# Two Exceptions in the Large SEP Events of Solar Cycles 23 and 24

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## Abstract
We discuss our findings from a survey of all large solar energetic particle (SEP) events of Solar Cycles 23 and 24, *i.e.* the SEP events where the intensity of >10 MeV protons observed by GOES was >10 pfu. In our previous work (Gopalswamy *et al.*, 2014 *Geophys. Res. Lett.* **41**, 2673) we suggested that ground level enhancements (GLEs) in Cycles 23 and 24 also produce an intensity increase in the GOES >700 MeV proton channel. Our survey, now extended to include all large SEP events of Cycle 23, confirms this to be true for all but two events: i) the GLE of 6 May 1998 (GLE57) for which GOES did not observe enhancement in >700 MeV protons intensities and ii) a high-energy SEP event of 8 November 2000, for which GOES observed >700 MeV protons but no GLE was recorded. Here we discuss these two exceptions. We compare GLE57 with other small GLEs, and the 8 November 2000 SEP event with those that showed similar intensity increases in the GOES >700 MeV protons but produced GLEs. We find that because GOES >700 MeV proton intensity enhancements are typically small for small GLEs, they are difficult to discern near solar minima due to higher background. Our results also support that GLEs are generally observed when shocks of the associated coronal mass ejections (CMEs) form at heights 1.2-1.93 solar radii [$R_\odot$] and when the solar particle release occurs between 2 – 6 $R_\odot$. Our secondary findings support the view that the nose region of the CME-shock may be accelerating the first-arriving GLE particles and the observation of a GLE is also dependent on the latitudinal connectivity of the observer to the CME-shock nose. We conclude that the GOES >700 MeV proton channel can be used as an indicator of GLEs excluding some rare exceptions, such as those discussed here.

Keywords: Solar Energetic Particles, Ground Level Enhancement, Coronal Mass Ejections

## 1. Introduction
Solar energetic particles (SEPs) have energies ranging from a few keV to several GeV. The highest-energy SEPs, *i.e.* at energies ≈1 GeV and beyond, produce ground level enhancements (GLEs) above the cosmic ray background and are typically observed by neutron monitors (NMs) (Cliver *et al.*, 1982; Kahler, Simnett, and Reiner, 2003; Gopalswamy *et al.*, 2005; Cliver, 2006; Shea and Smart, 2008; Reames, 2009a, 2009b; Gopalswamy *et al.*, 2012; Bieber *et al.*, 2013a; Reames, 2013; Gopalswamy *et al.*, 2014). Properties of GLEs have been studied using neutron monitor as well as *in-situ* particle measurements. NMs detect particles above specific threshold rigidities that depend on the NM location and altitude, whereas the spacecraft experiments, *e.g.*, the *Geostationary Operational Environmental Satellites (*GOES: Rodriguez, Krosschell, and Green, 2014), have typically observed

protons up to 700 MeV in differential energy channels and >700 MeV in the integral channel. The white-light images of CMEs from the *Solar and Heliospheric Observatory's Large Angle and Spectrometric Coronagraph* (SOHO/LASCO: Brueckner *et al*., 1995) and *Solar TErrestrial RElations Observatory's* (STEREO) coronagraph (COR1, COR2: Thompson *et al*., 2003), are typically used to study the associated coronal mass ejections (CMEs). CME-driven shocks (CME-shocks) that produce Type-II radio bursts at metric wavelengths can be studied using radio spectrographs from the ground-based radio observatories, whereas interplanetary Type-II bursts can be measured only by space-borne radio and plasma wave receivers.

Particles producing GLEs are widely believed to have been primarily accelerated by CME-driven shocks. There have been arguments regarding whether the first arriving, anisotropic beam of particles is accelerated at the nose or the flanks of the shock (Gopalswamy *et al*., 2013a). While the longitudinal connectivity of the GLE particle source regions has been long accepted to be a driving factor (Reames, 2009a, b, 2013; Gopalswamy *et al*., 2012, 2013a), recent studies have started exploring the impact of the latitudinal connectivity of the CME-shock nose as well (Gopalswamy and Mäkelä, 2014; Gopalswamy *et al*., 2014).

Studies of the GLEs in Cycles 23 and 24 have shown that typically GOES observed an enhancement in intensities of protons at energies >700 MeV (Gopalswamy *et al*., 2014; Tylka and Dietrich, 2009). Similarly, all large SEP events for which GOES observed an increase in intensities of >700 MeV protons also resulted in GLEs (Gopalswamy *et al*., 2014). We extended our survey (Gopalswamy *et al*., 2014) to include all of Cycle 23 and 24 GLEs and large SEP events to explore this useful relationship because it suggests that the GOES detectors can identify GLEs. GOES particle instruments also have better energy resolution than NMs that measure integral fluxes above certain cutoff rigidity. Therefore GOES observations can be used to extend the proton energy spectra up to around 700 MeV, which could provide additional information on the properties of the CME-driven shock waves that accelerate the high-energy particles. In contrast, the energy spectra of the high-energy particles can be obtained from NM measurements only if multiple NMs with different cutoff rigidities have observed the event.

We found this GLE–GOES proton intensity correlation to be true for all GLE and large SEP events in our data set with two exceptions: i) the GLE of 6 May 1998 (GLE57: Kahler, Simnett, and Reiner, 2003; Gopalswamy *et al*., 2005; Cliver, 2006) did not show an enhancement in the GOES >700 MeV proton channel; and ii) GOES observed a clear enhancement in >700 MeV channel for the large SEP event of 8 November 2000, but there was no GLE. The purpose of this article is to investigate these two "unusual" events in order to understand the reasons behind these exceptions. The role of GOES as a GLE indicator becomes especially important because small GLEs may be missed even though the highest energy particles arrive at Earth, if their narrow particle beams do not encounter any NMs or if their enhancement is small above the background.

## 2. Observations

We surveyed all large SEP events of Solar Cycles 23 and 24. Large SEP events are those for which the GOES >10 MeV proton peak flux is >10 pfu, where 1 pfu is the particle flux unit = 1 particle $cm^{-2}s^{-1}sr^{-1}$. We selected SEP events regardless of their location, soft X-ray class of the associated flares, or speed of the associated CMEs. Thus our data set consisted of 142 large SEP events, out of which 18 were GLEs (CDAW SEP catalog: cdaw.gsfc.nasa.gov/CME_list/sepe/). We examined five-minute resolution proton data from GOES 08 – 15, to study the proton intensity–time profiles in the differential energy channels ranging from 9.0 – 700.0 MeV and in the integral channel >700 MeV. Particle spectra were derived by averaging proton measurements to one-hour intervals. The neutron monitor data were taken from Oulu NM (cosmicrays.oulu.fi), Bartol NM (neutronm.bartol.udel.edu), and the neutron monitor database (nmdb.eu) websites. We studied CMEs associated with the SEP events to correlate observed particle phenomena with the physical processes at the Sun. The CME characteristics were taken from the CDAW CME catalog (cdaw.gsfc.nasa.gov, Gopalswamy *et al.,* 2009), which is based on the measurements from SOHO/LASCO. The radio observations were taken from the Learmonth and Culgoora ground-based radio observatories (www.ips.gov.au) and the *Radio and Plasma Wave Investigation* (WAVES: Bougeret *et al*., 1995) instrument onboard the *Wind* spacecraft. The onset of radio Type-II emission, either in the metric (m) or decameter-hectometric (DH) wavelengths, marks the formation of a CME-shock. The starting frequency of Type-II burst indicates the height at which the CME-shock is formed (Gopalswamy *et al*., 2012, 2013b; Mäkelä *et al*., 2015). As a CME-shock travels in the interplanetary medium, the frequency of its Type-II radio burst drifts towards lower frequencies because the electron density decreases with distance from the Sun. Thus the type-II emission depends on the location of a CME-shock and the properties of the ambient plasma. Therefore, we study radio Type-II bursts in order to follow the propagation of the CME-shock associated with a SEP event and to determine the shock height at various times, including the times of shock formation, and solar particle release (SPR), as it travels in the interplanetary medium.

We utilized these multi-wavelength measurements to study the two exceptions in our dataset, *viz*., the GLE of 6 May 1998 (GLE57) without a GOES >700 MeV enhancement and the large SEP event of 8 November 2000 with a GOES > 700 MeV enhancement but without an observed GLE.

