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Key Points:

- Extreme solar events have travel times that form families
- The fastest events over the flare site arrive in as short as 13 h
- The August 1972 event was faster and probably stronger than the Carrington event

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Travel time classification of extreme solar events: Two families and an outlier

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Abstract Extreme solar events are of great interest because of the extensive damage that could be experienced by technological systems such as electrical transformers during such periods. In studying geophysical phenomena, it is helpful to have a quantitative measure of event strength so that similar events can be intercompared. Such a measure also allows the calculation of the occurrence rates of events with varying strength. We use historical fast travel time solar events to develop a measure of strength based on the Sun-Earth trip time. We find that these fast events can be grouped into two distinct families with one even faster outlier. That outlier is not the Carrington event of 1859 but the extremely intense solar particle event of August 1972.

1. Introduction

The field of space weather began on 1 September 1859, when a white light solar flare occurred on the Sun followed by a sudden commencement 17.6 h after the flare [*Stewart*, 1861; *Cliver and Svalgaard*, 2004]. The strength of this event has reached mythical proportions with a *National Research Council* [2008] estimating that if the Carrington event occurred today, the recovery from the event would cost $1–2 trillion. This estimate of course depends on the actual intensity of the particle fluxes during the Carrington event. While fluxes are perhaps the best indicator of the strength of the solar events, along with the solar wind pressure and interplanetary magnetic field direction and strength, they remain unknown.

For most of the events since 1859, all we have available is the onset of the flare and the time of arrival of the compression of the magnetopause when the expelled plasma reached the Earth. *Cliver et al*. [1990] and later *Cliver and Svalgaard* [2004] compiled lists of the fastest solar events to reach Earth. With the one exception of the Carrington event in 1859, these events span the period from 1938 to 2003. It would be informative to understand if any of these events, especially those with energetic particle measurements in and outside the magnetosphere, were similar in strength to the Carrington event, and if so, to deduce their frequency of occurrence. Furthermore, it would be of interest to determine what properties any comparable events had so we might better understand the conditions that led to the phenomena associated with the Carrington event.

2. Comparing the Different Events

For each of the events in Cliver's lists, we have the location of the flare relative to the sub-Earth point on the Sun and the travel time to Earth. Often the time of the flare can be determined from the same magnetogram as recorded the compression of the magnetic field. This is shown in Figure 1. The crochet or sudden ionospheric disturbance just after 1100 UT on 1 September 1859 is caused by the energetic photons from the flare reaching the Earth's atmosphere enhancing the electrical conductivity, and hence the current since we do not expect the voltage in the ionosphere to be affected by the photons. At 0500 UT the next day, a geomagnetic storm began when the ejected solar wind plasma reached the Earth.

For our comparison, we take the Carrington event and the 11 post-1938 events of *Cliver and Svalgaard* [2004] and add information for the 20 October 1989 event and the STEREO A detected event on 23 July 2012 [*Russell et al*., 2013]. In Figure 2, we plot the transit times for each event corrected to their arrival at 1 AU, and not necessarily at Earth that is only at 1 AU twice a year, versus the observer-flare angle. Thus, these transit times differ slightly from those in the original source. We have fit two straight lines to this plot because the data points appeared to lie on two straight lines. One event, the August 1972 event, exceeds the speeds of the other events by a wide margin. The slopes of the two lines are the same within statistical error. We use the average slope to draw a third line through the August 1972 event and estimate its travel time right above the flare to be close to 13 h.

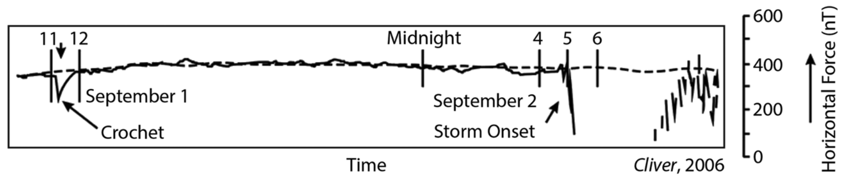

Figure 1. Magnetogram (adapted from *Cliver* [2006]) of the horizontal component of the magnetic field obtained by *Stewart* [1861] in London in 1859. Dashed line represents the quiet day variation.

