Can multiple shocks trigger ground level events?

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***Abstract*. A total of 16 Ground Level Events (GLE) occurred in solar cycle 23. These events, in which particle energies reach above 1 GeV/nuc, are the most energetic examples of Gradual Solar Energetic Particle (SEP) events. Over the past solar cycle, a great deal has been learned about these events observationally. However, the process by which particles are accelerated to these high energies is still presently unknown. We know the fact that they are often associated with both flares and Coronal Mass Ejection (CME) driven shocks, yet in many other SEP events where both strong flares and fast CMEs are found, the intensities and the maximum energies of energetic particles are often more than 10 to 100 times smaller. So questions such as what triggers a GLE and what differentiates a GLE from other gradual SEP events remain open. We discuss here a scenario in which two CMEs occur closely in time but offset in propagation direction. We show that the resulting magnetic field configuration can lead to magnetic reconnection. This reconnection process will provide both an excess of seed population and enhanced turbulence level at the shock front of the second CME-driven shock. Enhanced particle acceleration can therefore be achieved. The implications of our proposed scenario will be discussed.**

***Keywords*: Particle acceleration, CME, GLE event, MHD reconnection, CME-driven shocks**

I. INTRODUCTION

Ground Level Enhancements (GLEs) are gradual SEP events in which protons are accelerated to over ~ 500 MeV. The intensities of these events often reach 10 to 100 times larger than normal gradual SEP events. At ground, these events have been observed since 1940s by ionization chambers and neutron monitors. However, even today, questions such as what triggers a GLE and what differentiates a GLE from other gradual SEP events remain open. On one hand, these events may just well be a subset of gradual SEP events lying in the higher energy end of the spectrum; on the other, it is possible that some fortuitous conditions must be met in order for them to occur. In addition to the maximum energies and event intensities being much larger, the spectrum and composition in GLE events are also different from normal SEP events. If indeed, GLE events are due to some fortuitous conditions that do not occur mundanely in normal SEP event, then investigation of the composition and particle spectrum in GLE events can be used to place constraints on such conditions.

Recently *Gopalswamy et al.* [1] examined a possible correlation between large SEP events and the interaction of multiple CMEs. In a survey of 57 events between 1996-2002, all with intensity $>$ 10pfu at $>$ 10 MeV, where 23 had preceding CMEs (within 1 day) and 20 did not have preceding CMEs, they found a strong correlation between high particle intensity events and the existence of preceding CMEs. They concluded that "higher SEP intensities result whenever a CME is preceded by another wide CME from the same source region and the correlation between the peak intensity and the CME speed is improved substantially over earlier work by *Kahler*, [2]". This finding suggested that the occurrence of multiple shocks may provide a favorable condition for highly efficient particle acceleration at CME-driven shocks. As shown by *Li and Zank* [3], it is possible that the preceding CME creates an excess of interplanetary turbulence which significantly enhance the scattering rate of particles at the shock driven by the second CME, leading to a more effective diffusive shock acceleration process. *Li and Zank* [3] estimated the acceleration time scale at the second shock and showed that if the wave intensity at the downstream of the first shock (which is the upstream of the 2nd shock) is enhanced by a factor of 10, an increase of 32 for the maximum particle kinetic energy may be reached.

However, in the scenario of *Li and Zank* [3], the relative configuration between the two shocks (thus the two CMEs) was ignored. As an implicit assumption, it is assumed that the material in the downstream of the first shock can be later processed by the second shock. This ignores the presence of the first CME, which is a very effective barrier of separating solar wind that is in front from that is behind of it. Furthermore, because the CMEs are often spatially extended, so that if the second CME occurs right beneath the first one and close in time, it may not even have enough time to produce a second shock. Numerical simulations [4] showed that complicated interactions between the two CMEs may occur and eventually they will merge into one large ejection. Clearly, in this case, no second shock is generated, therefore no second acceleration process. If the second CME does not occur too close to the first one, it can produce its own shock. If it happens that the 2nd CME occurs right beneath the 1st one, then this shock can process the driver of the first CME, and because the density of the driver is higher than the solar

