

THE MAJOR CAUSES OF SPACE WEATHER AND HOW TO DETECT THEM

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Introduction

We all know about the Sun and its importance to us all. It helped to create us and it sustains us – without the Sun life on Earth would never have existed. There is not a single form of energy here on Earth that did not originate from the Sun or the cloud from which the Sun and planets formed. (Go ahead and try it, think of any form of energy and trace it back through all of its changes to its origin.)

Although the big-picture view of the Sun is known to everybody, in this ever-increasingly technological world in which we live more subtle effects from the Sun begin to make their presence known. Further, as we become more and more technologically advanced, these effects become more and more significant. I am referring to the phenomenon known as space weather.

The term “space weather” covers a large variety of phenomena, but the most important to us is the most intense form of space weather called the (geo)magnetic storm. Magnetic storms are large disruptions to the Earth’s magnetic field that oscillate and reconfigure geomagnetic field lines, drive currents in the ionosphere and increase charged particle density in the ionosphere and magnetosphere. Consequently, they are known to be responsible for a variety of damaging effects to our infrastructure. Some examples include spacecraft damage and destruction, power station damage, communications disruption and increased radiation dosage to aircraft pilots, passengers and astronauts. One magnetic storm in March 1989, for example, left millions of people without electricity for 9 hours while another storm in January 1994 damaged spacecraft and cost the parent company around 70 million dollars [1]. The damaging potential of magnetic storms combined with the increasing demands for more advanced technology by society have made the study of the causes of major space weather a high priority for research, technological and defense institutions.

The Cause of Space Weather (Magnetic Storms)

Contrary to popular belief, these major space weather events are not caused by solar flares. They are caused by solar eruptions that are often associated with flares, which is why they are often mistaken for being caused by them. There is also a historical blunder here, as the solar eruptions that actually cause magnetic storms were discovered a century after flares were, when a thriving flare research community had been established. They would not give up their firmly-held beliefs (and livelihood) without a fight and to this day most people outside the professional solar and space communities believe in the Solar Flare Myth [2].

Magnetic storms are actually caused by coronal mass ejections. Coronal mass ejections, or CMEs are large massive eruptions of plasma and magnetic field from the Sun. They are known to contain masses in excess of 10^{13} kg and can achieve speeds as high as 4000 km/s (14 million km/hr). The energy contained in a CME is over a factor of 10 greater than that in a solar flare. As their name implies, they are only detectable in the solar corona, and so it is necessary to block out the bright light from the solar disk to reveal the faint corona. This is achieved either during a solar eclipse, or by instruments known as coronagraphs.

Coronagraphs block out the solar disk permanently with a disk in the instrument called an occulting disk. Unfortunately even coronagraphs cannot easily detect CMEs, which is why they were not officially discovered until 1973 when we had begun flying coronagraphs on spacecraft. Since their discovery we have developed more and more sophisticated instruments for detecting them, and they are today observed regularly. Figure 1 shows how CMEs appear in coronagraphs. Note the event on the right, which appears to encircle the Sun, is a CME that is heading towards the Earth.

A number of spacecraft have flown coronagraphs over the years (Table 1) and we now know a great deal about these eruptions. We know that their occurrence rate increases with the rise in the solar cycle and that the launch location moves from the solar equator to all over the Sun as the cycle moves toward maximum. We know about the varieties of structures, from erupting loops to so-called “streamer blowouts” to thin jets of material, and we know about their speeds, accelerations and masses. We even have a good idea for why they erupt – it is the Sun trying to remove large amounts of built-up magnetic energy – and we have a good idea of how they end their life in the outer heliosphere. We also know that CMEs, not solar flares, are the primary source of severe space weather at the Earth, and we understand (for the most part) the mechanism by which CMEs achieve this.

