Forecasting Solar Energetic Particle Events and Associated False Alarms

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Abstract. Because of the significant dangers they pose, accurate forecasting of Solar Energetic Particle (SEP) events is vital. Whilst it has long been known that SEP-production is associated with high-energy solar events, forecasting algorithms based upon the observation of these types of solar event suffer from high false alarm rates. Here we analyse the parameters of 4 very high energy solar events which were false alarms, with a view to reaching an understanding as to why SEPs were not detected at Earth. We find that in each case at least two factors were present which have been shown to be detrimental to SEP production.

Keywords. Sun: flares, coronal mass ejections, particle emission

1. Introduction

Solar Energetic Particles (SEPs) are a significant component of space weather. They may damage satellites, pose a radiation hazard to astronauts and humans in high-flying aircraft (particularly at high latitudes), and interfere with high-frequency communications' systems (Desai & Giacalone 2016). Therefore, accurately forecasting their arrival at Earth has become vital.

It has long been known that the detection of SEPs at Earth is associated with solar flares which exhibit high emission in soft X-rays (SXR) and fast Coronal Mass Ejections (CMEs) (*e.g.* Dierckxsens *et al.* 2015). The difficulty for SEP forecasting algorithms is, however, that SEPs are not detected at Earth following all such large solar events. For example, Klein *et al.* 2011 investigated all X class flares between longitudes W0° and W90° in the period 1996 to 2006, and found that 30% did not produce an enhancement of >10 MeV protons above the background level.

Figure 1 shows two plots of proton intensity as measured by the ∼40-80 MeV energy channel of the Geostationary Orbital Environmental Satellites' (GOES) Energetic Particle Sensor (EPS) instruments (Onsager *et al.* 1996). In Figure 1a, a steep rise is seen following a magnetically well-connected large solar event which occurred on 17 May 2012 as may be expected; by contrast Figure 1b shows that a similar large event which occurred on 18 March 2003 produced no rise at all. Such an event, which might reasonably have been expected to produce SEPs at Earth, may be termed a "false alarm". Here we examine 4 sample false alarm events with a view to determining why they failed to produce SEPs at Earth.

2. False alarms for simple forecasting algorithms

In Swalwell *et al.* 2017 we defined two simple SEP forecasting algorithms: the first, A.1, is based upon the observation of magnetically well-connected CMEs with a speed reported by the CDAW catalogue (Gopalswamy *et al.* 2009) to be greater than 1500 km/s
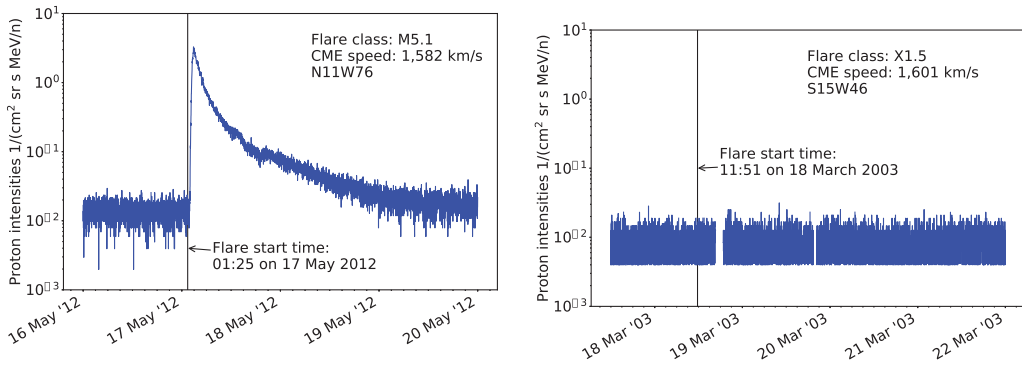
(a) A steep rise in energetic proton intensity is seen following a magnetically well-connected M5.1 large solar event.

(b) A similarly large solar event produced no rise in energetic proton intensity. This event may be termed a "false alarm".

Figure 1. A comparison of 40-80 MeV proton intensity following two different magnetically-well-connected large solar events.

("fast CMEs"); the second, A.2, is based upon the observation of well-connected flares of class X. We compared the forecasts of each with historical data sets between January 1996 and March 2013.