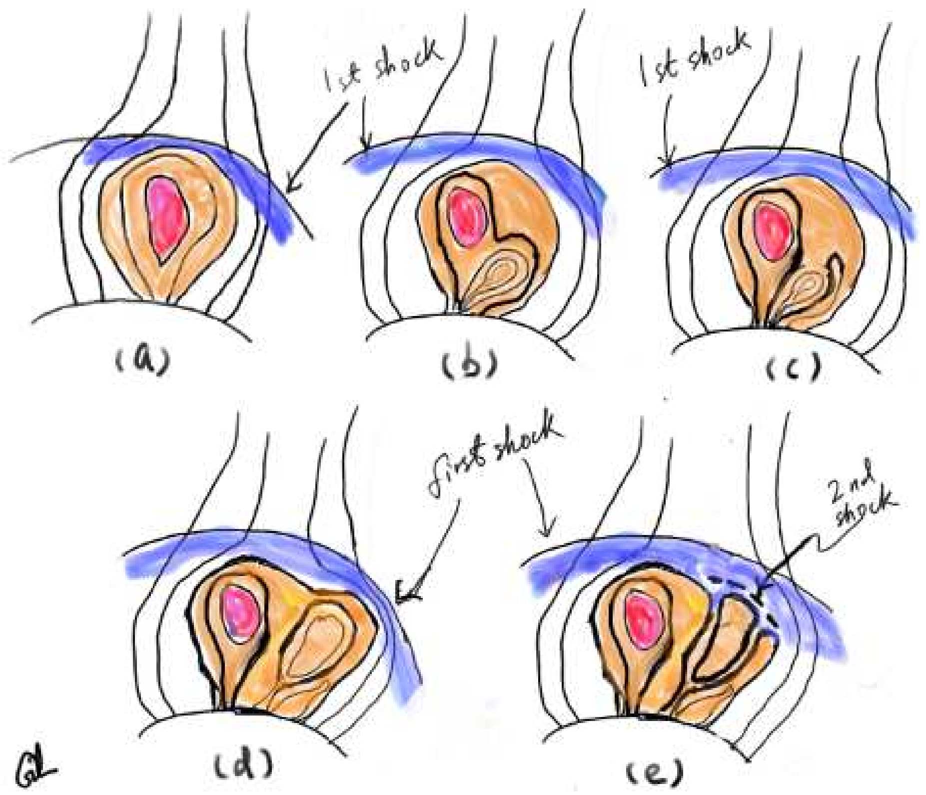

Fig. 1. Cartoon showing the evolution of two CMEs and their associated shock. The second CME occurs shortly after the first and propagates offset to the right of the first CME. As the 2nd CME catches the first CME and deforms its magnetic field lines, reconnection happens such that the material inside the driver of the first CME get mixed up with the material downstream of the first shock and can be accessed by the second shock. See text for details.

wind, the intensity of the resulting SEPs will be larger, a tempting explanation to what is happening in a GLE event. However, since the CME driver itself does not mix up with the downstream of the first shock (note that the driver, mainly ICME material, and the downstream solar wind are essentially two different plasmas), so the enhanced turbulence level in the downstream of the first shock does not apply to the driver material. Without this enhanced turbulence level, even though the seed population can be much higher, the acceleration time scale at the 2nd shock does not reduce significantly, and the maximum energy can be only comparable to that of the first shock.