We know of no prediction that solar energetic events would fall into discrete classes of strength (as measured by arrival time) and know of no obvious reason for this behavior. It suggests that the energy storage that precedes the event can accumulate in discrete configurations, each of which can store a particular total energy. The configuration that stored the greatest energy has been achieved least often during our study period.

3. Comparisons of Particles and Fields During These Events

Useful diagnostic solar wind data on these super events exist only during the 1989 and 2012 events. While energetic particle data are available in 1972, monitors of the interplanetary data useful for space weather purposes were not available. In the 2003 events, the solar wind data are not available, and the energetic particle data are available only in a restricted energy range. Figure 3 shows, for the 23 July 2012 event detected by STEREO A for the 3 days around the arrival at 1 AU, the pressure in the solar wind contributed by the magnetic field (thick line) and the pressure contributed in three energy ranges of energetic particle fluxes and their total pressure. Generally, the magnetic energy density (i.e., pressure) dominates that of the energetic particles so that the particles are guided by the magnetic field. This is true until about 0900 UT on 23 July when the particle energy density equals the magnetic field energy density. During this following period, the sound speed in the plasma is being determined by the temperature of the energetic plasma and not the lower energy solar wind plasma. Thus, the solar wind and energetic plasma can behave subsonically, and when the compressional wave arrives from the Sun at about 1900 UT, the plasma density increase (seen here as a pressure increase in energetic particles) is accompanied by a magnetic field decrease. This is not a fast mode compression where the plasma and field both increase, but a slow-mode wave [*Russell et al.*, 2013]. At about 2300 UT, the STEREO spacecraft encounters the giant magnetic cloud launched from the Sun which then dynamically controls the energetic particles and plasma for the rest of the event. The duration and speed of the interplanetary coronal mass ejection and the very strong magnetic field >100 nT indicate that an unusually high magnetic flux was carried away from the Sun in the event.

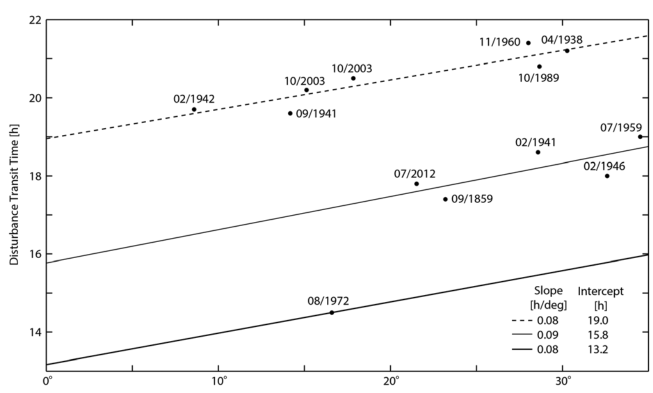

Figure 2. Transit time from the Sun to 1 AU for the 12 fastest events since 1938, plus the Carrington event of 1859 plotted versus the angle between the flare site and the observer. The two events in 2003 occurred on 28 October and 29 October.

Figure 4 compares data obtained in the 1989 event (adapted from *Lario and Decker* [2002]) and the 2012 event [*Russell et al.*, 2013]. The GOES data are obtained at geosynchronous orbit. IMP-8 is in the solar wind. There appears to be a weak shock in the solar wind at about 0900 on October 20. This is similar to one on STEREO in 2012 at around 1700 UT. This behavior is suggestive of a generally subsonic flow close to Mach 1, pushing its way through the preexisting solar wind. In both cases when the compressional front arrives, the magnetic field drops as the energetic particle flux increases (at line 2 in both panels). Then the magnetic field and the velocity jump (at line 3). We note one