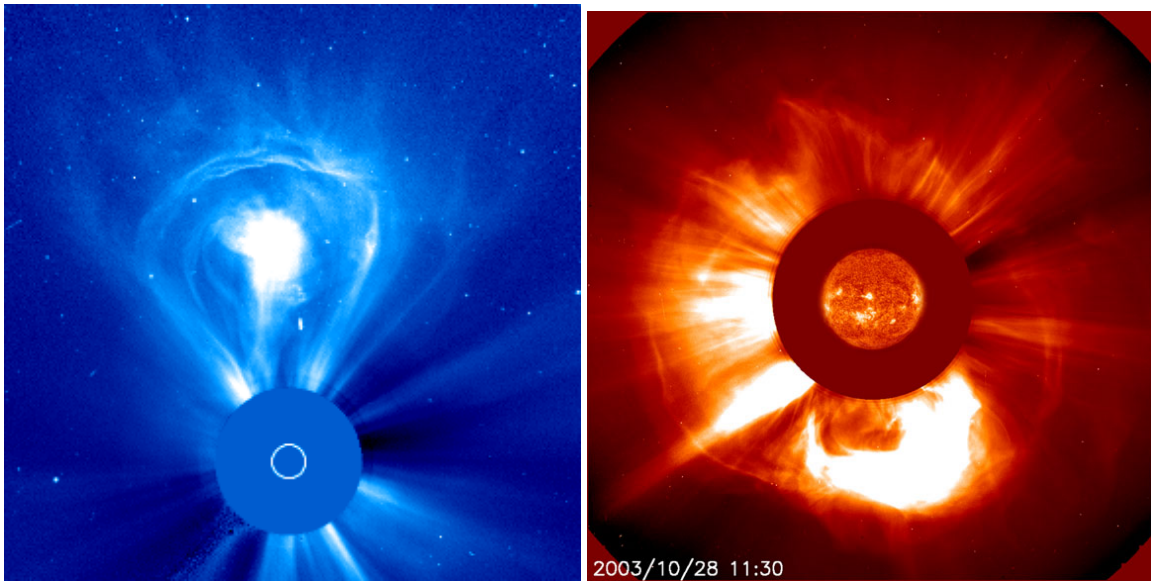


Figure 1: Two images of coronal mass ejections (CMEs) as observed by spacecraft coronagraphs. These coronagraphs are part of the Large Angle Spectroscopic Coronagraph, or LASCO on board SOHO. The solid disk (blue on the left, red on the right) is the occulting disk and the white circle in the left image represents the surface of the Sun. On the right an extreme ultraviolet image of the Sun has been included and is to scale. The CME on the left is the loop structure extending away from the Sun and the one on the right appears to encircle the Sun because it is heading towards us. This type of CME is called a halo CME. Images courtesy of NASA/ESA.

Table 1: Spacecraft that have flown coronagraphs and heliospheric imagers over the years.

Name	Launch Date	End Date
<i>OSO-7</i>	29 September 1971	9 July 1974
<i>Skylab</i>	14 May 1973	11 July 1979
<i>Helios 1</i>	10 September 1974	1982
<i>Helios 2</i>	15 January 1976	1982
<i>Solwind</i>	24 February 1979	13 September 1985
<i>SMM</i>	14 February 1980	2 December 1989
The Shuttle	8 April 1993	7 November 1998
<i>SOHO</i>	2 December 1995	Continues to date.
<i>Coriolis</i>	6 January 2003	Continues to date.
<i>STEREO</i>	25 October 2006	Continues to date.

Aside from all those things we know, there are still a number of unknowns about CMEs. For example, we do not yet know what causes them, from where in the solar atmosphere they originate or the physics describing their evolution as they continue away from the Sun through the heliosphere. Working on these questions is a community of scientists with tools at their disposal including mathematical models and a large suite of ground-based and spacecraft data. Among this community are myself and some of my colleagues at the Southwest Research Institute.

While coronagraphs have enhanced our understanding of CMEs and space weather a great deal, they do have their limitations. One major problem is that coronagraph images of CMEs are only projections into the sky plane and contain no depth information. How can we tell, for example whether a CME is moving slowly or just looks like it is slow because its images are heavily projected? How can we identify three dimensional structural information about a CME when we only see it in two dimensions? To make matters worse, the CMEs that are of most interest to us (the ones heading directly towards us) are also the ones that suffer the largest projection effects. This limits the ability of individual coronagraphs to improve our understanding of CMEs beyond what we already know, and it also limits our ability to use them for space weather forecasting.

Recent attempts have been made to overcome these projection problems. Most notably is the launch of the *STEREO* spacecraft in October 2006. *STEREO* is a unique spacecraft pair that share an orbit about the Sun with the Earth, but with an increasing angular separation between each other and the Earth. One spacecraft leads the Earth while the other lags, and the separation increases by around 22° each year. As they move apart their coronagraphs observe CMEs at the same time from different viewpoints, so geometry can be used to remove the projection effects and identify 3-D information about the CME. Developments in this area are still new [3].

Heliospheric Imagers

More recently, more sophisticated instruments have been able to identify and image the very faint CME further from the Sun as it moves through the heliosphere. These represent a major advance to CME study because they can monitor how the structure, speed and acceleration change as CMEs evolve through the solar wind. The first instrument capable of observing them at large distances from the Sun was the E9 zodiacal light experiment on board the *Helios* spacecraft pair (launched 1974 and 1976). This had a very limited field of view and it was not until 20 years after *Helios* that an (almost) all sky version was launched. This was the Solar Mass Ejection Imager (SMEI) which was launched in 2003 and continues to operate to date. The *STEREO* spacecraft, launched in 2006, also carry such an instrument, called the Heliospheric Imager or HI. Figure 2 shows images from HI (a) and SMEI (b) of a single CME observed in January 2007. While they do not detect every CME that is observed by coronagraphs, a large number have been detected and we are beginning to understand more about their evolution.

