Heliocentric Distance of CMEs at the Time of Energetic Particle Release: Revisiting the Ground Level Enhancement Events of Solar Cycle 23

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Abstract: Using the kinematics of coronal mass ejections (CMEs), onset time of soft X-ray flares, and the finite size of the pre-eruption CME structure, we derive the heliocentric release distance of the energetic particles during the ground level enhancement (GLE) events of Solar Cycle 23. We find that the GLE particles are released when the CMEs reach an average heliocentric distance of ~3.6 solar radii (Rs). For well-connected events, the average height is only ~2.6 Rs. Observations of metric type II radio bursts indicate that the CMEs are at much lower distances (average ~1.4 Rs) when the CME-driven shock first forms. This means the shocks have typically ~6 min to accelerate and release the GLE protons from the time the shock forms closer to the surface.

Keywords: ground level enhancement, coronal mass ejection, type II radio burst, shock.

1 Introduction

When and where do shocks driven by coronal mass ejections (CMEs) form near the Sun when they accelerate energetic particles are fundamental scientific questions that are not fully answered. Answering these questions involves determining the near-Sun variation of CME speed with respect to the Alfven speed of the ambient medium and inferring the injection time of ions from particle detector observations and electrons from radio remote-sensing observations. The underlying paradigm is that CME-driven shocks accelerate electrons (that produce type II radio bursts) and ions detected in situ as solar energetic particle (SEP) events when the particles reach the detector. Of particular interest are the ground level enhancement (GLE) events, in which the protons are able to reach Earth’s atmosphere and produce secondary particles such as neutrons detected by neutron monitors. The GLE events are extreme events and only a dozen or so occur during a solar cycle, so detailed analysis is possible for these events. Unfortunately, CME observations are available for a large number of GLEs only during Solar Cycle 23. The behavior of CMEs at the time of energetic particle release are often masked by the occulting disk of the coronagraphs that observe them. Therefore, one has to resort to extrapolation techniques to determine the CME height at the time of the particle release near the Sun. Another factor that needs to be incorporated into the CME height determination is the pre-eruption height of the CMEs. This is often assumed to be the solar surface, but there are many indications that the pre-eruption structure may have a finite size. Finally, we resort to one of the key principles of the standard model of solar eruption (the CSHKP model) on the simultaneity of the flare and CME onsets in a given eruption.

In this paper, we apply these three assumptions to derive the CME heights at the onset of metric type II radio bursts and solar particle release (SPR) in GLE events. The metric type II bursts start very close to the solar surface [≤1.4 solar radii (Rs)], indicating the existence of the CME-driven shocks at these heights [1]. Acceleration of ~GeV protons takes additional time and hence the SPR usually follows the type II burst, which requires only <10 keV electrons. We also present evidence from EUV observations of a shock that the type II bursts start within seconds after shock formation.

2 Extrapolation of CME Height – Time Measurements

2.1 Basic Measurements

The basic measurements used in this paper are (i) the GLE onset time derived from worldwide neutron monitors, (ii) the first appearance height and time of the associated CMEs, (iii) the start time of the metric type II radio bursts, and (iv) the soft X-ray flare onset time. (i) and (iii) are ground-based measurements, while (ii) and (iv) are from space. (iii) is accompanied by the frequency of the type II burst, which gives an idea of the plasma density in the corona where the type II burst occurs, but we do not know the height at which the emission takes place. Figure 1 shows the CME and the GOES soft X-ray flare associated with GLE#60. The GLE onset was estimated to be at 14:00 UT at Earth. Assuming a path length of 1.2 AU, the SPR time at the Sun can be estimated as 13:57 UT for ~1 GeV particles. Note that this time is normalized to the electromagnetic signatures that identify CMEs (white light) flares (X-rays), and type II bursts (radio). Essentially we need to subtract 3 minutes from the Earth onset times of GLEs to get the SPR time.

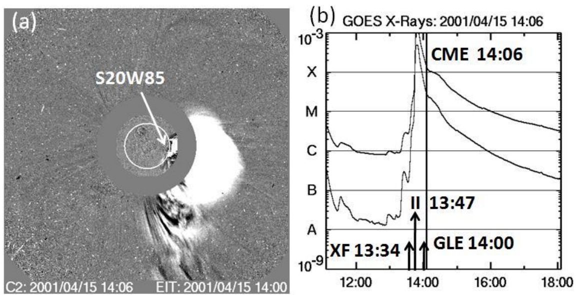

Figure 1. (a) CME's first appearance (14:06 UT) from the source location S20W85 near the west limb. The CME leading edge is at a height of 4.29 Rs. (b) GOES light curve in the 1–8 Å and 0.5–4 Å channels showing the X14 flare (XF) starting at 13:34 UT. Onsets of type II at 13:47 UT and the Earth onset of the GLE (14:00 UT), and the CME appearance time (14:06 UT) are also marked.