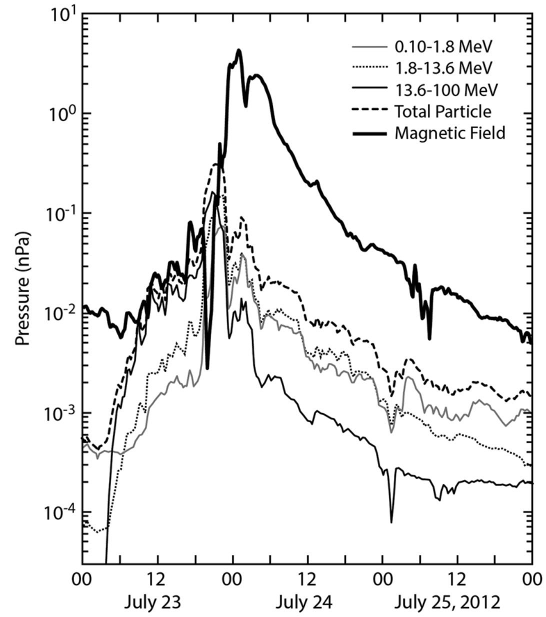

Figure 3. The pressure/energy density in the magnetic field and in three energy ranges of energetic particles (and their total) during the 23 July 2012 solar event at STEREO A 22° away from the center of the flare [after *Russell et al*., 2013].

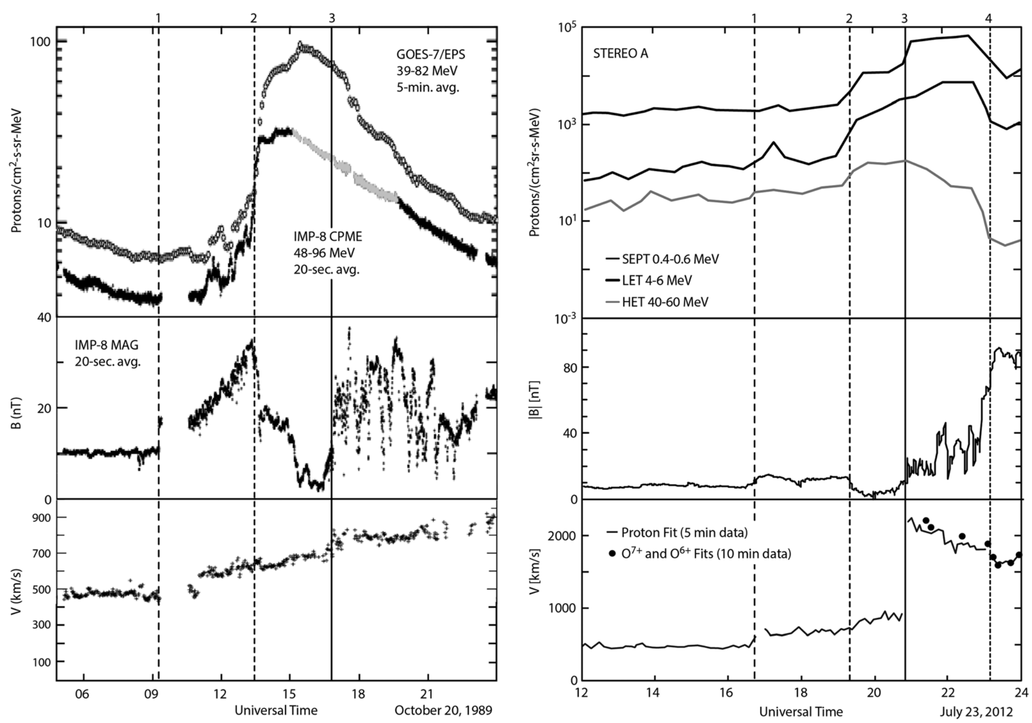

Figure 4. (left) Energetic particle fluxes on 20 October 1989 GOES-7 and IMP-8 with the IMP-8 interplanetary magnetic field and plasma velocity [*Lario and Decker*, 2002]. (right) Energetic particle data on 23 July 2012 from STEREO A [after *Russell et al*., 2013]. Line 1 marks a compression of the magnetic field and solar wind velocity increase; line 2 marks the arrival of the compression of the particle fluxes and entry of a slow-mode wave; line 3 marks a fast-mode shock and velocity jump while line 4 marks the entry of the spacecraft into the magnetic cloud.

