07/14/00), the data points (squares) are from actual measurements of CME speeds (SOHO data) and shock travel times. The two fastest historical events are marked as 1 (1972 August 4) and 2 (1859 September 1).

The strong shocks producing type II radio bursts also produce SEP events because the same shocks accelerate electrons (to produce the radio bursts) and ions (detected in situ). All the type II radio bursts that had counterparts at various wavelengths were associated with SEP events because the shocks are the strongest with consequences far into the heliosphere. Figure 5 shows that there were six large SEP enhancements (intensity >10 pfu in the >10 MeV channel) associated with five large CMEs: the first one was from AR484 on October

26 and the other four were from AR486. The two most intense events were from AR 486 on October 28 and 29. In both cases the energetic storm particle (ESP) event was larger. This is common for events originating from close to the disk center because of poorer magnetic connection (see e.g., Reames, 1999) early in the event. The October 28, 2003 SEP event was the most intense in solar cycle 23 in terms of >10 MeV flux and third largest in recorded history since 1976. The first and second largest events with 43,000 pfu and 40,000 pfu occurred in cycle 22 during March 1989 and October 1989, respectively. Three of the SEP events from the Halloween period (associated with the 2nd, 3rd, and 4th CMEs in Fig. 5) produced ground level enhancements (GLEs). In GLE events the SEPs penetrate all the way to Earth's atmosphere causing air showers detected by neutron monitors. There were only 14 GLE events in cycle 23 with 3 of them (21%) occurring during the Halloween 2003 period. Such a high concentration of GLE events were observed once during cycle 22 (19- 23 October 1989).

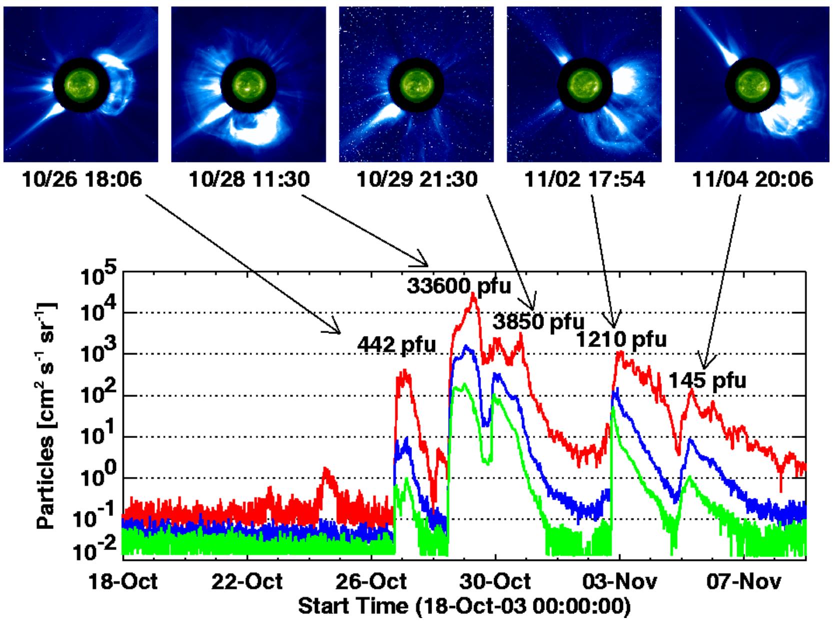

Figure 5. SEP events from GOES (>10 MeV, >50 MeV and >100 MeV channels in red, blue and green, respectively) and the associated LASCO CMEs from the October-November 2003 period. The peak SEP intensities are marked on the plot.

