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Coronal Mass Ejections and Ground Level Enhancements

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We explore the possibility of GLE acceleration by shocks driven by coronal mass ejections (CMEs). The Solar and Heliospheric Observatory (SOHO) spacecraft has observed CMEs during 13 of the 14 GLEs recorded during cycle 23. The GLE-associated CMEs represent the fastest known population of CMEs. All the GLEs were also associated with metric type II bursts. Comparison between GLE and metric type II onsets suggests that coronal shocks are formed before the GLEs are released at the Sun. These results are consistent with particle acceleration by CME-driven shocks.

1. Introduction

Ground level enhancements (GLEs) are sudden increases in cosmic ray intensity recorded by ground based detectors such as neutron monitors [1]. To date, 68 GLEs have been reported with GLEs 55-68 occurring in cycle 23. While it is well known that GLEs are associated with large flares, their connection to coronal mass ejections (CMEs) is not well understood mainly because CMEs were discovered only in the early 1970s while the GLEs were first detected in the early 1940s. Apart from case studies [2], the first statistical study of 10 GLEs involving CMEs was reported by Kahler et al. [3]. Four more GLEs occurred since then, so we analyze this expanded data set to clarify the connection between CMEs and GLEs. We pay particular attention to the 2005 January 20 GLE, which is the largest event of cycle 23 as of this writing. Kahler et al. were mainly concerned with the relative timing between electron and proton release at the Sun. We are concerned with the properties of GLE-associated CMEs and their shock-driving capability.

Table 1. List of Cycle 23 GLEs (1996-2005)

Event #	GLE event Date	GLE Onset (Obs)	GLE Onset (Inf)	Peak time (T_{pk})	GLE Intensity (%)	Type II Onset	Type III Onset (UT)	Flare onset (UT)	Flare Class /Location	CME onset (UT)	CME height (Ro)	CME speed (km/s)
1	1997Nov06	12:10	12:07	14:00	11.3	11:53	11:52	11:49	X9.4/S18W63	11:39	5.2	1726
2	1998May02	13:55	13:52	14:05	6.8	13:41	13:35	13:31	X1.1S15W15	13:32	3.3	1332
3	1998May06	08:25	08:22	09:30	4.2	08:03	08:01	07:58	X2.7/S11W65	07:55	3.8	1208
4	1998Aug24	22:50	22:47	02:05	3.3	22:02	22:04	21:50	X1.0/N35E09	DG	DG	DG
5	2000Jul14	10:30	10:27	11:00	29.3	10:28	10:18	10:03	X5.7/N22W07	10:25	1.4	1741
6	2001Apr15	14:00	13:57	14:35	56.7	13:47	13:49	13:19	X14/S20W85	13:35	3.3	1203
7	2001Apr18	02:35	02:32	03:10	13.8	02:17	02:15	02:11	?/S23W117	02:11	5.9	2712
8	2001Nov04	17:00	16:57	17:20	3.3	16:10	16:13	16:03	X1.0/N06W18	16:13	8.0	1846
9	2001Dec26	05:30	05:27	06:10	7.2	05:12	05:13	04:32	M7.1/N08W54	05:06	4.2	1779
10	2002Aug24	01:18	01:15	01:35	5.1	01:01	01:01	00:49	X3.1/S02W81	00:59	3.6	1937
11	2003Oct28	11:22	11:19	11:51	12.4	11:02	11:03	11:00	X17/S20E02	11:07	3.9	2754
12	2003Oct29	21:30	21:27	00:42	8.1	20:42	20:41	20:37	X10/S19W09	20:43	8.7	2049
13	2003Nov02	17:30	17:27	17:55	7.0	17:14	17:16	17:18	X8.3/S18W59	17:19	3.0	2981
14	2005Jan20	06:51	06:48	07:00	277.3	06:44	06:45	06:39	X7.1/N14W61	06:33	4.0	3675

2. Data

Table 1 lists the 14 GLEs detected by the Oulu Neutron Monitor (http:// cosmicrays.oulu.fi/GLE.html). The dates and Earth onset times of the GLEs are listed in columns 2 and 3. The inferred onset time of GeV particles near the Sun assuming a path length of 1.2 AU is given in column 4. The solar release and peak times (column 5) of GLEs are relative to the Earth-arrival times of electromagnetic signals from the Sun. The enhancement above background (referred to as the GLE intensity), onset times of the metric type II bursts (column 7), decameter-hectometric (DH) type III bursts (column 8), GOES X-ray flare onset (column 9), flare size with heliographic location (column 10), CME onset (column 11), CME height at GLE onset (column 12), and CME speed (column 13) are also listed. The speeds are deprojected based on a cone model [4]. CME onsets were obtained by extrapolating the first appearance time in the LASCO FOV to the surface using the corrected speed. For event #14, the LASCO data were not reliable, so we estimated the speed and onset by combining LASCO and EIT data. Event #4 occurred during a SOHO data gap.