### 2.1 GLE of 6 May 1998 (GLE57)

GLE57 was associated with an X2.7 flare that originated at S11W65 and a fast partial-halo CME (speed ≈1208 km $s^{-1}$), which was first observed by SOHO/LASCO at 08:29 UT. GLE57 was primarily observed by the Oulu NM at 08:25 UT as an increase of 2 – 4 % above the background count rates (Kahler, Simnett, and Reiner, 2003; Gopalswamy *et al.,* 2005; Cliver, 2006; cosmicrays.oulu.fi/GLE.html). Figure 1a shows ten-minute particle-count rates from the Oulu NM, with a dashed-vertical line marking the onset of the event.

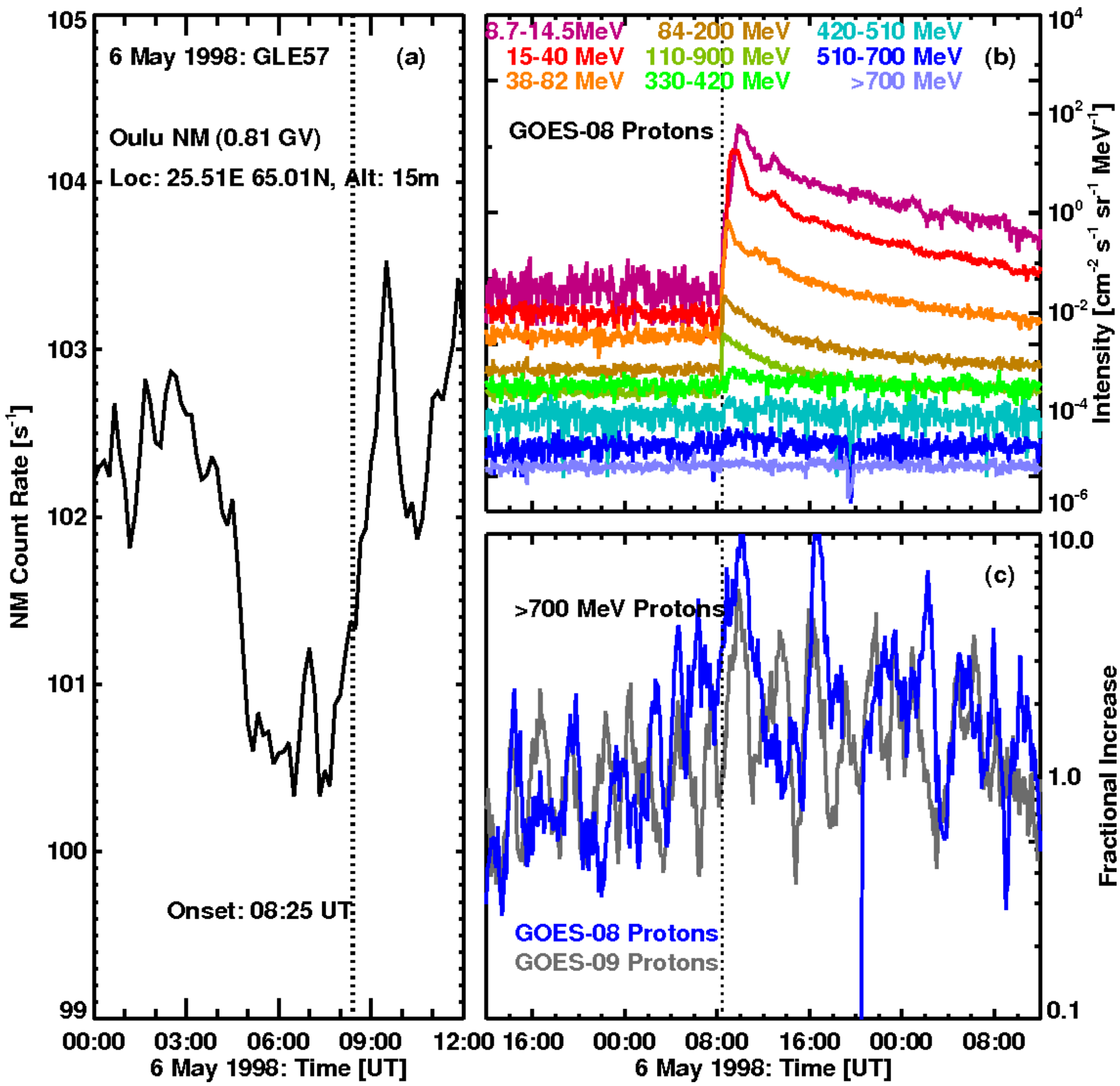


**Figure 1:** (a) Oulu neutron monitor count rates for GLE57. An intensity rise of 2–4% above the background was reported. (b): The proton intensity time profile from GOES-08. The SEP event was seen up to 700 MeV but no clear enhancement was observed above 700 MeV. (c) The fractional change in intensities from the >700 MeV proton channels in GOES-08 and GOES-09 (one-hour averaged). The background is fluctuating but there is a small spike (<3σ above background) near the onset of GLE57.

The GOES-08 proton intensity–time profile for this event is shown in Figure 1b. The SEP event was also observed by GOES-09. Both GOES-08 and GOES-09 observed proton-intensity enhancement up to 700 MeV, but neither recorded an increase in proton intensity in the >700 MeV channel. Figure 1c shows the fractional change (intensity-background)/background in proton intensities for GOES-08 and GOES-09.

There is an indication of a possible enhancement near the GLE57 onset (marked by the dashed-vertical line), although this is not clearly discernible from other small spikes. Both Figures1a and 1c indicate that GLE57 occurred during the recovery phase of a small intensity depression.

**2.2 The Large SEP Event of 8 November 2000**

The large, well-connected SEP event of 8 November 2000 was associated with an M7.4 flare that originated at N10W77and a fast CME (speed ≈1881 km $s^{-1}$), which was first observed by SOHO/LASCO at 23:06 UT. This event was observed by GOES-08, GOES-10, and GOES-11 as a rapid enhancement in proton intensities in the differential channels at energies up to 700 MeV and in the >700 MeV integral channel.

Figure 2a shows the proton intensity–time profiles from GOES-11 proton channels, which recorded the maximum rise of ≈133 % in the >700 MeV proton channel. The percent enhancements were determined from one-hour averaged GOES proton data. The background subtracted proton intensities from the >700 MeV channels in GOES-08 (rise ≈76 %), GOES-09 (rise ≈82 %), and GOES-11 are shown in Figure 2b. The dashed vertical line marks the onset of this SEP event in GOES.