II. Offset CMEs with field line reconnection as a possible scenario for GLEs

What is clear from last section's discussion is how to obtain both a high turbulence level and a high seed population at the second shock. Put into context, how to mix up the dense but less turbulent ICME material inside the driver of the 1st CME with the more turbulent but less dense solar wind downstream of the 1st shock and have this mixture effectively processed by the second shock. As we discuss below, a possible scenario where these conditions are satisfied can be achieved if the second CME occurs temporally close to, but spatially offset from the first CME, i.e. propagating sideways from the first CME. In this case, through magnetic reconnections, the 2nd CME shock can process the dense ICME material of the first CME and experience the enhanced turbulence downstream of the first shock at the same time. This scenario is shown by the Cartoon in Figure 1, We refer to this scenario as the "offset CME scenario" in this paper. Panel (a) shows at time t_0, the first CME, which is colored as orange with two field lines enclosing the driver and closed back to the Sun. The inner most region is colored in pink, representing a closed magnetic loop by its own. The shock in front of the CME is also shown as the solid black line with the downstream region colored in blue. Two open field lines on either side of the CME are also shown. Panel (b) corresponds to a later time t_1, which should be not too late from t_0 (see later discussions on this point). A second CME propagating to the right side of the first CME is shown in this panel. Again, three field lines enclosing this second CME are shown, with the first two connected to the Sun and the third one as a closed loop. Assuming it is faster than the 1st CME, then as it is propagating outward, it pushes one of the field line (shown in dark black) enclosing the first CME to yield a "kink" configuration. Such a "kinked" field line is not stable and it will relax itself by reconnecting to the outermost field line that is enclosing the second

CME. The magnetic field configuration right after the reconnection is shown in panel (c). Comparing (b) and (c), we find that the number of loops (including both those closed on to the surface of the Sun and that closed on itself) of the first CME is still the same, i. e. 3; the number of loops enclosing the second CME decreases by 1, becoming 2; and a new loop to the right of the second CME is produced. As the 2nd CME further propagates out, we come to panel (d) (at $t = t_3$). Here we find the outermost field line enclosing the first CME is being distorted. Again the distortion will cause magnetic reconnection, after which the configuration of magnetic field is shown in panel (e). Note that in this step, as the utmost field line of the 1st CME being distorted and reconnected to that enclosing the second CME, the downstream region of the first shock (blue) and the CME driver material (orange) can be mixed. The mixture happens exactly in front of the second CME. Plowing into this mixture, the second CME can generate a shock, which is represented by the dashed line in panel (e). This shock now "sees" both an enhanced turbulence level and an enhanced seed population, the two most important conditions for a GLE to occur.

Note, the role of magnetic reconnection is crucial for this "offset CME scenario". It is exactly this reconnection that leads to the mixture of the downstream solar wind of the first shock with the ICME material inside the CME driver. This reconnection is caused by the distortion of the field line by the 2nd CME that is coming from behind and inside the 1st CME. If there is no second CME or if there is a 2nd CME, but the speed is smaller than the 1st CME, then it is impossible for this reconnection to occur. Clearly, for this whole sequence of (a) to (e) to occur, various conditions have to be met:

- the second CME must occur beneath and inside the first CME (presumably both CMEs lift off from the same active region).
- the second CME must occur closely in time to the first CME.
- the second CME must be faster than the first CME.
- the second CME must propagate to a different direction from the first CME.
- the polarities (directions) of the magnetic fields enclosing the first and the second CMEs should be such that magnetic reconnection can occur.

Satisfying these conditions all at once may not be common, which suggests that GLE events should be rare, agreeing with observations.