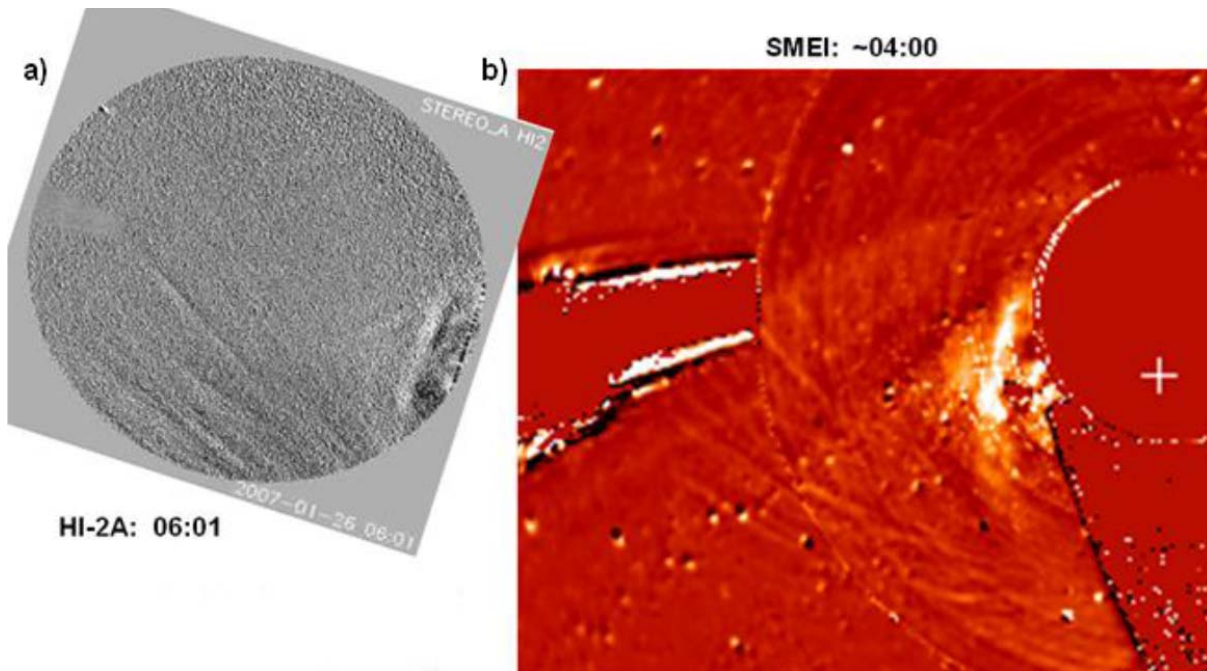


Figure 2: Images of a CME obtained with a) SMEI and b) HI at 06:01 and 04:00 on 26 January 2007 respectively (From Figure 4 of Webb et al. (2009) [4]). In both cases the Sun is to the right and the + in the SMEI image is its location. The CME is the bright structure towards the right of both images. The streaks toward the bottom are from Comet McNaught, which was passing through the sky at this time.

One discovery about CME evolution made possible by heliospheric imagers is that the physics describing their movement through the interplanetary medium is more complicated than we once thought. Many workers assumed that once the CME had left the Sun its propagation would be governed entirely by the surrounding solar wind. Fast CMEs would slow down and slow ones would speed up in order to equalize their speed with that of the solar wind. We are now aware of a type of CME that do not behave this rule, specifically that some fast CMEs are known to speed up as they move through the heliosphere [5].

Aside from the advantages of tracking CMEs all the way from the Sun to the Earth, heliospheric imagers also provide us with an opportunity to remove the projection problems we are faced with in coronagraphs. Simply put, the geometrical laws and the physics that enable us to observe CMEs (called Thomson scattering) necessarily remove 3-D information from coronagraphs. They do so, however, with the advantage of far simpler analysis of coronagraph images. With heliospheric imagers this breaks down, and while the analysis becomes far more complex it does so with the advantage that 3-D information is retained. So, with careful analysis of heliospheric images of CMEs we can dig through the analysis and extract the 3-D parameters. This represents a major advance in CME analysis.