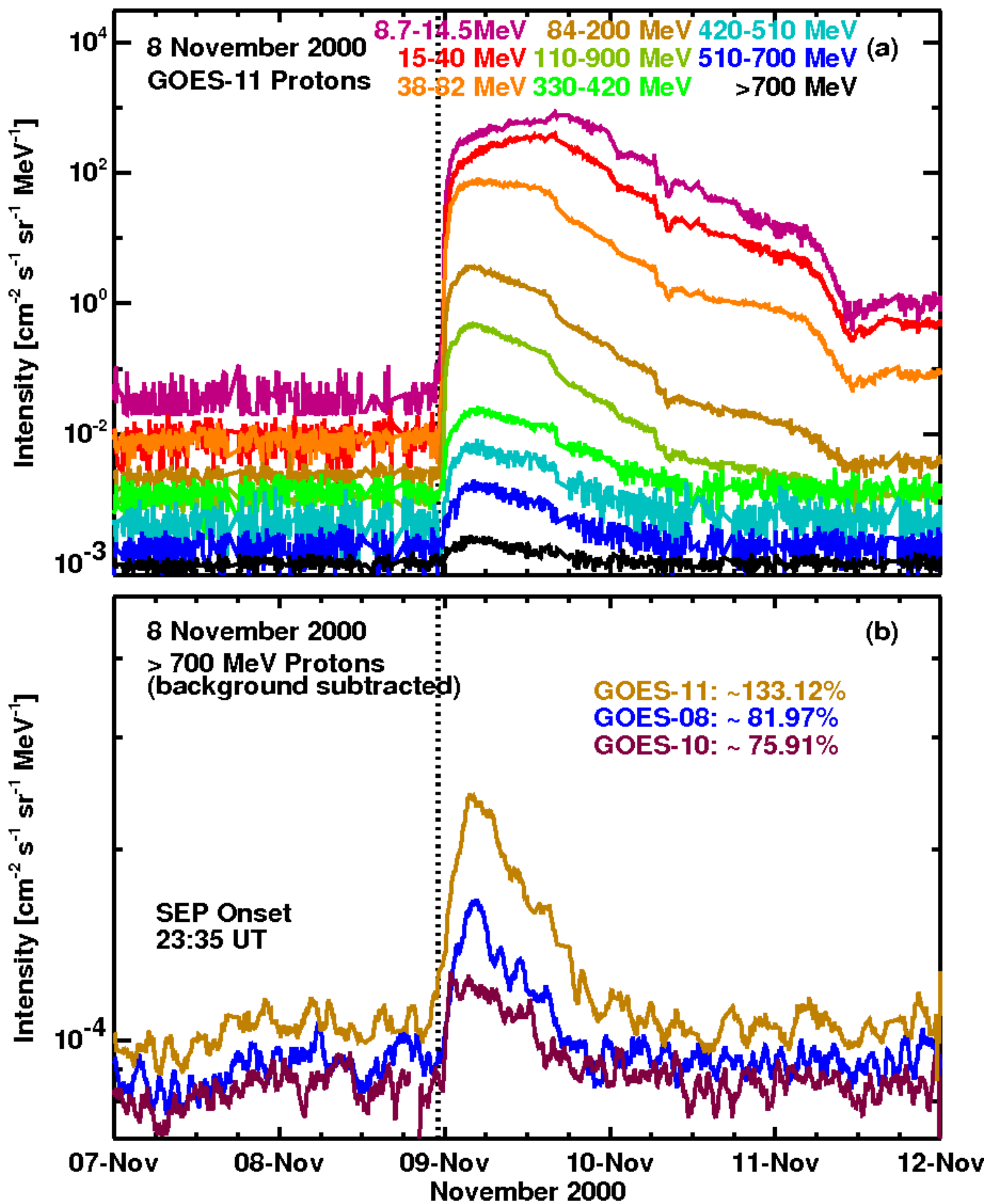


**Figure 2**: (a) Proton intensity–time profile for GOES-11 proton channels. (b) Background subtracted proton intensities for >700 MeV proton channel for all operational GOES satellites. GOES-08, GOES-10, and GOES-11 observed an enhancement of ≈76 %, 82 %, and 133 % respectively. The dashed-vertical line marks the event onset.

Because no GLE was recorded for the 8 November 2000 event, and no clear enhancement was seen by NMs near the GOES onset of this event, we studied the fraction of the background-subtracted count rates [% increase] to explore finer details. Figure 3 shows these fractional changes in count rates from 14 NMs for which data are available. Each of the three panels in Figure 3 show data overlapped for a few NMs. A curve of a specific color represents the fractional change for a specific NM, whose name and cutoff rigidity are noted in the panel. The count rates shown for the Bartol NMs (McMurdo, Swarthmore/Newark, South Pole, Thule, Fort Smith, Peawanuck, Nain, and Inuvik) have one-hour resolution. All other NM data in this figure are ten-minute averaged. The dashed-vertical line marks the onset of this event at GOES. For a nominal path length of 1.2 AU, the GLE protons (≈1 GeV) would arrive roughly 46 seconds prior to those of energies at 700 MeV. But it is clear that NMs did not observe any GLE during this event. Although a few NMs (Thule, Swarthmore *etc*.) recorded tiny spikes near the GOES onset of this event, the rises are <1 % above the background and hence, do not represent real intensity increases. We note that similar to GLE57, the 8 November 2000 SEP event occurred on the recovery phase of a small intensity depression.

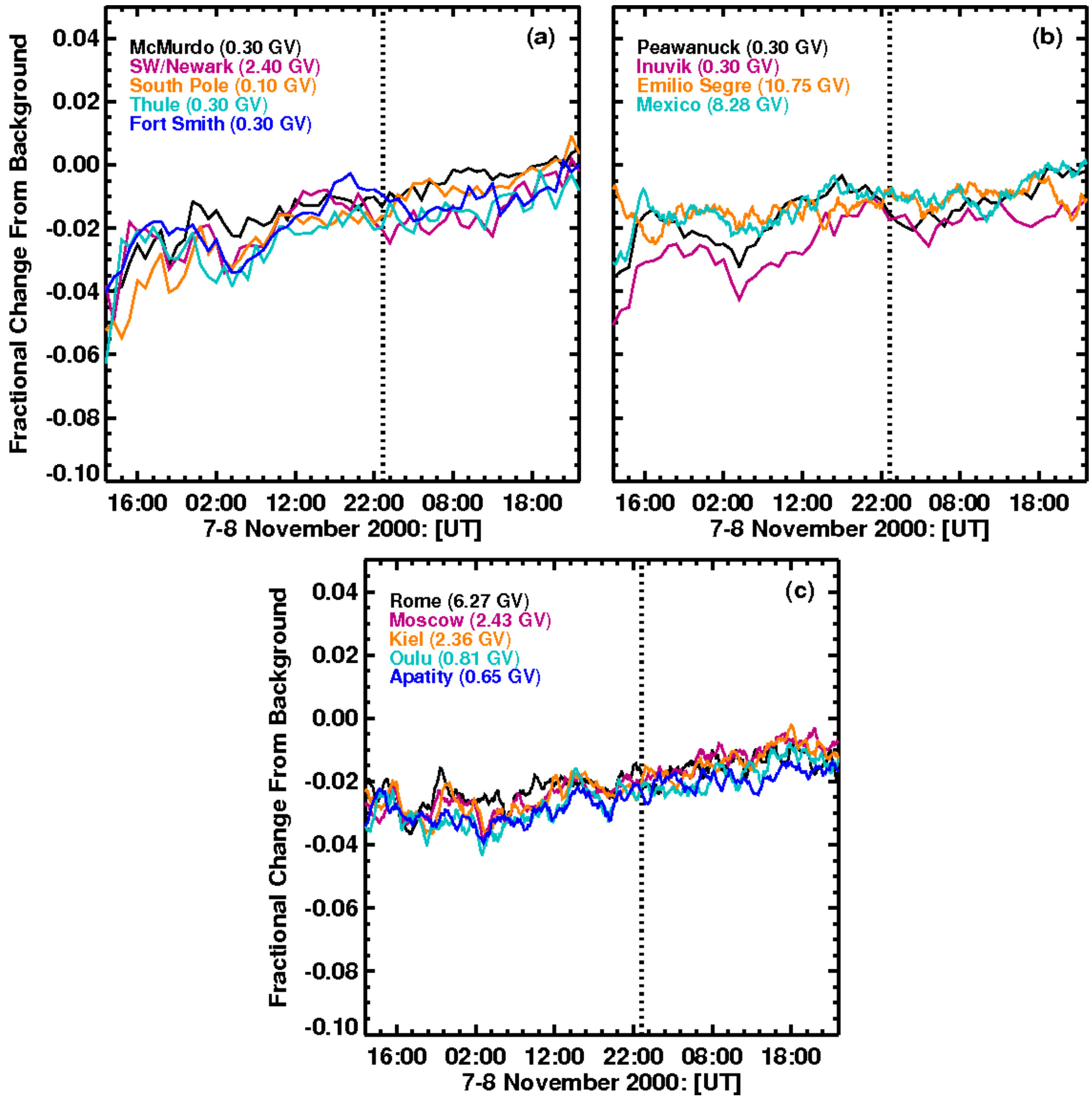


**Figure 3:** Neutron monitor count rates during the 8 November 2000 SEP event. In each of the panels a, b, and c, curves of a specific color represents fractional change in count rates for a specific neutron monitor (noted in the figure). The dashed-vertical line marks the onset in the GOES >700 MeV proton channel. The spikes in count rates for Emilio Segre, Rome, and Oulu were <1 % above the background, so there was no clear GLE.

Based on all of the characteristics, GLE57 should have been observed by the GOES >700 MeV proton channel, and the 8 November 2000 SEP event should have produced a GLE.

### 3. Why Are These Events Unusual?

To understand the two exceptions, we studied their associated CMEs, and CME-driven shocks using supplemental data from multi-wavelength observations. We also compared GLE57 with other GLEs of similar percentage increase and the 8

November 2000 SEP event with SEP events with similar GOES >700 MeV proton enhancements but that had GLEs.

**3.1 GLE57**

The neutron-monitor count rates represent the intensity of energetic particles arriving at the NM. The primary cosmic rays and SEPs that arrive at the top of Earth's atmosphere interact with the particles in the atmosphere during their transit to the ground. As a result, some primary particles shift to lower energies due to energy loss, while some produce secondary particles that cascade to the ground, but the lowest energy primary particles do not make it to the ground. While the cutoff rigidity reflects the NM's location with respect to the geomagnetic field, which governs the paths of particles entering the Earth, generally the atmospheric effects dominate observations of GLEs by NMs. Therefore, typically only protons of energies 1 GeV or above are detected on the ground. This is true more so for the Oulu NM (cut off rigidity: 0.81 GV), which is located at a low altitude of 15 m. This means that the GLE57 protons must have been accelerated to at least 1 GeV energies, but GOES did not seem to have detected protons at energies >700 MeV.