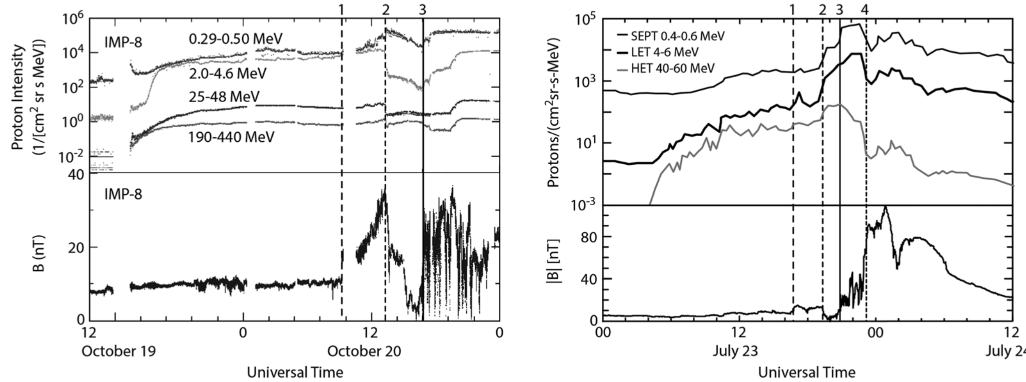

Figure 5. (left) IMP energetic particle fluxes and magnetic field strength obtained from NASA website. (right) STEREO energetic particle fluxes and magnetic field strength [after *Russell et al.*, 2013]. Lines are the same as marked in Figure 4.

important difference between the 1989 and 2012 events. In the 1989 event, the Earth does not appear to have entered the magnetic cloud ejected during the eruption, while in 2012 STEREO A clearly entered the cloud. This is most probably due to the 10° greater subobserver angle of the Earth in the 1989 event.

One final comparison we can make between the 1989 event and the 2012 event is the apparent streaming limit in the particle fluxes prior to the arrival of the magnetic clouds. Figure 5 shows the proton intensity seen at IMP-8 and STEREO A prior to the arrivals of the compression. In both cases, a maximum flux is approached by the particle fluxes which appear to be qualitatively in accord with the streaming limit predicted by *Reames and Ng* [1998].

4. Summary and Conclusions

Some solar eruptions eject a magnetic cloud that reaches 1 AU in less than 24 h. The time of arrival of these events at 1 AU does not appear to form a continuum, but rather there are two families of events, plus an outlier in 1972 that arrived at 1 AU in about 13 h. Using the same slopes to extrapolate the two families to the point above the flare site, we find that those that arrive at 1 AU above the flare site do so in about 19 h and about 16 h. The number of these events is about once a decade for the slower, more numerous class and about once every 20 years for the faster, less numerous class. We have no idea how often events the strength of the 1972 event occurs other than one occurred in the 76 years examined. There are few in situ particles and field data available for those superfast events. There are only two events that can be compared other than by arrival time. They do appear to be similar once their different locations relative to the flare site are noted. The solar wind becomes subsonic before the arrival of the shock because the hot ions in front of the shock raise the sound speed in the plasma and drop the magnetosonic Mach number below unity [*Russell et al.*, 2013]. The occurrence of these families, rather than a continuum of arrival times, is very unexpected. It suggests that there are different configurations of the magnetic stresses leading to the eruptions. The most intense (fastest) event is the rarest type of event, suggesting that the configuration of stresses that leads to such an eruption is the most difficult to construct.

It is impossible to tell if there is a yet more powerful configuration of magnetic fields that the Sun achieves once every century or more, but if the fastest event seen to date is indeed the maximum strength event, then we have a 13 h period from the time of the eruption to when the most intense particle fluxes appear at 1 AU. This duration would allow astronauts on the surface of the Moon to take cover if a shelter were available for them to enter during hazardous times, but would not be of assistance during transit to or from the Moon without shelter [*Townsend et al.*, 1991].

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