Figure 3 shows one such reconstruction for a CME that was observed in November 2007. The locations of the Sun, Earth and both *STEREO* spacecraft at the time of observation are shown. This image not only demonstrates the enormous structure that is the CME, but it was reconstructed purely from heliospheric images of this event. Comparison with other observations of this event from other spacecraft have shown this to be a fairly accurate representation of the structure of this particular CME.

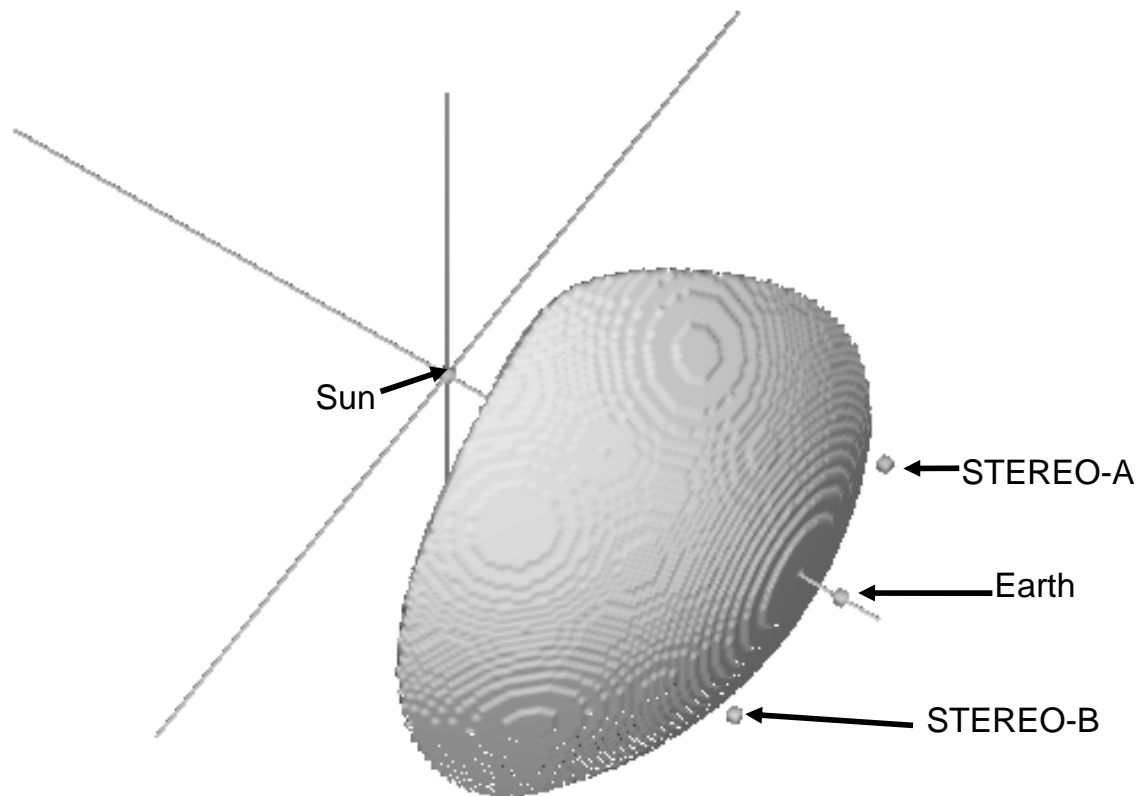


Figure 3: Three-dimensional reconstruction of a CME using entirely heliospheric image data from SME and the HIs [6]. The location of the Sun, Earth and both STEREO spacecraft at the time of this event are indicated. This demonstrates the utility of heliospheric image data for accurate CME reconstruction (removal of projection effects).

Concluding Remarks

Coronal mass ejections are very difficult to detect, only noticeable when we are able to observe the solar corona. We have instruments capable of observing them there, and while they have provided us with a great deal of information about them, they are limited in what they can tell us (3-D information, for example). A new class of instrument capable of observing CMEs when they are even harder to detect are now available, called the heliospheric imager. A heliospheric imager needs to be able to observe brightness levels of the same order as a 10th magnitude star. Not only is their observation here difficult, but the necessary analysis for interpreting heliospheric images is far more complex than coronagraph images. The hard work in detection in analysis does pay off, as we can use heliospheric imagers to extract 3-D information about CMEs in ways that no other instrument can.

By writing this article I hope to raise awareness of both coronal mass ejections and of heliospheric imagers. It is important to debunk the continuing popular belief that major space weather events – magnetic storms – are caused by solar flares. They are not. The energy contained within even the brightest solar flare is insignificant compared with your average CME, and it is the CME that is responsible for the most severe magnetic storms. CMEs are not only an important mechanism for driving space weather at Earth, but they are also important for the evolution of the Sun. They are therefore crucial phenomena worthy of far greater appreciation than is currently provided by the general public.

References

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