The rapid onset of the intensity enhancement in lower energy channels (Figure 1b) suggests that the GLE source region must have been well connected to the GOES satellites. There were no reported or known efficiency issues with the >700 MeV proton channels for either of these two satellites (Rodriguez 2015; personal communication). So there is no obvious reason for the lack of detection of >700 MeV protons.

**3.1.1 Comparison of GLE57 with other Small GLEs**

GLE57 was a small GLE, originating from a well-connected location. We compare it with other small GLEs (24 August 1998: GLE58, 17 January 2005: GLE68, and 6 January 2014: GLE72). A brief summary of this comparison is shown in Table 1. The GOES >700 MeV proton enhancements noted in Table 1 is from the GOES spacecraft that detected the greatest background-to-peak enhancement (with the time of peak accuracy of five minutes) out of all of the GOES stations that observed a specific event. GLE58, GLE68, and GLE72 showed clear proton intensity increases in the GOES > 700 MeV channel, in contrast to no such enhancements for GLE57 (see Figure 1b and 1c). GLE68 and GLE57 were associated with X-class flares but the CMEs associated with GLE68 and GLE72 had much higher speeds than that associated with GLE57. Due to its behind-the-limb location, the observed particles of GLE72 were understandably accelerated at a greater height (Thakur *et al*., 2014). Of these events, the CME-shock for GLE57 formed closest to the Sun and the solar particle release for GLE57 occurred at the smallest height (Reames, 2009a,b; Gopalswamy *et al*., 2013a).

**Table 1**: Characteristics of GLEs 57, 58, 68, and 72 (Gopalswamy *et al.* 2012, 2013a).

| Small GLEs of Cycles 23 and 24 | GLE 57 | GLE 58 | GLE 68 | GLE 72 |
|---|---|---|---|---|
| Date | 6 May 1998 | 24 August 1998 | 17 January 2005 | 6 January 2014 |
| GLE onset time [UT] | 08:25 | 22:50 | 09:55 | 07:58 |
| GLE % increase | 2 – 4 | 4 | 3 | 2.5 |
| GOES > 10 MeV SEP maximum intensity [pfu] | 207 | 187 | 5040 | 42 |
| Flare size | X2.7 | X1.0 | X3.8 | Backside |
| Flare time [UT] | 07:58 | 21:50 | 09:42 | Backside |
| Location | S11W65 | N35E09 | N14W25 | W102 |
| CME speed [km $s^{-1}$] | 1208 | 1420 | 2802 | 1960 |
| CME first appearance time in LASCO FOV [UT] | 08:29 | LASCO data-gap | 09:24 | 08:00 |
| Metric Type-II onset [UT] | 08:05 | 22:02 | 09:43 | 07:48 |
| CME-shock formation height [R¤] | 1.29 | 1.43 | 1.44 | 1.61 |
| CME height at SPR [R¤] | 2.21 | 5.14 | 2.72 | 2.96 |
| GOES > 700 MeV Background [pfu] | $1.43 \times 10^{-4}$ | $1.47 \times 10^{-4}$ | $1.55 \times 10^{-4}$ | $1.2 \times 10^{-4}$ |
| GOES > 700 MeV Peak Intensity [pfu] | $1.66 \times 10^{-4}$ | $1.99 \times 10^{-4}$ | $2.49 \times 10^{-4}$ | $1.49 \times 10^{-4}$ |
| GOES > 700 MeV intensity rise | None | ≈36 % | ≈ 41 % | ≈24 % |

An intensity enhancement in the GOES > 700 MeV proton channel was observed for all of the smallest GLEs of Solar Cycles 23 and 24. This comparison suggests that GLE57 should also have been detected by the GOES > 700 MeV proton channel.

**Comparison of GLE and SEP Intensities**

Figure 4 shows a comparison of GLE % increase *vs.* SEP intensities (the peak intensities of the GOES >10 MeV protons) and the corresponding straight-line fit for the GLEs of Cycles 21 through the present. The scatter plot is an extension of that reported by Gopalswamy *et al*. (2012) for Cycle-23 GLEs. The data for Figure 4 were taken from Cliver *et al*. ,1982; Cliver, 2006; Gopalswamy *et al.,* 2012.; the SEP events list at the CDAW Data Center, and the solar-proton-events list at NOAA (ftp://ftp.swpc.noaa.gov). The blue diamonds mark small GLEs (<5 % intensity rise). The filled diamonds mark GLEs 57, 58, 68, and 72, all of which were small GLEs (≤ 4 %) but had SEP peak intensities varying from ≈42 pfu to ≈5040 pfu. We note that GLEs 58, 57, and 72 fall within 1σ of the fit whereas GLE68 is within 2σ.

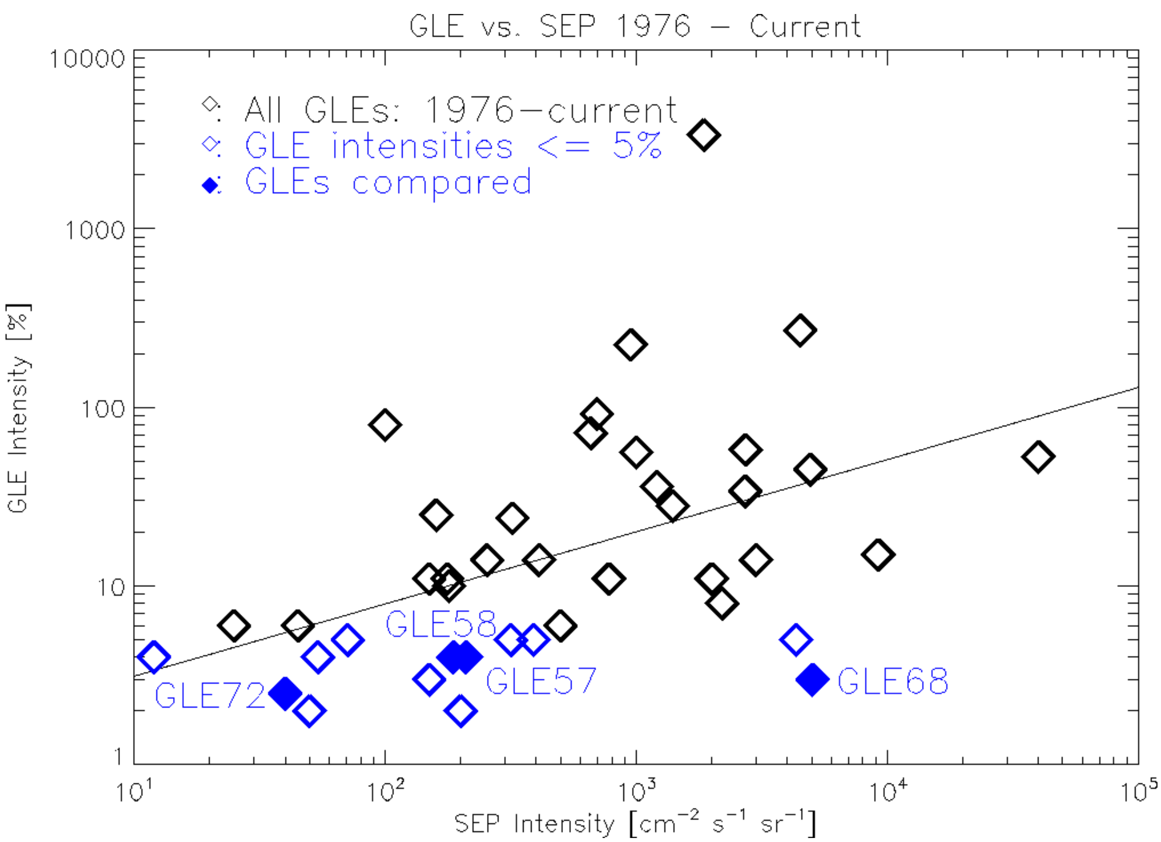


**Figure 4**: GLE intensities (maximum % increase observed by NMs) and SEP peak intensities in GOES >10 MeV protons for all GLEs from 1976 to present. The blue diamonds represent all of the small GLEs that had a NM–intensity enhancement ≤ 5%. GLEs compared here (GLEs 57, 58, 68, and 72) are marked with filled diamonds.