It is interesting to note that the first appearance time of the CME (14:06 UT) is very close to the Earth onset time of the GLE, so the SPR must have occurred when the CME was only slightly below the position shown in Fig. 1. The CME height at 4.29 Rs needs to be back-extrapolated by 9 minutes to get the height at SPR. The CME speed within the LASCO field of view (FOV) was 1199 km/s, which is likely to be close to the space speed because this is a limb event and the projection effects are minimal. If we assume the speed remained constant, the CME height at SPR is ~1 Rs smaller: ~3.3 Rs. We need to back-extrapolate by another 10 min to get the CME height at type II onset (13:47 UT) as 2.3 Rs. This is an upper limit to the shock formation height and consistent with statistical results [2]. We can already see that the shock forms at least ~19 min before the SPR. These extrapolated heights are clearly rough estimates because the CME speed changes rapidly below ~3 Rs when the CME accelerates from rest to attain a high speed of 1199 km/s. Unfortunately, we do not have CME height-time measurements covering this early phase for most of the CMEs. If the CME started from the surface (height = 1 Rs), and attained 1199 km/s instantaneously, we can get the CME onset time as 13:34 UT, very close to the flare onset. In order to allow for the initial acceleration of the CME and the finite height of the pre-eruption structure, we need to make some assumptions: first, the pre-eruption structure may be at a height of 1.25 Rs, which is based on the height of cavities [3] and prominences [4] in the pre-eruption stage. Second, the CME onset coincides with the flare onset (13:34 UT). Third, the CME has a constant acceleration from the onset to the first appearance (14:06 UT) where it attains a constant speed of 1199 km/s. Thus the CME gains 1199 km/s in 32 min, indicating an acceleration of ~0.62 km/s^2. Accelerations of this magnitude have been found from a few cases that do have CME measurements closer to the surface [5]. With this acceleration, one can determine the CME height at metric type II onset and SPR time as 1.5 Rs and 2.1 Rs, respectively. There is observational support for such low CME heights at type II burst onset whenever height-time measurements are available closer to the solar surface [1,6]. The CME speed at type II onset and SPR is 465 km/s and 857 km/s, respectively based on the estimated acceleration. Since the Alfven speed is very low in the inner corona, these speeds are sufficient for the CME to be super-Alfvénic and hence drive shocks.

2.2 GLEs of Solar Cycle 23

We applied the procedure described in section 2.1 for all the 16 GLE events of Solar Cycle 23. CME observations are available for all CMEs, except one (#58), which occurred when SOHO was temporarily disabled. However, the interplanetary CME and its shock are observed by the ACE spacecraft. We used these observations to estimate the speed near the Sun. For three events (## 61, 62, and 66) the SPR is after the first appearance of the CMEs. In these cases, we linearly extrapolate the CME height-time plot to the SPR time. For example, the CME of GLE #62 appeared at 16:35 UT, but the SPR is at 16:57 UT. The first appearance height is 4.41 Rs. The sky-plane speed is 1810 km/s. Since this is a disk event, we used a cone model to obtain the space speed as 1846 km/s. Similarly, the deprojected height at first appearance is 4.49 Rs. To this height we add the distance traveled by the CME in 22 min, and get the CME height at SPR time as 7.98 Rs. The acceleration itself was calculated as before and used to estimate the CME height at type II burst onset. These three events have generally larger CME height at SPR, probably because of the poorer connectivity, which improves as the CME propagates out.

Table 1 lists the 16 GLEs of Solar Cycle 23 (##55 – 70), their SPR time (column2) normalized to electromagnetic signals, metric type II onset (column 3), flare onset (column 4), flare location (column 5), CME first appearance time (column 6) and height (column 7), sky-plane speed of the CME (column 8), CME space speed (column 9) obtained using a cone model, CME height at SPR time (column 10), CME height at metric type II burst onset (column 11) and the average acceleration of the CME before first appearance (column 12).

2.3 CME Height at SPR and Type II Onset

The CME heights in columns 10 and 11 indicate that the CMEs start driving shocks very close to the surface and that the first accelerated particles are released when the CMEs are about a solar radius above the surface. The CME height at SPR varies from 1.74 Rs to 8.74 Rs, with an average value of ~3.6 Rs. The CME height at type II onset, on the other hand is even closer to the surface with an average height of only 1.4 Rs. Figure 2 compares the distributions of CME heights at SPR and metric type II onset times.

