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Carrington Class Solar Events and How to Recognize Them

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Abstract. The so-called Carrington Event on September 1, 1859, is clearly the solar outburst that brought the realization to the inhabitants of Earth that weather existed in space, and that space weather was important to the rapidly developing technological infrastructure on Earth. It is important to understand not only how space weather affects our technological systems, but like the case of atmospheric weather, the possible intensity of such weather, the frequency of extreme events, and how to predict them. This paper reviews what we know about one class of extreme space weather events, the superfast arrival events, how best to compare them given our limited diagnostics in past events and even at the current time, and suggests a direction for progress in this field.

1. Introduction

The work featured at this conference largely focused on other stars and planetary systems, but we know much more about our local conditions—at least in the present epoch—from relatively close-up, comprehensive observations over decades. In living around our own active star, the Sun, we have learned much about how the Sun works and its many and varied impacts on the planets of this solar system. Here we take a brief look at a topic of growing interest in light of the observations of superflares on sun-like stars, and of ongoing efforts to predict extreme solar events and their effects on the Earth.

By the middle of the nineteenth century, the solar cycle had been studied for approximately 250 years, and its average properties were well determined. However, we had no realization that there were connections between the Sun and the Earth by any mechanisms than through light and heat. Furthermore, during these times, it was relatively unimportant that there were sunspot cycles, solar storms and space weather, because civilizations were not sensitive to these variations. The industrial revolution brought new technology with new requirements to humankind, and they became dependent upon this technology with its attendant risks. The Carrington Event on September 1, 1859 (Carrington, 1859), brought about the realizations that the Sun was violently unstable at times and that this violence could be sensed on Earth with its new electrical distribution systems. Since that time, the reputation of the Carrington event has reached mythic proportions as possibly the greatest solar event of recorded history, far outstripping present-day activity. If we are to both evaluate the magnitude of the Carrington event compared to major events of the space age, as well as the likelihood of such events occurring in the future, we need to use a method of classifying these rare, large events by some measure of size available at the time. However, first we quickly review the

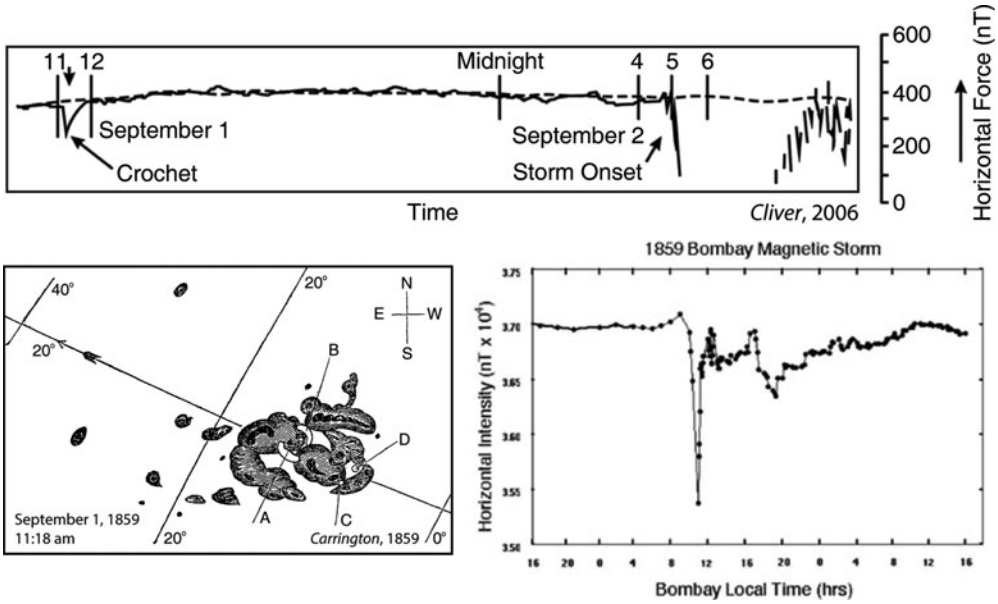

Figure 1. Top panel. Horizontal components of the magnetic field measured in London, England, on September 1 and 2, 1859 (Carrington, 1859). Bottom left panel. The solar flare seen on the Sun at the beginning of the September 1, 1989 event. Bottom right panel. The temporal behavior of the horizontal component of the magnetic field near the equatorial electrojet during the period of the Carrington event. (Tsurutani *et al.*, 2003)

Carrington Event itself to separate fact from fiction regarding what occurred at that time, based on what we know about the physics of the Sun-Earth connection.