There have been several small GLEs with small SEP peak intensities. The closest in comparison to GLE57 are the GLEs of 19 September 1977 (GLE28, rise 2 %, SEP peak intensity 200 pfu) and 10 May 1981 (GLE35, rise 3 %, SEP peak intensity 150 pfu) from Solar Cycle 21 (Cliver *et a*l. 1982; cosmicrays.oulu.fi/GLE.html). GLE28 and GLE35 could not be compared here because GOES proton data at comparable energies did not become available before 1986 (GOES-06, > 685 MeV) and the > 700 MeV GOES measurements started in 1995.

In this article we have compared the GLE events only for Cycles 23 and 24. The 17 January 2005 GLE had a rise of ≈3 % but the SEP peak intensity of > 10 MeV protons was 5040 pfu. A clear enhancement above the background was detected by GOES for > 700 MeV protons. In addition, the small GLE of 6 January 2014 also had a small but definite rise of ≈ 22 % in > 700 MeV proton intensities. This suggests that even the smallest GLEs can be observed by the GOES >700 MeV proton channels but GLE57 was not.

**3.1.2: Near-Earth Space Conditions**

GLE57 was also possibly the only GLE in our dataset that occurred during the recovery phase of a small Forbush decrease (Forbush, 1958), which started ≈ 02:00 UT on the same day (Figure 1a, 1c). A Forbush Decrease (FD) is observed as a sudden drop in the NM count rates, followed by a gradual recovery phase. NMs primarily measure galactic cosmic rays (GCRs), but detect GLEs when count rates rise above the GCR background due to high-energy SEPs. If a GLE occurs during a FD when the GCR background is reduced, it is easier to observe a small spike in NM count rates, which might have been otherwise missed. Therefore, had the background not been suppressed due to a FD, the observed GLE would have had an even smaller percent rise that could have been indistinguishable from fluctuations of the GCR background. In this sense, the GLE57 can be considered as an "accidental" GLE. The Kyoto World Data Center (wde.kugi.kyoto-u.ac.jp) reported 6 May 1998 to be one of the geomagnetically quietest days of the month whereas the prior four days were geomagnetically the most disturbed in the month with Dst index close to -200 nT. All of these observations indicate the presence of interplanetary magnetic structures that affected observed SEP intensities at NMs just prior to the GLE onset. Therefore, if there was any small enhancement in the GOES >700 MeV proton intensities, any particle-deflecting disturbances might have depressed the intensities even further, thus rendering it practically indiscernible above the background.

**3.1.3 Effects of Solar Modulation**

GLEs are rare during solar minimum (Tylka and Dietrich, 2010) but GLE57 occurred close to a solar minimum. We explored possible effects of solar modulation on the GOES background intensity. The background intensity is due to the galactic cosmic rays, which are known to undergo solar modulation. Figure 5a, b, and c show monthly sunspot number (www.sidc.be), the Oulu NM count rates, and GOES >700 MeV proton fluxes, respectively, for the duration of 1995 to 2010. It is clear that the proton intensities undergo solar modulation. As the solar cycle started towards its maximum, the background NM counts and GOES proton intensities were still near their maximum in 1998, *i.e.* the GOES > 700 MeV proton background remained elevated near its maximum when GLE57 occurred.

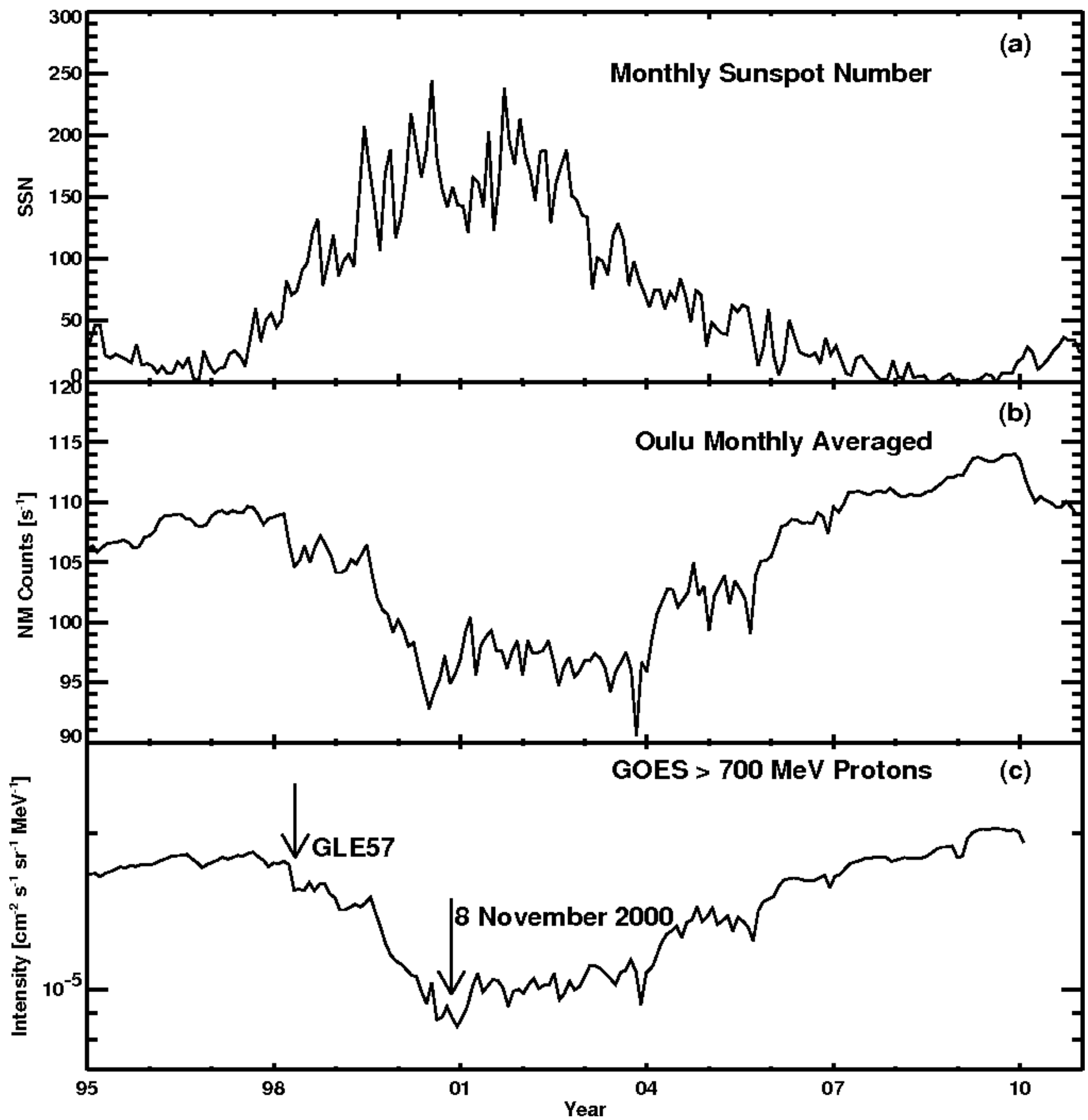


**Figure 5**: Effect of solar modulation on GOES >700 MeV proton background during Solar Cycles 23 and 24. (a) Monthly sunspot number. We have used the revised sunspot number series (version 2.0) from www.sidc.be. (Clette *et al*., 2014). (b) Count rates at the Oulu neutron monitor. (c) GOES > 700 MeV proton fluxes. The arrows mark GLE57 and the 8 November 2000 SEP event. GLE57 occurred when the background was close to its maximum and the 8 November 2000 SEP event occurred when the background was at its minimum.

We also note that the >700 MeV proton channel background was fluctuating just before and after GLE57 (Figure 1). We wondered if there were any known issue with this GOES channel, but no such issues have been reported. In addition, this fluctuation was seen by GOES-08 and GOES-09 independently, as well as by the Oulu NM. So this background fluctuation must have been real.

As mentioned earlier, we could not compare GLE28 and GLE35, both of which were small GLEs that occurred during a solar-cycle phase similar to GLE57. However, we examined GOES > 685 MeV proton data for a few of the GLEs of Cycle 21. The GLE of 25 July 1989 (GLE40) was one of the smallest GLEs, with a 4 % increase in NM count rates and the > 10 MeV peak flux of 54 pfu. GOES-06 detected a clear enhancement of ≈ 133 % in its highest energy channel of > 685 MeV for GLE40. However, GLE40 occurred during solar maximum when the background was near its minimum, thus making it possible to detect smaller intensity enhancements. So we cannot rule out the presence of > 700 MeV protons in the GOES channel.