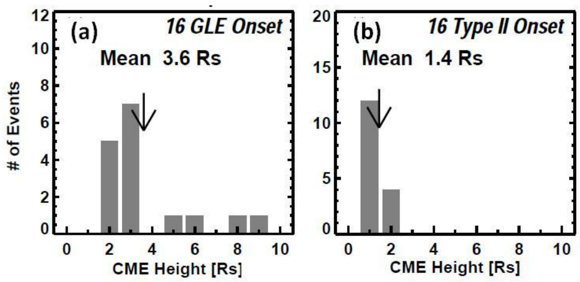

Figure 2. CME height at the onset of (a) GLE events near the Sun and (b) metric type II Radio bursts.

The mean values differ by ~2.2 Rs between the metric type II onset and SPR times. Since the average space speed of the GLE-associated CMEs is ~2083 km/s (from column 9 of Table 1), we infer that it takes a little more than 12 min for the shocks to accelerate and release GLE protons after the shock forms in the inner corona (indicated by metric type II radio bursts). If we take only the well-connected events (around W60), we get an average CME height of only ~2.6 Rs at SPR time. However, the average CME height at type II onset is the same for well-connected and poorly connected GLE events. Part of this may be due to the connectivity issue: the shock needs to cross the field lines connecting to Earth to detect the GLE event, whereas type II bursts are electromagnetic signals, which can arrive at Earth even from behind the limb (connectivity is not an issue).

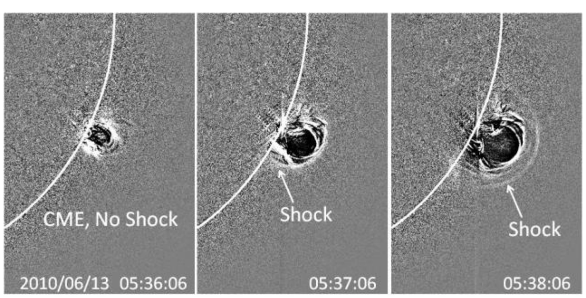

Figure 3. Three snapshots of a CME observed in EUV (193 Å) by SDO/AIA. The shock formation was directly observed in the event and coincided with the onset of a metric type II burst.

2.4 CME Initial Height

The assumption we made on the initial height of the CME (1.25 Rs) is of course not exact. Different events may have different sizes of the pre-eruption structures. Figure 3 shows a CME recently observed by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). The CME was observed initially without the shock and developed a shock only after ~2 min. When the shock formed, the CME was at a height of 1.17 Rs. The pre-eruption structure was at a height of 1.13 Rs. Interestingly, the shock formation coincided with the onset of a type II burst at 150 MHz [7]. The inferred local plasma density of ~2.8×10^{8} cm^{-3}, is consistent with the burst originating deep in the corona. Of course this was not a GLE event, but provides useful information on the shock formation height coinciding with the onset of type II radio burst. If this were a GLE event, we would have made an error of ~3% and 9%, respectively in the CME height at SPR time and type II burst onset, respectively.

2.5 CME Acceleration

The accelerations given in Table 1 range from 0.48 to 3.4 km/s^2, with a mean value of ~1.5 km/s^2. CME observations made closer to the solar surface using the C1 telescope of SOHO/LASCO have yielded accelerations of this order. For GLE #55, the derived acceleration was in the range 4.5–7 km/s^2 with large uncertainties [6]. Estimates of CME acceleration from the height of type II radio bursts in radioheliograms are in the range 0.6–1.2 km/s^2 [8]. Recall that one of the assumptions made in computing the initial acceleration is that the flare and CME onsets coincide. We can also estimate the CME acceleration without making such an assumption using the first appearance height (H) of the CME and the speed measured in the LASCO FOV. Since CMEs accelerate from rest and traverses a distance of (H -1.25) Rs and attains the final speed V in the LASCO FOV, we can calculate the acceleration as $a = V^2/2(H-1.25)$. For the 2001 April 15 event, this method gives an acceleration of 0.34 km/s^2, which is only ~45% lower than the value obtained by the flare onset = CME onset assumption. Accordingly, the onset time of the CME precedes that of the flare by ~27 min because of the lower acceleration. Figure 4 compares the accelerations obtained by the two methods. The mean values of the acceleration from the two methods differ by ~40%. Note that in both methods we have assumed that the acceleration is constant from the onset to the first appearance. In reality, this is not the case because we know that CME acceleration increases early on and peaks somewhere in the range 2–3 Rs. However, the flare onset = CME onset method seems to be closer to reality.