III. Observational signatures

The "offset CME scenario" can be tested by various observations. In the following, we present some preliminary data analyses as an effort to examine our scenario. First, one may examine if there is a correlation between a GLE and the occurrence of two closely ejected CMEs. This would be a natural extension of the study done in [1]. Indeed, as shown in Table I, out of the 16 GLEs that occurred in solar cycle 23, 11 were found to have at least one preceding CME within 24 hours; 2 were found to have no preceding CMEs within 24 hours. For the rest 3 GLE events, the 8/24/1998 event has no data available to tell if there are preceding CMEs. The remaining two GLE events, 11/4/2001 and 12/26/2001, have some preceding ejections, but not CMEs. [1] Consequently, in this paper, we do not consider these three GLEs. For further detailed properties of the GLE events occurred in solar cycle 23, the reader is referred to the paper by *Mewaldt et al.* [5] in this volume. The first column in table I shows the date of the CME that is associated with the GLE event. The second column is the solar longitude. The third column is the delay duration from the preceding CMEs based on *Gopalswamy et al.*[1], [6]. In Table I, the first two GLEs do not have preceding CMEs associated with them. The rest do. The 4th to 8th column are the ratio of heavy ions to oxygen in the energy range of $10 - 30$ MeV/nucleon. We use the data from the SIS instrument onboard ACE. The last column (γ) is the fitted fluence spectral index at high energies. These are pretty hard spectra, which is what one expects for GLE events.

One practical question is how close do the two CMEs need to be in order for the offset CMEs scenario to work. Clearly, a 24-hour gap may be too long since a 800 km/s CME can travel a distance of ~ 0.46 AU (assuming little deceleration) in a day. Assuming the first CME has a speed of 800 km/s and the second CME has a speed of 2400 km/s, if the delay between them is four hours, then the front of the second CME will catch the front of the first CME in two hours at a distance of 0.12 AU (25 $R_\odot$). Therefore a four-hour delay perhaps is a thumb of rule for the lag time since timing studies often find that the release time of high energy particles tend to occur when the shock is within $r \leq 20R_\odot$. This of course, may vary from event to event depending on the speeds of the CMEs.

Another study is to examine the composition of the accelerated energetic particles. The ratio of Mg/O, Si/O, Fe/O and Ne/O , have been used to distinguish solar wind material from ICME material (see e.g. [7], [8], [9]). Recently, *Mewaldt et al.*, [2007], using 2 hours average data from ACE/SWICS, showed that the Fe/O ratio in the ICME material (see figure 9 in their paper) increases significantly from the solar wind value. If ICME material can be regarded as a reasonable proxy for the material inside the driver of the first CME, then one consequence of the "offset CMEs scenario" will be the acceleration of this material by the second shock. This is in stark contrast to the single CME case where mainly solar wind material are accelerated (suprathermals that result from earlier flares and CMEs etc may present). Note since flares often occur together with CMEs, the

[1] In [1], there are some events in which a 2nd CME catches a preceding CME below the view of the coronagraph. *Gopalswamy et al.* classify these as "Other" category. These perhaps are good candidates for our scenario.

TABLE I
PROPERTIES OF THE GLE EVENTS IN SOLAR CYCLE 23

date	Flare Longitude	delay (hrs)[a]	Ne/O	Mg/O	Si/O	Fe/O	(Mg+Si+Fe)/O	γ [b]
2001.4.18	120	–	0.17	0.293	0.188	0.16	0.643	2.43
2006.12.13	23	–	0.205	0.210	0.20	0.778	1.188	2.71
1997.11.6	63	16.2	0.26	0.202	0.169	0.650	1.021	2.44
1998.5.2	15	8.6	0.33	0.298	0.203	0.636	1.136	2.7
1998.5.6	65	8.4	0.32	0.249	0.157	0.502	0.909	2.89
2000.7.14	7	14.4	0.16	0.219	0.149	0.09	0.461	3.78
2001.4.15	85	20.2	0.18	0.231	0.196	0.42	0.849	2.09
2002.8.24	81	12	0.15	0.208	0.138	0.19	0.534	2.9
2003.10.28	-8	0.6	0.11	0.201	0.164	0.04	0.406	4.36
2003.10.29	2	10.6	0.24	0.241	0.172	0.14	0.548	3.15
2003.11.2	56	18.4	0.13	0.193	0.119	0.04	0.351	3.44
2005.1.17	25	0.6	0.18	0.185	0.114	0.04	0.340	3.14
2005.1.20	61	22.5	0.23	0.231	0.1620	0.17	0.568	2.14
slow SW	–	–	0.10 ± 0.03	0.15 ± 0.03	0.15 ± 0.03	0.11 ± 0.03	–	–

[a] these delays are from [1], [6] and SOHO/LASCO CME catalog.
[b] adapted from [5], γ values are for protons ≥ 40 MeV.

same reconnection process will allow the flare material from the flare accompanying the first CME to undergo the same acceleration process. Therefore, a composition of the energetic particles similar to that of CMEs or flares provide strong support for the proposed scenario.