Small GLEs that have small SEP peak intensities of the > 10 MeV protons seem to produce a very small rise above the background for > 700 MeV protons in GOES. It is possible that for GLE57 a small enhancement in the GOES >700 MeV proton intensities occurred but was not clearly detected. Any combination of the following could have contributed to lack of observation of > 700 MeV protons in GOES for GLE57: i) the background was at its highest, ii) the background was fluctuating, and iii) there were particle-deflecting disturbances present.

### 3.2 The 8 November 2000 Large SEP Event

In order to explore the contributing factors for the lack of a GLE in the 8 November 2000 SEP event, we compared its characteristics with those of observed GLEs.

GLEs have been typically associated with m-Type-II radio bursts (Tylka *et al.*, 2003; Reames, 2009a; Gopalswamy *et al.*, 2010, 2012; 2013a,b). M-Type-II bursts indicate the formation of a CME driven shock close to the Sun. A DH-Type-II radio burst is indicative of an energetic CME driving a strong shock that accelerates particles to high energies in the interplanetary medium (Gopalswamy *et al.*, 2001). The shock needs to travel for a few minutes after its formation before it can accelerate particles to high energies. SEP events have also been correlated with complex Type-III radio bursts, but a complex Type-III emission is not necessary for SEP events (Gopalswamy and Mäkelä, 2010).

#### 3.2.1 Determination of CME-shock height

The radio dynamic spectrum of the 8 November 2000 SEP event is shown in Figure 6. There was a faint m-Type-II burst starting at 40 MHz around 23:05 UT, followed by a long-lived DH-Type-II burst. The low starting frequency of Type-II burst indicates that the CME-shock formed at a greater heliocentric distance, where the ambient plasma density was smaller (Gopalswamy *et al.*, 2015; Mäkelä *et al.*, 2015). There was also a complex Type-III radio burst that lasted for ≈ 50 minutes.

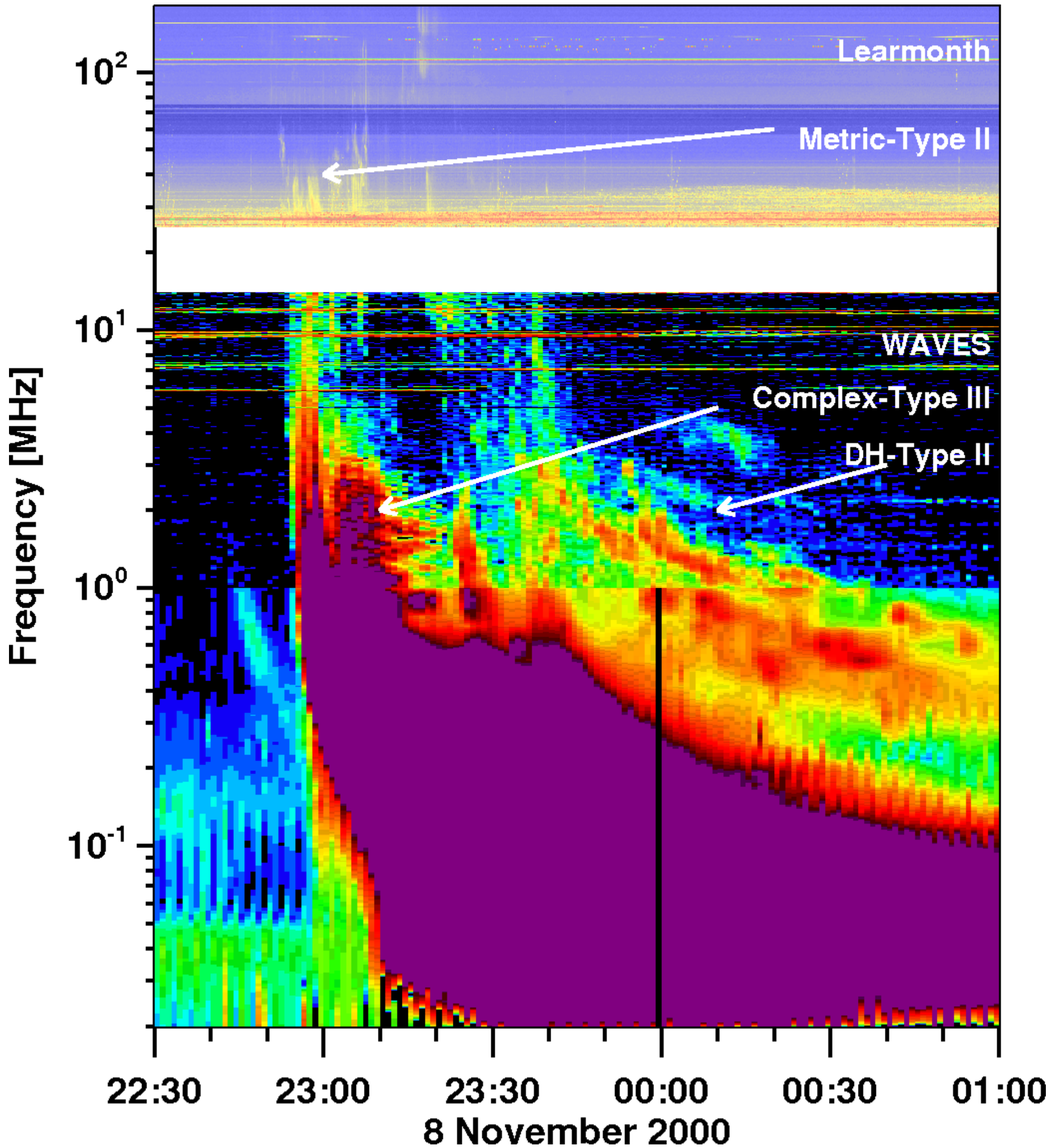


**Figure 6**: Metric Type-II (starting at 40 MHz around 23:05 UT), long-lived DH-Type-II, and complex Type-III bursts associated with the SEP event of 8 November 2000.

Using the m-Type-II onset along with the CME height–time measurements from SOHO/LASCO white light images, we determined the CME height at the time of CME-shock formation to be 3.46 $R_\odot$.

### 3.2.2 Comparison of 8 November 2000 SEP Event with Other Large SEP Events

We compare the 8 November 2000 SEP event with other large SEP events that had a similar or smaller increase in the > 700 MeV proton intensities but had GLEs: GLE56 (2 May 1998), GLE58 (24 August 1998), and GLE63 (26 December 2001). Table 2 summarizes this comparison. Similar to Table 1, the GOES > 700 MeV proton enhancement noted in Table 2 is that taken from the GOES satellite that detected the greatest background-to-peak enhancement (with the time of peak accuracy of five minutes) out of all of the GOES spacecraft that observed a specific event. GLE63 and the 8 November 2000 event are most similar in characteristics. GLE63 and the 8 November 2000 SEP events were associated with M7.1 and M7.4 flares originating at a longitude of W54 and W77 respectively. The associated CMEs also had similar speeds of 1779 km $s^{-1}$ and 1881 km $s^{-1}$. However, the 8 November 2000 large SEP event did not produce a GLE.