5 Geoeffectiveness and SEPeffectiveness

Two of the largest geomagnetic storms of cycle 23 occurred due to the two full halo CMEs from AR 486: on 28 October (Dst = -363 nT) and on 29 October (Dst = -401 nT. Figure 6 shows the evolution of the Dst index and the CMEs associated with the storms. Even though the four CMEs in Figure 5 were roughly homologous, their geoimpact were quite different. This is mainly a geometrical effect because CMEs originating from close to the disk center directly impact the magnetosphere while those ejected off to the Sun-Earth line result only in a glancing impact. The sheath of the November 2 CME impacted Earth's magnetosphere causing a modest storm (-84 nT), while the November 4 CME produced only a sudden commencement. Figure 6 demonstrates that only CMEs originating close to the disk center cause significant storms. The magnitudes of the storms are certainly consistent with the energy contents of the associated CMEs. However, there are other parameters that control the geomagnetic storms such as the inclination of the interplanetary CME with respect to the ecliptic among other solar and interplanetary parameters (see e.g., Srivastava and Venkatakrishnan, 2004). Comparison between Figs. 5 and 6 shows that the CMEs were also SEPeffective (producing large SEP events). The SEPeffective CMEs originate generally on the western hemisphere because the flux tubes carrying the SEPs need to be connected to an observer near Earth. On the other hand, geoeffective CMEs need to originate from close to the disk center for direct impact on the magnetosphere. Thus the center-west CMEs have the most important space weather consequences because they can be simultaneously geoeffective and SEPeffective (Gopalswamy, 2006).

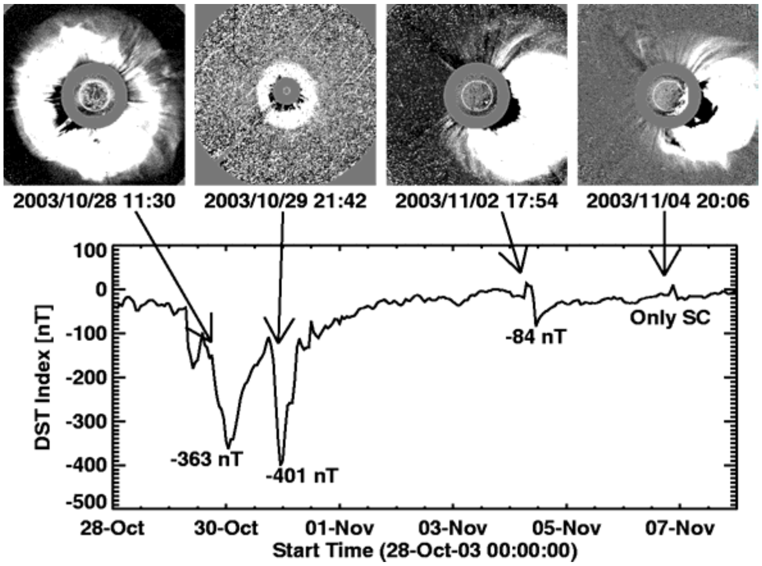

Figure 6. Snapshots of LASCO CMEs (top panel) associated with geomagnetic storms of the Halloween 2003 period as identified in the Dst index plot (bottom panel). The Dst responses of the four CMEs are marked. The last CME produced only a sudden commencement (SC).

6. Summary

The October – November 2003 CMEs and the associated events represent one of the best observed episodes of solar activity and hence provided information on several key aspects of solar eruptions and their space weather effects (including active region size and potential energy, flare occurrence rate and peak intensity, CME speed and energy, shock occurrence rate, SEP occurrence rate and peak intensity, geomagnetic storm intensity). These events helped us assess the severity of solar eruptions for space weather. Some key results are: the largest soft X-ray flare (X28) of the cycle occurred during the October – November 2003 (X28) and was associated with an ultrafast CME (2657 km/s) on 2003/11/04. Fortunately, this CME occurred when the underlying active region was already at the west limb, so the CME was not Earth-directed. Other CMEs with comparable energy caused major geoeffects because they were ejected when the active region was close to the disk center. There was a high rate of energetic CMEs during this period. As a consequence, there was a high concentration of interplanetary shocks and CMEs that produced intense SEP events and super-intense (Dst = -363 and -401 nT) geomagnetic storms. The eruptions originated from active regions with largest areas reported for the current solar cycle. The large kinetic energies of CMEs are also consistent with the estimated free energy available in the active regions. One of the key results is that the Sun-Earth travel time of CME-driven shocks seems to be at least half a day, providing a practical limit for space weather applications.

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