We point out here that the "offset CMEs scenario" can be equally well applied to other large SEP events. Indeed, in the "offset CMEs scenario", if the resulting accelerated particle spectrum is not hard enough, then the event will fail to become a GLE, but become a large SEP only. This suggests that the procedure outlined here should be applied to a larger database consisting of many more large SEP events as well.

We examine only the GLEs in the solar cycle 23 in this study. Shown in Table I are the ratios of Ne/O, Si/O, Mg/O and Fe/O at $10 - 30$ MeV/nucleon. Although scattered, comparing these to nominal slow solar wind values [11] (shown as the last line in the table), we do see frequent examples of enhancements that suggest the presence of ICME material. Furthermore, we note that the Ne/O value has been used as a proxy for identification of flare material [12]. *Mason et al.* [13] showed that flare material has an average Ne/O ratio of $0.261 \pm .004$. From the table it is clear that a few of the GLEs have their Ne/O ratios comparable to that for flare material, hinting that there may be even flare material in these events. As we discussed early, this is possible in the offset CME scenario if the flare associated with the first CME occurs in the same active region as the second CME.

While it is clear that many GLEs do tend to be ICME and/or flare rich, our study do not show a clear distinctions between the events that have a preceding CME and those that lack a preceding CME. However note that only 2 GLE events do not have preceding CMEs, therefore the statistics are poor. In the future, to help to examine the validity of the "offset CMEs scenario", one should extend our study to large SEP events (which are not necessary GLEs) and examine if there is a strong correlation between the composition and preceding CMEs. If this "offset CMEs scenario" is correct, one will find that smaller events tend to be solar wind in composition and have no preceding CMEs; while bigger events tend to be ICME/flare in composition and have preceding CMEs that are occur very closely in time.

IV. CONCLUSION

We examine here a possible scenario, namely, the "offset CMEs scenario" as the trigger for GLE events. When two CMEs occur closely in time and offset in propagation direction, the second CME, if having a larger speed, as it propagates out, will distort the magnetic fields enclosing the first CME and lead to magnetic reconnection. This reconnection opens up the material inside the first CME, allowing them to be mixed up with the solar wind downstream of the shock (driven by the first CME), and be accelerated by the second shock. This scenario, comparing to traditional shock acceleration by a single CME-driven shock, naturally provides both an enhanced turbulence and an enhanced seed population that is rich in ICME/flare material.

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REFERENCES

[1] Gopalswamy et al., JGR, 109, A12015, 2004.
[2] Kahler, S.W., JGR, 106, A12015, 2004.
[3] Li, G. & Zank, G. P., 29th ICRC proc., Vol. 1, p173, 2006.
[4] Wang, A.H., et al., Geophysical Mono., 156, p185, 2005.
[5] Mewaldt, R. A., et al., this volume, 2009.
[6] Gopalswamy, N. et al., JGR 110, doi:10.1029/2004JA010958, 2005.
[7] Ipavich, F. M., et al.,JGR, 91, 4133, 1986.
[8] Zurbuchen, T. et al., GRL, 29, doi:10.1029/2001GL013946, 2002.
[9] Richardson, I. G. and H. V. Cane, JGR, 109, doi:10.1029/2004JA010598, 2004.
[10] Mewaldt, R. A., et al., Space Sci. Rev., 130, p207, 2007.
[11] von Steiger et al. JGR 105, 27217, 2000.
[12] Reames, D.V. et al., ApJS 90, 649, 1994.
[13] Mason, G. M., ApJ, 606, p555, 2004.