**Table 2:** Comparison of the 8 November 2000 SEP event with events that had similar increase in intensity of > 700 MeV protons in GOES but had a GLE.

| Smallest GLEs of Cycles 23 and 24 with > 700 MeV increases | 8 November 2000 | GLE 56 | GLE 58 | GLE 63 | GLE 72 |
|---|---|---|---|---|---|
| Date | 8 November 2000 | 2 May 1998 | 24 August 1998 | 26 December 2001 | 6 January 2014 |
| % Increase | Non-GLE | 11 | 4 | 7 | 2.5 |
| SEP > 10 MeV peak intensity [pfu,] | 14800 | 146 | 187 | 780 | 42 |
| Flare size | M7.4 | X1.1 | X1.0 | M7.1 | Backside |
| Flare time [UT] | 23:04 | 13:31 | 21:50 | 04:32 | 07:30 (backside) |
| Location | N10W77 | S11W15 | N35E09 | N08W54 | W102 |
| CME speed [$kms^{-1}$] | 1881 | 1332 | 1420 | 1779 | 1960 |
| CME first appearance time in LASCO FOV [UT] | 23:06 | 14:06 | LASCO data gap | 05:30 | 08:00 |
| Metric Type-II onset [UT] | 23:15 | 13:41 | 22:02 | 05:12 | 07:48 |
| CME-shock formation height [$R_\odot$] | 3.46 | 1.41 | 1.43 | 1.48 | 1.61 |
| CME height at SPR [$R_\odot$] | N/A | 1.97 | 5.14 | 2.88 | 2.96 |
| GOES > 700 | $9.04 \times 10^{-5}$ | $1.55 \times 10^{-4}$ | $1.47 \times 10^{-4}$ | $1.0 \times 10^{-4}$ | $1.2 \times 10^{-4}$ |

| | | | | | |
|---|---|---|---|---|---|
| MeV Background [pfu] | | | | | |
| GOES > 700 MeV Peak Intensity [pfu] | $2.4x10^{-4}$ | $2.15x10^{-4}$ | $1.99x10^{-4}$ | $2.0x10^{-4}$ | $1.49x10^{-4}$ |
| GOES >700 MeV rise | ≈ 133% | ≈ 39% | ≈ 36% | ≈ 99% | ≈ 24% |

Most of the characteristics were comparable for the GLE and the SEP events in Table 2. Hence, we see that for the 8 November 2000 event all of the ingredients required for a GLE were present, namely a well-connected source, a large flare, a strong shock indicated by a fast CME, a long-lasting Type-II radio emission, and complex Type-III radio emission. However, no GLE was produced. What sets the 8 November 2000 SEP event apart from the rest is that the height of formation of its CME-shock is 3.46 $R_{\odot}$, which is generally greater than CME-shock heights for GLE associated CMEs (the median CME-shock height for the Cycle 23 and 24 GLE-CMEs is ≈1.43 $R_{\odot}$).

### 3.2.3 Importance of CME-Shock Formation Height in the Observation of a GLE

After their formation, the shocks associated with GLE-CMEs typically travel for 2 – 30 minutes, and in some cases up to 40 minutes, before accelerating and releasing the GLE particles (Reames, 2009a, b; Gopalswamy *et al*., 2012). Regardless of their source locations, the CME-shock for all GLEs in Cycles 23 and 24 formed between 1.2 – 1.93 $R_{\odot}$, with the mean and median CME-shock formation heights of 1.45 $R_{\odot}$ and 1.43 $R_{\odot}$ respectively. The CME heights at the time of particle release were found to be between 2 – 6 $R_{\odot}$ for most GLEs and 6 – 8 $R_{\odot}$ for a couple of GLEs. Gopalswamy *et al*. (Figure 2b, 2012) fit a parabola to the CME height at SPR as a function of source longitude. Based on this parabolic fit, for a GLE with a source location of W77 the typical CME-shock height at the SPR time is around 3 $R_{\odot}$. However, the shock for the 8 November 2000 SEP event formed at a height of 3.46 $R_{\odot}$. Therefore, the CME-shock for the 8 November 2000 SEP event formed farther away from the Sun than is typical for shocks driven by GLE-CMEs (Gopalswamy *et al.*, 2013a, b; Thakur *et al*., 2014; Mäkelä *et al*., 2015). If this shock then accelerated GeV particles after traveling for some time, the acceleration site would be at a location that was no longer well connected to Earth for a GLE to be observed by NMs. The shock formation height affects the associated SEP energy spectrum, which in turn affects the production of highest energy SEPs, *i.e.* >700 MeV protons and the resulting GLEs. In addition, because the shock formed farther from the Sun, it is possible that the ambient magnetic field was weaker than that at the typical shock formation height for GLE-CMEs. This might have led to a reduced efficiency of particle acceleration and thus no GLE was observed (Gopalswamy *et al.,* 2014). It is known that SEP events with such large CME heights at shock formation have a soft spectrum, similar to SEP events due to CMEs associated with quiescent-filament eruptions (Gopalswamy et al. 2015).

As the CME-shock travels, it continues to accelerate particles at its nose and flanks, but the GLE particles constitute the first arriving, short-lived, highly anisotropic beam. So if the GeV particles have been accelerated, a GLE is observed by a NM if i) the acceleration site is well connected to Earth and ii) the NM has its asymptotic viewing direction towards the arriving particle beam. Large GLEs can have particle-beam extent wide enough to be observed by several NMs but particle beams for very small GLEs may not have wide-enough extent and hence may be more easily missed.

However, although there was no GLE, the 8 November 2000 SEP event was a large SEP event and GOES did observe > 700 MeV protons. We note that because the GOES >700 MeV proton channels simply integrates the spectrum above 700 MeV, an intensity enhancement can be detected even in the absence of GeV protons, as long as protons of energies even slightly greater than 700 MeV are present in the SEP beam. In addition, it was easier to observe a rise in > 700 MeV proton intensities because the galactic cosmic-ray background was at its minimum (Figure 5c). We also note that at the sea level, the NM responses are typically at their best between 2 – 5 GV rigidities during low solar modulation, corresponding to 1.2 – 4.1 GeV for protons (Clem and Dorman, 2000; Bieber *et al*., 2013b; Mishev, Usoskin, and Kovaltsov, 2013). So if protons of energies only slightly higher than 700 MeV were present, the NMs would not have detected a GLE. However, high-energy particles were definitely accelerated and reached Earth, so it seems more likely that because the CME-shock formed at a greater height, it did not have enough time to accelerate GLE particles when it was well connected to Earth. This would be consistent with the suggestion that the CME-shock nose may be accelerating the GLE particles (Gopalswamy and Mäkelä, 2014; Gopalswamy *et al*., 2014). In this case, a lack of a GLE for the 8 November 2000 SEP event may be explained if the CME-shock nose region was not well connected to Earth when it accelerated the GeV particles. The observation of the > 700 MeV protons was possible because they can be accelerated at regions closer to the shock flanks, parts of which became well connected to Earth later than the shock nose.

### 3.2.4 CME-shock nose connectivity

If the GLE particles are accelerated by the CME-shock-nose, we must examine the connectivity of the shock-nose during the 8 November 2000 SEP event. Recent studies on the latitudinal connectivity of the CME-shock nose to Earth (Gopalswamy *et al.*, 2013a; Gopalswamy and Mäkelä, 2014) have shown that for GLEs it is not only the longitudinal connectivity of the source location that matters, but also its latitudinal connectivity. A survey of Cycle-23 GLEs has shown that GLEs occurred when the nose of the CME-shock was at a latitudinal distance within ± 13.6° (Gopalswamy *et al*., 2013a) from the Ecliptic. The latitudinal connectivity can be determined by taking into account the solar $B_0$ angle, which gives the heliographic latitude of the central point of the solar disk. Variation in $B_0$ during the year represents the fact that the ecliptic plane and Sun's equatorial plane are not aligned. The $B_0$ angle for the 8 November 2000 SEP event is 3.6°N. Using the central position angle, 299° of the associated CME (from the CDAW CME catalog), we determine this

CME to be heading 29° North of the Ecliptic. Thus the nose of the CME-driven shock associated with the 8 November 2000 event was at an ecliptic distance of 29°N – 3.6°N ≈ 25.4°N. This is beyond the average distance of 13.6°, and this large latitudinal distance of the shock nose could explain why such a large, longitudinally well-connected event did not produce a GLE. We note that for GLE58 the flare location was N35W15 and $B_0$ was 7°N, which makes the ecliptic distance 28°N. This is beyond the favorable latitudinal distance for a GLE, but a large polar coronal hole was located immediately to the North of the CME source region and deflected the CME towards the Ecliptic, and thus a GLE was observed (Gopalswamy and Mäkelä 2014). On the other hand, there was no large polar coronal hole at the time of the 8 November 2000 SEP event to deflect the CME closer to the Ecliptic.