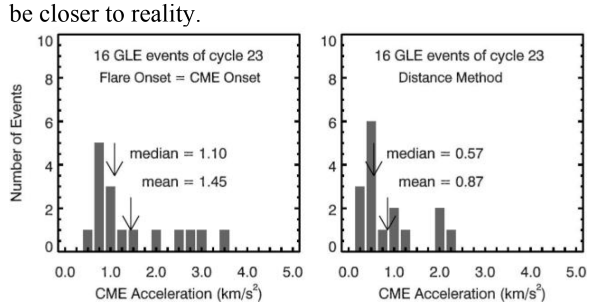

Figure 4. Initial acceleration of CMEs derived from two methods: (left) assumes flare onset = CME onset, and

(right) uses the distance traveled from rest to the height of first appearance.

3 Discussion and Conclusions

We have shown that one can estimate the initial acceleration of CMEs using their first appearance time in the SOHO/LASCO coronagraphic field of view beyond ~2.5 Rs. This is a happy coincidence because CMEs generally finish accelerating in the height range 2–3 Rs and hence attain roughly constant speed (or slowly decreasing due to the drag force). The assumption that flare onset = CME onset seems to result in realistic acceleration values mainly because the resulting CME height at type II onset is consistent with observations [1]. The type II bursts start when the CME height is typically around 1.4 Rs.

Reality checks are possible at least for two events. For GLE #55 we obtain the CME height at type II onset as 1.31 Rs, which is nearly the same (1.33 Rs) as the height obtained from actual observations from LASCO/C1. Two other GLEs (##66, 67) had Mauna Loa K-coronameter data. GLE #67 is a limb event, so projection corrections are minimal. Initial estimate shows that the CME height at type II onset is ~1.23 Rs, compared to the 1.28 Rs in Table 2. Thus we are confident that the CME height estimates are reasonable. The CME height at GLE onset near the Sun is ~3.6 Rs for all the events. For well-connected events, the height drops to ~2.6 Rs. This value is more realistic because one has to worry about connectivity issues for the other events.

In conclusion, we find that the GLE onset near the Sun occurs when the associated CME is at a height of ~2.6 Rs, which coincides with the region where the CME reaches its maximum speed. For limb events, the height is higher because additional time is needed for the shock to cross the observer's field line. These results are consistent with CME heights at GLE particle release obtained by an independent method [9]. Since the onset of the metric type II burst indicates the time of shock formation, The CME typically travels additional 1.2 Rs from the height of metric type II onset (1.4 Rs) before the GLE protons are accelerated and released. This corresponds to an acceleration time of ~6 min.

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GLE # (1)	GLE Date UT (2)	Type II onset (3)	Flare Onset (4)	Flare Location (5)	CME 1st Obs. (6)	CME 1st Ht (Rs) (7)	Sky Speed (km/s (8)	Space Speed (km/s) (9)	GLE Ht (Rs) (10)	Type II Ht (Rs) (11)	CME Acc. km/s^2 (12)
55	971106-12:07	11:53	11:49	S18W63	12:10	5.18	1556	1726	2.39	1.31	1.37
56	980502-13:52	13:41	13:31	S15W15	14:06	3.48	938	1332	1.97	1.41	0.63
57	980506-08:22	08:03	07:58	S11W65	08:29	4.09	1099	1208	2.21	1.29	0.65
58	980824-22:47	22:02	21:50	N35E09	----	----	----	1420	5.26	1.43	0.48
59	000714-10:27	10:19	10:10	N22W07	10:54	5.21	1674	1741	1.74	1.80	0.66
60	010415-13:57	13:47	13:34	S20W85	14:06	4.29	1199	1203	2.10	1.52	0.63
61	010418-02:32	02:17	02:11	S23W117	02:30	4.94	2465	2712	5.90	1.47	2.38
62	011104-16:57	16:10	16:03	N06W18	16:35	4.41	1810	1846	7.98	1.37	0.96
63	011226-05:27	05:12	05:03	N08W54	05:30	3.84	1446	1779	2.88	1.48	1.10
64	020824-01:17	01:01	00:49	S02W81	01:27	5.90	1913	1937	2.73	1.56	0.85
65	031028-11:17	11:02	11:00	S20E02	11:30	5.84	2459	2754	2.67	1.27	1.53
66	031029-21:02	20:42	20:37	S19W09	20:54	2.92	2029	2049	8.74	1.38	2.01
67	031102-17:27	17:14	17:12	S18W59	17:30	3.27	2598	2981	2.85	1.28	2.76
68	050117-09:52	09:43	09:38	N14W25	09:54	3.02	2547	2802	2.72	1.44	2.92
69	050120-06:47	06:44	06:39	N14W61	06:54	4.48	3242	3675	2.51	1.81	3.40
70	061213-02:42	02:26	02:17	S06W23	02:54	5.31	1774	2164	3.07	1.58	0.90

Table 1. GLE events of solar cycle 23 and the associated CMEs, type II bursts, and flares.