2. The Carrington Event of September 1, 1859

The Earth's magnetosphere is a very good monitor of the solar wind, and the ionosphere is quite sensitive to changes in solar x-rays and extreme ultraviolet emissions. The pressure of the outflowing solar wind pushes on the Earth's magnetic field, shaping it into its characteristic teardrop shape with a long geomagnetic tail. When the outward (from the Sun) dynamic pressure of the solar wind increases, the magnetic field in the magnetosphere is compressed. This can be measured on the surface of the Earth. The magnetic field expelled by the Sun in such an outburst can interact with the Earth's magnetic field through a process known as reconnection in which the momentum in the solar wind is transferred to the magnetosphere pulling on it. For the nearly dipolar field of Earth, the reconnection efficiency is highest for interplanetary fields with a large southward component. It is this momentum transfer that produces the most dramatic (for those on the surface of the Earth) effects of the space weather storms: the auroras, the ring current or energetic plasma content of the magnetosphere, and the radiation belts.

The effect of the Carrington Event at the Earth's surface was recorded in the ground based magnetic field measurements shown in Figure 1 -, including the magnetic record obtained in London, England, on September 1, 1859, by Carrington. The lower panel shows a sketch of the magnetic complex observed on the surface of the Sun that was either illuminated by the solar flare or erupted as part of the flare. We know from the magnetic record when the flare occurred as it left its mark in the ionosphere almost immediately as the energetic solar photons hit the Earth's atmosphere and ionized it. The ionosphere is constantly in motion, and this motion creates an electric field. When the photons hit

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the ionosphere, it became more electrically conducting, creating a larger current than what previously existed which then decayed as the solar photon flux declined. Later another electric current appeared. We now interpret this second event as the arrival of the solar plasma that erupted with the flare, but traveled far more slowly (even at an inferred 1000s of km/s) than the speed of light. While this impact initially produced a brief increase in the magnetic field on the surface of the Earth via compression, its longer term effect was to weaken the Earth's field by inflating it with energetic plasma.

Since the solar observatory where the flare was observed was near the magnetic observatory, the scientists involved could communicate easily and quickly confirm that the two events were associated, and the field of space weather was born.

Clearly this was the first widely recognized space weather event, but was it the greatest of all time (or even since 1859)? There are several ways to characterize the Carrington event in retrospect. The first would be the initial compression of the magnetosphere, the sudden impulse or sudden compression as it is called. This is not possible from the available information. Another way would be to look at the depression of the Earth's magnetic field after the arrival of the plasma. However, the depth of that depression is not well resolved, and its the duration is also shorter than one would expect. Perhaps changes in the solar wind counteracted the effect of the plasma injection. The only measure we can reliably trust is the timing. We know when the event began and when it reached Earth, so we can deduce the average speed of the erupted material. Simultaneous records also exist near the Earth's magnetic equator. This region is sensitive to changes in the circulation of the ionospheric plasma, and due to an effect called Cowling conductivity causes a narrow but strong current along the magnetic equator known as the equatorial electrojet. Also recorded at Bombay (now Mumbai) was a very short but intense drop in the magnetic field strength near the equator. Its suddenness indicates that it was not an increase in the ring current caused by an injection of hot plasma deep into the magnetosphere, so this does not represent an extreme value of the Dst index, rather a healthy equatorial electrojet, responding to increased electric fields associated with the arrival of the plasma from the Sun.

One important additional aspect of these events that we have not mentioned until now is the accompanying generation of enhanced fluxes of solar energetic particles, accelerated either at the flare site, or by the shock wave that precedes the erupted plasma as it travels outward, or both. We now know that solar flares can produce intense bursts of 100s of keV to 100s of MeV protons and electrons that are dangerous to living organisms. We only recently have been able to monitor these properly and our records are still spotty. However, as discussed below, this energetic particle contribution to the solar wind seems to play a special role in the coronal and interplanetary propagation and evolution of extreme events like the Carrington event.

3. The Speed of Solar Initiated Disturbances

It is instructive to compare the speeds of modern events with historical ones. Cliver and Svalgaard (2004) provide a list of the fastest events between 1938 and 2003. We add two more: October 19, 1989, and July 23, 2012, as well as the 1859 Carrington event. In calculating an event speed, we must recognize that the speed will vary with angle away from the flare site. The strongest force will be upward along the line joining the center of the Sun to the flare site. Much weaker forces will extend horizontally from the flare site, tangential to the solar surface.