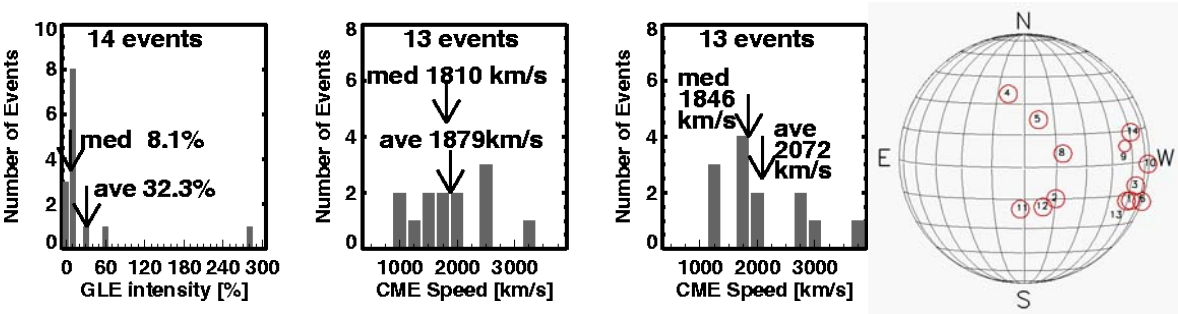

Figure 1. (left-to-right) GLE intensity, sky-plane speed of CMEs, space speed of CMEs and the solar sources. The mean and median values of the distribution are shown. The outlier in the intensity distribution is the 2005 January 20 CME.

3. Analysis and Results

Figure 1 shows that the GLE intensity ranged from 3.3% to 277%, with a median value of ~8%. The largest GLE (277.3%) of solar cycle 23 occurred on 2005 January 20, which was a well-connected event originating from N14W61 from AR 720. The GLE was also associated with an X7.1 flare. The speed distributions show that the GLE-associated CMEs are extremely fast with the average speeds of 1879 (sky-plane) and 2072 km/s (deprojected), respectively. The GLE-related CMEs are faster than the two fastest known populations: SEP-related CMEs (average speed ~1446 km/s [5]) and CMEs associated with type II bursts having emission components from the corona (metric wavelengths) to the inner heliosphere (kilometric wavelengths) (average speed ~1490 km/s [6]). The CMEs were either full or partial halos, so they must be of very high kinetic energy. Except for the single backside event (#7) of unknown flare size, all were major X-ray flares (12 X-class and one high M-class). Thus, the GLEs are associated with not only big flares, but also with the most energetic CMEs. The source locations fall into disk-center and western groups (see Fig.1). There is a tendency for the disk-center group to have a softer SEP spectrum compared to the western (well-connected) group by ~44%. This needs further investigation.

Timing relations: Figure 2 shows the delay time of GLE onset (proton injection) with respect to the standard markers of transient solar activity: metric type II bursts, DH type III bursts, soft X-ray flares and CMEs. The median delay is the smallest for metric type II bursts (19 min) and the largest for soft X-ray flares (30 min). The onset of DH type III bursts very close to that of metric type IIs. The delay with respect to the CME onset is intermediate, with a median value of 21 min. The average speed corresponds to 10.7 Ro/hr implying that the GLE-related CME cross the LASCO field of view in 2-3 hours. With the current cadence of LASCO images, it is hard to determine the actual height-time profiles of these CMEs, resulting in large uncertainties in the derived onset times of CMEs. In Table 1, we see that the CME onset apparently lags behind the metric type II onset for 4 events (##8, 11, 12, and 13) by 1-5 min. However, the CME onset is typically earlier than observed because most CMEs have to accelerate in the beginning. The 1-5 min delay is well within the uncertainties in the inferred CME onset.

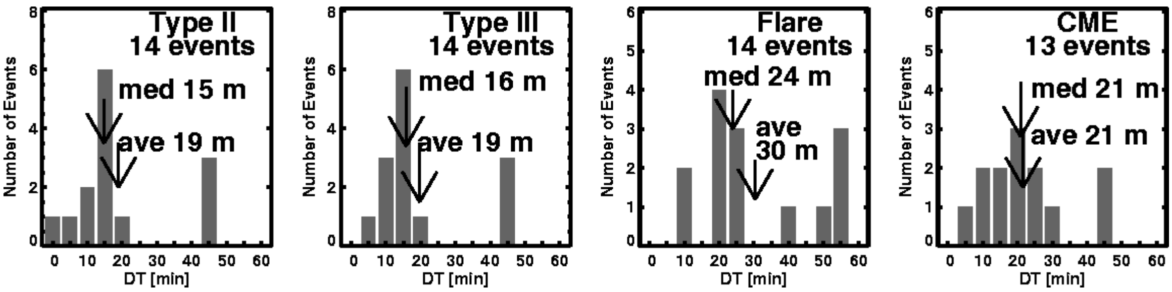

Figure 2. GLE delay times with respect to metric type II, DH type III, GOES X-ray flare and CMEs.