### 3.2.5 Energy Spectrum at the Time of Maximum

Due to its similarities with the characteristics of GLEs, we compared the proton-energy spectrum of the 8 November 2000 SEP event with the GLEs of 14 July 2000 (GLE59) and 4 November 2001 (GLE62) as shown in Figure 7. Although we compared the proton energy spectrum at the time of maximum for the 8 November 2000 SEP event with those of all the GLEs of Cycles 23 and 24, only the spectra of GLE59 and GLE62 are shown here because their SEP peak flux for GOES > 10 MeV protons was closest to that of the 8 November 2000 SEP event. The peak flux of the > 10 MeV protons in the 8 November 2000 SEP event was 14, 800 pfu, making it the only non-GLE event in Solar Cycles 23 and 24 with > 10 MeV proton peak flux > 5000 pfu. This peak flux is actually greater than that for most GLEs. The peak flux for GLE59 and GLE62 were 24, 000 pfu and 31, 000 pfu respectively. The spectra shown here were derived using proton measurements from GOES differential energy channels. We used GOES calibrations of Sandberg *et al* (2014) for GOES proton data. The solid lines correspond to spectral fits in the form $dF/dE = CE^{-\gamma}$ between 50-700 MeV. The spectrum of the 8 November 2000 SEP event is similar to those of GLEs with

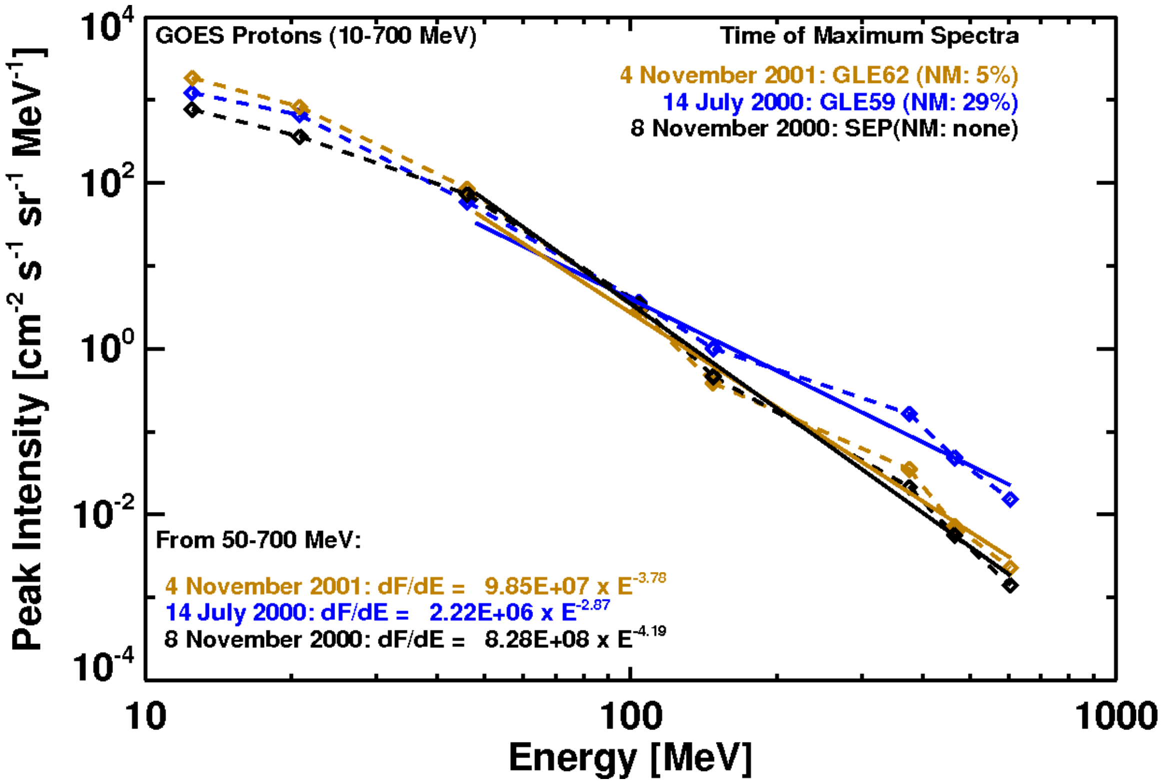


**Figure 7**: The energy spectrum at the time-of-maximum for the 8 November 2000 SEP event. Overlapped are the time-of-maximum spectra for GLE59 and GLE62. The 8 November 2000 spectrum is similar to those of GLEs.. The solid lines show fit to the data from 50–700 MeV. The three spectra are comparable. At higher energies, the 8 November 2000 SEP spectrum is similar to that of GLE62 but steeper than GLE59.

## 4. Summary and Conclusions

We surveyed all of the large SEP events and GLEs of Cycles 23 and 24 to confirm that a discernible signal in the GOES > 700 MeV proton channel is indicative of GLE events.

Although our survey included large SEP events from only Cycles 23 and 24, the association between the observation of GLEs and GOES >700 MeV protons should also apply to large SEP events and GLEs of all solar cycles in general. This is confirmed by the fact that clear flux enhancements are observed in the >685 MeV channel of earlier GOES satellites for the few GLEs we examined from solar Cycle 22. Because the studied GLEs included some of the smallest GLEs of Cycles 22-24, it is reasonable to expect that GOES >685 MeV and >700 MeV proton channels recorded bigger GLEs too.

We confirm that GOES can be used as an indicator of GLEs for all GLEs except for the rare very small GLEs occurring when the galactic cosmic-ray background is elevated (*e.g.* GLE57), or other exceptional events such as the 8 November 2000 SEP event. Use of GOES as a GLE indicator becomes especially important because a small GLE may be missed by NMs due to the narrowness of GLE beams. The high-energy particles from such small events can also enter Earth's atmosphere and affect the space weather. In addition, GOES measurements are preferable due to better energy resolution and measurement of spectra whereas NMs detect GLEs only as threshold detectors and their spectra are complex.

The main conclusions of our work are as follows:

(i) We confirm that GLEs are typically associated with an intensity enhancement in the GOES > 700 MeV proton channel. All GLEs in Cycles 23-24 but one (GLE57: 6 May 1998) produced a discernible enhancement in the intensity of > 700 MeV protons in GOES.

(ii) All of the large SEP events that had produced an enhancement of GOES > 700 MeV proton intensity also had GLEs. The only exception was the major, longitudinally well-connected SEP event of 8 November 2000.

(iii) GLE57 compares well with similar, small GLEs in terms of % increase, flare sizes, CME speeds, CME heights at the times of shock formation, and solar particle release. Based on our analysis, we suggest that a combination of effects may have contributed to the lack of observed enhancement in the GOES > 700 MeV proton channel for GLE57:

   a. GOES > 700 MeV background was elevated to near its maximum due to low solar modulation as the solar cycle was near its minimum. Although GLE57, a small GLE, appears to have produced a small spike in the > 700 MeV proton intensities, this enhancement was not discernible above the already increased background. This enhancement might have been observed had the background been lower.
   b. The > 700 MeV background was fluctuating during this period, and this may have affected the observation of any small rise in intensities.
   c. Particle deflecting disturbances were present near Earth, as is evident from the observed small Forbush decrease where the particle intensities were affected even at the neutron monitor energies. Therefore, if any small intensity enhancement was present, such disturbances might have suppressed the enhancement even further.

(iv) The characteristics of the 8 November 2000 SEP event (source location, CME speeds, GOES >700 MeV proton enhancement etc.) suggest that this could have been a GLE but it was not. Most likely, protons of energies only slightly above 700 MeV were present and were not of GeV energies to be observed as a GLE. Our possible explanations as to why this was not a GLE are:

   a. The CME–shock formed at a height of 3.46 $R_\odot$, which is much greater than typical height of shocks (median height ≈ 1.43 $R_\odot$) for GLE-CMEs. The shock did not have enough time to accelerate GeV particles at locations that would be well connected to Earth.
   b. Due to a greater height at its formation, the shock may have formed at lower ambient magnetic field than is typical for GLE-CME-shocks. This

might have led to a reduced efficiency of particle acceleration and thus no GLE was observed.

c. The time-of-maximum energy spectrum (from GOES), for the 8 November 2000 SEP event, is similar to those of GLEs, although there is a clear indication that the spectrum seems to be steepening at high energies for the non-GLE event.
d. The nose of the CME-driven shock was at an ecliptic distance of 26°N, which is beyond the ecliptic distance of ± 13.6° that has been typically favored by the nose of GLE–CME-shocks (Gopalswamy *et al*., 2013a).
e. Incidentally, the discussion d) above also argues in favor of the suggestion that the first-arriving, anisotropic, highest-energy GLE particles may be getting accelerated at the nose of CME-driven shock. And that is why, although no GLE was observed, GOES detected the > 700 MeV protons, which might have come from the regions closer to the flanks of the shock.

All of these factors resulted in a spectrum that was steeper above 700 MeV, so the 8 November 2000 event was observed by GOES but was missed by NMs because NMs are most sensitive at a higher energy.

(v) Therefore, the relation between the observation of GLEs and > 700 MeV protons in GOES holds good for all large SEP events of Cycles 23 and 24.

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**Disclosure of Potential Conflicts of Interest**
The authors declare that they have no conflicts of interest.

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