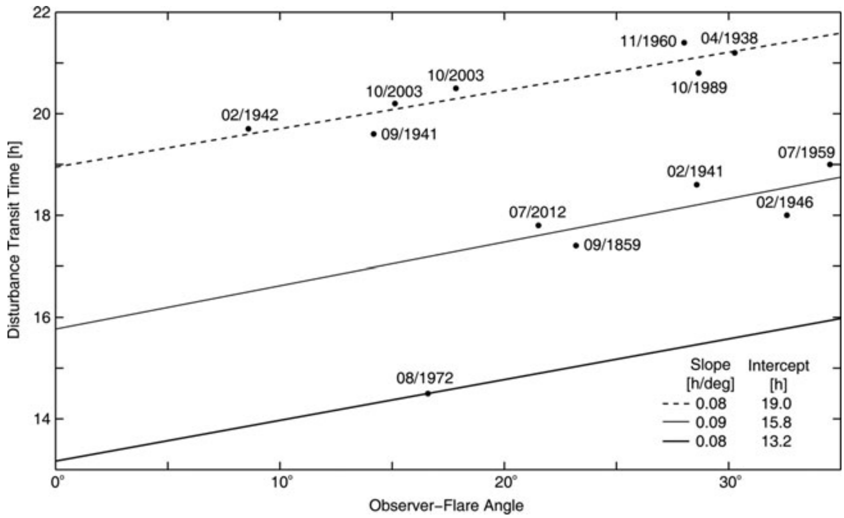

Figure 2. Travel time of the solar disturbance to one AU from the flare site for all reported fast events since 1938, plus the Carrington event. Plotted versus the angle between the flare site and the observer (Freed and Russell, 2014).

Because results from recent missions have shown that large events appear to expand outward self-similarly from the flare site, we can empirically determine the velocity angular dependence by simply plotting the transit times versus angle from the flare site, as shown in Figure 2. These can be viewed as defining three distinct sets of events. The slowest consist of the seven events near the top of this figure. This set includes the two "Halloween events" in 2003 and another modern event for which we have in situ data in 10/1989. These events would have caused disturbances at Earth in 19 hours if the Earth were directly over the flare site.

The middle line shows five faster events lying on a line with the same slope as the slower seven above. This includes the Carrington event and an extreme modern event in July 2012, which we will call the STEREO event. The twin STEREO spacecraft are in solar orbit at 1 AU. The STEREO event erupted plasma appears to have made a direct hit on the STEREO Ahead (-A) spacecraft, providing an extraordinary data set from which to reconstruct solar cause and 1 AU effects.However, although they arewell instrumented for interplanetary and solar studies, these observations cannot tell us what would have happened had this hit the Earth's magnetosphere.

The third event is the fastest of all. It of course cannot definea slope by itself, so we have used the slope that was appropriate for the other 12 events. This event occurred between the Apollo 16 and 17 moon landings. In this case the related energetic particle flux was so intense that some have speculated that the astronauts would have been harmed by this event had it occurred while they were on the surface of the Moon. It is not evident how these events are connected to the magnetic solar cycle as the STEREO event occurred during the current lull in solar activity (Russell *et al.*, 2013) that appears to be as deep as the lull during the Dalton minimum 200 years ago. Assuming symmetry around the radial axis through the flare site, fitting the arrival time versus angle from that axis gives the shapes seen in Figure 3.

4. The Ejected Particles and Plasma

With these rare events, the data are not usually sufficient to perform convincing statistical studies of their properties but what data we do have is very interesting. Figure

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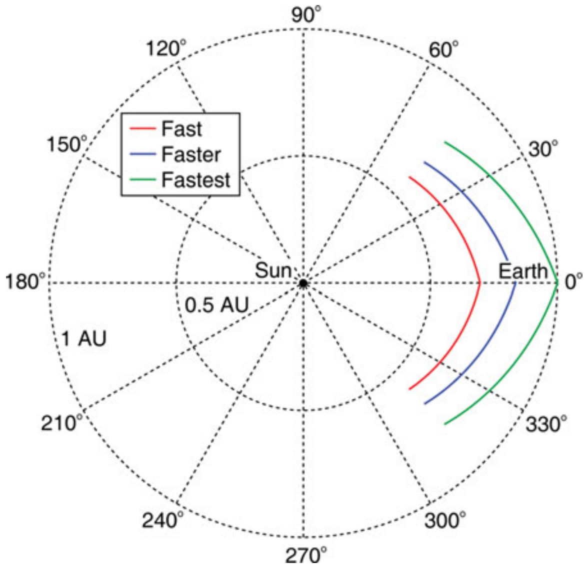

Figure 3. The inferred shapes of the expanding blast wave from the solar flare site (Freed and Russell, 2014).