CME height at GLE onset: The average CME height at metric type II onset is ~2.2 Ro, as in other studies [6]. The average CME height (see Fig. 3) at GLE onset (~4.4 Ro) and peak (~12 Ro) are slightly higher than the corresponding values found by Kahler et al. [3]. The CME heights at metric type II onset and GLE onset fall on either side of the Alfven speed hump [7] around 3 Ro. The CME-driven shock is the strongest at the height of GLE release because the CME finishes acceleration and the Alfven speed decreases substantially from its peak value around this height.

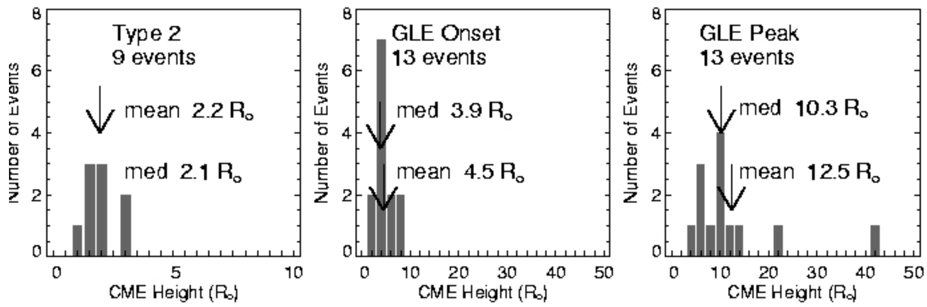

Figure 3. Height of CME at metric type II onset (left), GLE onset (middle), and GLE peak (right).

Type II association: The fact that all the GLEs were preceded by metric type IIs means that a shock was present in the corona before the GLEs were released. Most of the GLE events (12/14 or 86%) had type II bursts in the metric to kilometric (m-to-km) range, implying strong shocks with energetic CMEs. Of the two exceptions, event #2 had type II from metric to 0.3 km; #3 had an intense noise storm in progress, which might have masked any weak type II burst. It is possible that the strong shocks accelerate both electrons (m-to-km type II bursts) and protons (GLE events). The threshold shock strength for metric type II must be smaller because the metric type II bursts precede the GLE onset by ~19 min (see Fig. 2).

January 20, 2000 Event: The CME first appeared in the LASCO field of view at 06:54 UT with its leading edge at 4.48 Ro, already affected by the ‘snow storm’ (SEPs arriving at SOHO - see Fig. 5). The subsequent LASCO images were severely degraded so the height-time measurements have large uncertainties. Nevertheless, one can combine the first LASCO data point with the EIT data to obtain a height (h) – time (t) curve, $h = 6.052 - 0.3361t + 0.0057t^2$, where t is in min from 06:00 UT. This gives a speed of 3242 km/s when the CME first appeared in the LASCO field of view.

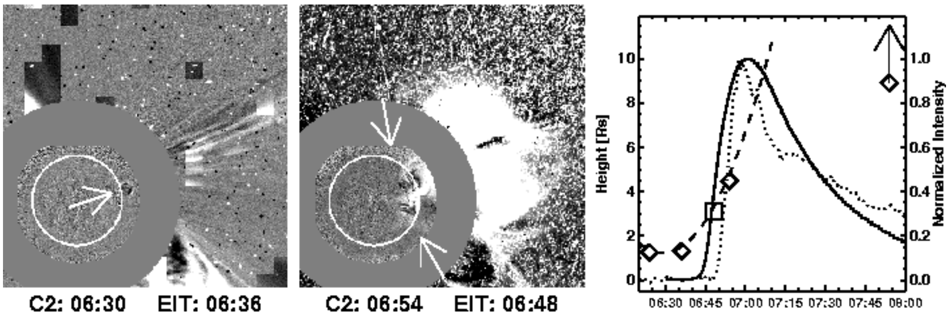

Figure 5. (left) SOHO’s LASCO (06:30) and EIT (06:36) difference images superposed. No CME in the LASCO image but the EIT image shows the early phase (arrow) of the 2005 January 20 CME. (middle) LASCO CME at 06:54 UT, with the overall extent of EUV disturbance at 06:48 UT (arrows). (right) CME height-time (diamonds with dashed line), GLE intensity (dotted lines) and GOES soft X-ray light curve (solid line). The square represents the inferred CME height from the EUV disturbance at 06:48 UT. The last LASCO height may be an underestimate due to ‘snow storm’.

4. Conclusions

The GLE-associated CMEs represent the fastest known population of CMEs. The GLE events constitute a subset of the large SEP events, but the GLE intensity is only weakly correlated with the SEP intensity of 10 MeV protons. The disk-center GLEs have a softer SEP spectrum than the well-connected events. The average CME leading-edge heights at the times of GLE proton injections was ~4.5 Ro, slightly higher than the 2.7 Ro obtained previously [3]. At this height, the CMEs should have attained the maximum speed, thus driving the strongest shocks. The largest GLE event of cycle 23 (2005 January 20) was a well-connected and the CME observations were affected by the SEPs arriving at the SOHO spacecraft. We estimated that the CME had the largest sky-plane speed, exceeding 3000 km/s. These results are consistent with the idea of a common shock origin for type II radio bursts and GLEs.

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