Algorithm A.1 had a lower false alarm rate (28.8%) than A.2 (50.6%) but both missed a significant number of SEP events (53.2% and 50.6% respectively). We determined that an algorithm which was based upon the parameters of both CMEs and flares produced better results than one based upon the observation of only one type of solar event.

We identified a number of factors which are important to SEP production. Fast CMEs were less likely to produce SEPs if they were associated with a flare of class <M3, if their associated flare was of relatively short duration ($< \sim 30$ minutes), and if they were not reported to be a halo. X class flares were less likely to produce SEPs if either they were not associated with a CME or were associated with a CME slower than 500 km/s, and if they were of relatively short duration ($< \sim 30$ minutes) (Swalwell *et al.* 2017).

3. Examples of false alarm events

Table 1 gives four examples of high-energy solar events which were expected to produce SEPs at Earth, but which failed to do so. Examination of some of their parameters sheds some light on why they resulted in false alarms.

3.1. *Event 1: 1,813 km/s CME from N24W35 on 6 Jan 2000*

This was a very well magnetically-connected, very fast, CME. However, it was associated with a flare which was both short (~ 21 minutes) and of relatively low class (C5.8). Furthermore, the angular width of the CME was also reported by CDAW to be small ($67°$).

3.2. *Event 2: X6.2 flare at N16E09 on 13 Dec 2001*

The event originated from the edge of the best magnetically-connected region, and included a large flare which was expected to produce at least some enhancement in energetic protons. The fact that it did not may be due to two parameters: (a) the CME was of

Table 1. Example false alarms.

Event no	Date	Event	Coordinates
1	6 Jan 2000	CME speed 1813 km/s	N24W35
2	13 Dec 2001	X6.2 flare	N16E09
3	3 Jul 2002	X1.5 flare	S20W51
4	18 Mar 2003	X1.5 flare associated with CME speed 1601 km/s	S15W46

relatively low speed (reported by CDAW to be 864 km/s), and (b) the flare was of very short duration ($\sim$15 minutes).

3.3. *Event 3: X1.5 flare at S20W51 on 3 Jul 2002*

This very well magnetically-connected flare was associated with a very slow (265 km/s) non-halo (width 261°) CME, and was of very short duration ($\sim$8 minutes).

3.4. *Event 4: X1.5 flare with 1601 km/s CME from S15W46 on 18 Mar 2003*

This is the event for which the energetic proton intensity is shown in Figure 1b. It was extremely well magnetically-connected to Earth, and in this instance both the flare class and CME speed were high. Flare duration, however, was relatively short (at $\sim$ 29 minutes) and the CME was reported by CDAW to have an angular width of 263°.

4. Conclusions

Some very high-energy solar events may fail to produce SEPs at Earth even if they are very well magnetically-connected. Understanding why such events are false alarms may provide an insight as to which of their associated parameters are important for SEP production.

Swalwell *et al.* 2017 reported that fast CMEs associated with flares of class <M3 or of relatively short duration (<$\sim$ 30 minutes), and fast CMEs which were not reported to be a halo were more likely to be false alarms. X class flares not associated with a CME, or associated with a CME slower than 500 km/s were more likely to be false alarms, as were those of relatively short duration.

Here we considered 4 sample false alarms. In each case 2 or more of the factors which were found to be detrimental to SEP production by Swalwell *et al.* (2017) were found to exist. In event number 1 there were 3: the associated flare was relatively short ($\sim$21 minutes); it was of class <M3 (C5.8); and the CME was not a halo (the width was 67°).

Event number 2 was a poorly magnetically-connected flare (from E09) but at X6.2 it was very intense; Event 3 was a lower class flare (albeit still large at X1.5) but very well connected. Neither produced SEPs but both had factors likely to result in a false alarm: each flare was short ($\sim$15 minutes and $\sim$8 minutes respectively), and each was associated with a CME of relatively low speed (864 km/s and 265 km/s respectively); and in the case of event 3, the associated CME was not a halo.

Event number 4 illustrates that even a fast CME associated with a high intensity flare may sometimes be a false alarm. In this case, too, however the fact that the CME was not a halo and the short duration of the flare may explain why SEPs were not detected.

The full results and a more detailed analysis are presented in Swalwell *et al.* 2017.

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