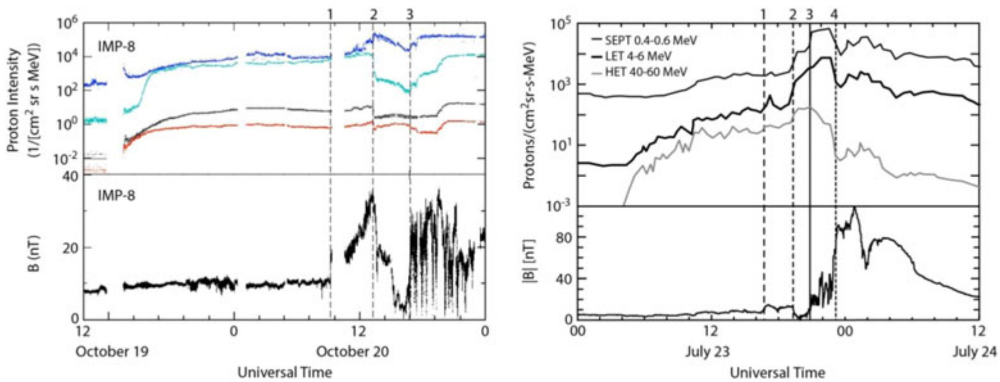

Figure 4. (Left) Measurements of the magnetic field strength and the energetic proton flux from the IMPS spacecraft on October 19–20, 1989, and (right) the STEREO A spacecraft during the July 23–24, 2012 event (Freed and Russell, 2014).

4 shows the in-situ energetic particle and magnetic field data from two of the extreme events. The solar wind becomes filled with highly-energetic, relativistic particles immediately, and they determine the temperature of the solar wind plasma. The solar wind continues to flow outward, but the high thermal speed of the particles in the event causes phenomena to occur at speeds less than that of the fast magnetosonic mode. In other words, these superfast disturbances from the Sun are traveling at subsonic speeds. So when the magnetic flux rope (ICME) arrives, it compresses the plasma in front of it, not as a fast-mode wave, but as a slow magnetosonic wave. Thus, the density of the solar wind plasma increases as it usually does across the compression front, but the magnetic field decreases as shown by the data between vertical line 2 and 3 on the panels of Figure 4. The 2012 STEREO event is accompanied by a very large magnetic cloud, while a strong magnetic cloud is not as evident in the weaker 1989 event. Figure 5 compares the plasma and magnetic pressures in the STEREO event directly. Until the magnetic cloud

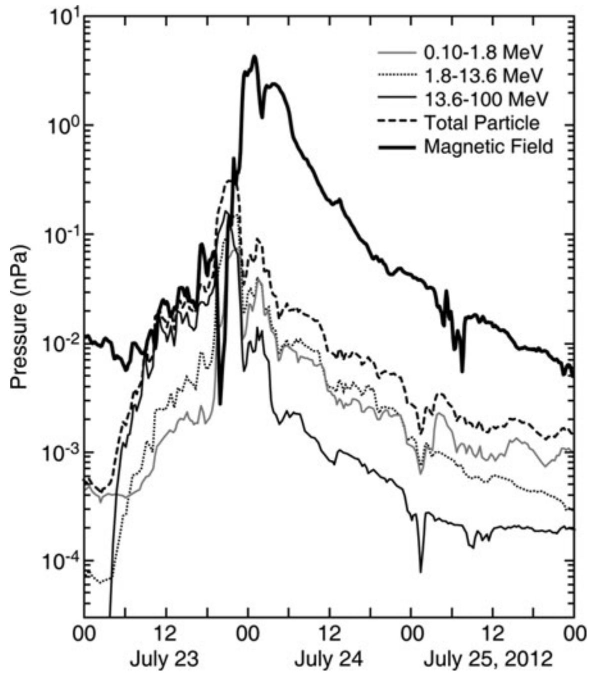

Figure 5. The pressure in the proton fluxes (gray lines) and in the magnetic field (black line) during the July 23–25, 2012 event (Russell *et al.*, 2013).

arrives, there is a steady increase in the thermal pressure of the energetic particles and the magnetic field maintains a beta equals unity plasma. The arrival of the magnetic cloud puts magnetic stresses firmly in control.

There is still much to learn from the STEREO data of the July 2012 event, and with the paucity of these events (cf. Riley, 2012), we should not expect to observe further such ejections during STEREO's lifetime. However, these events are so important that it makes sense from a space weather monitoring perspective to station a network of particle monitors around the Sun at 1 AU, perhaps with ion engines to position them at fixed locations relative to the Earth, and small but powerful energetic particle analyzers to characterize the relativistic plasma.

5. Conclusions

Our analysis of these 13 fast events has revealed that groups of large events become rarer as their intensity increases. However, the statistics of such large events does not allow us to be certain that there are three separate classes, as proposed here. We have used their arrival times as a proxy for their intensity. This inverse "correlation" of occurrence rate with intensity is consistent with the idea that these eventsresult from coronal magnetic configurations that store energy in at least three different ways, with one able to store the greatest magnetic potential. Regardless of whether the number is three or not, it is important to focus our efforts on the question of what allows so much energy energy to be stored for such rapid release? What magnetic configurations can lead to a greater storage capacity for magnetic and particle flux but only rarely occur? Thus we encourage renewed examination of magnetic data for these largest space weather events, and in particular the study of magnetic configurations on the

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Sun with high meta-stability with potential for rapid and strong outbursts when they destabilize.

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