

Introduction to special section: Global picture of solar eruptive events

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Abstract

This introduction highlights some of the scientific results reported in this special section on solar eruptive events and provides a brief description of issues related to the new results. Most of these papers grew out of the coordinated data analysis workshop held at the Goddard Space Flight Center during April 27-30, 1999, and the subsequent International Conference on Solar Eruptive Events held at the Catholic University of America, Washington, D. C. during March 6-9, 2000.

1. Introduction

Solar eruptive events have a number of manifestations near the Sun as well as in the interplanetary medium: white-light coronal mass ejections (CMEs), interplanetary shocks, magnetic clouds and ejecta, and solar energetic particles (SEPs). Availability of remote and local sensing instruments to obtain information on each of these manifestations has helped us obtain a global picture of the eruptive events and track solar eruptions from their origin at the Sun to the vicinity of Earth and beyond [see, e.g., *Fox et al.*, 1998]. White-light observations from spaceborne coronagraphs such as the Large Angle and Spectrometric Coronagraph (LASCO) instruments on board Solar and Heliospheric Observatory (SOHO) have revolutionized our perception and understanding of the solar eruptive events. Overlapping with SOHO, a complement of several missions operate under the International Solar Terrestrial Physics (ISTP) program, which combines resources and scientific communities on an international scale. This program brings together data from space-based and complementary ground-based facilities and combines them with theoretical efforts so that focused investigations of the Sun-Earth space environment could be performed over an extended period of time. Missions such as Yohkoh and the ground-based Nobeyama radioheliograph [*Nakajima et al.*, 1994] have helped us understand the manifestations of the CMEs near the solar surface [*Gopalswamy*, 1999; *Hudson*, 1999]. The Radio and Plasma Wave Experiment (WAVES) [*Bougeret et al.*, 1995] on board the Wind spacecraft can track CME-driven shocks using type II radio bursts in the spatial domain not accessible for direct coronagraphic imaging [*Gopalswamy et al.*, 2000]. The sensitive particle detectors on board Wind and the Advanced Composition Explorer (ACE) have accumulated extensive and valuable data on SEPs. In order to exploit the unprecedented availability of data on solar eruptive events, a coordinated data analysis workshop was conducted during April 27-30, 1999, at the Goddard Space Flight Center, Greenbelt, Maryland, under the sponsorship of the ISTP program and the Inter-Agency Consultative Group (IACG). A set of 27 “radio-rich” solar eruptive events (CMEs associated with interplanetary type II bursts) were chosen and all aspects of these events were studied: their origin, interplanetary propagation, and geoeffects. Following this workshop, the International Conference on Solar Eruptive Events was conducted at the Catholic University of America during March 6-9, 2000. Most

of the papers presented in the international conference are included in this special section of the *Journal of Geophysical Research-Space Physics*. This paper presents the highlights of the special section.

2. Solar Magnetism and CMEs

CMEs are launched from closed magnetic field regions on the Sun, such as active regions, filament regions, or a combination thereof. Understanding the structure, evolution, and stability of these regions is therefore an essential part of CME investigations. A broad physical description of the CME phenomenon including all forces and dynamics is provided by *Low* [this issue], which sets the global framework for posing questions and testing ideas on the eruptive events. *Low* [this issue] reviews the long-term implications of the CME phenomenon for the magnetic flux budgets of the photosphere and the corona and for solar magnetism itself by connecting atmospheric to interior properties. Emphasis is placed on the hydromagnetic nature of CMEs including the flux emergence, magnetic reconnection, formation of large-scale structure, and conservation of magnetic helicity.

2.1. Prominences and CMEs

One of the many controversial issues regarding filaments/prominences and their eruption is the magnetic configuration that supports them. In one paradigm, sheared or twisted magnetic fields form “dips” that can support prominence material [e.g., *Antiochos et al.*, 1994]. Another possibility is that prominence material is supported in the dips of helical field lines in a magnetic flux rope [e.g., *van Ballegoijen and Martens*, 1989]. *Linker et al.* [this issue] explore the possible role of flux ropes in prominence support and eruption by performing a numerical simulation of the filament-helmet streamer system. In their calculation a magnetic flux rope is formed due to the reduction of magnetic flux along the neutral line of a sheared arcade underneath a helmet streamer. These authors include the upper chromosphere and the transition region in their calculation, and the prominence is formed out of the chromospheric material brought up to the corona. The subsequent eruption of the prominence is achieved by further reducing the magnetic flux in the sheared coronal arcade. Apart from these two paradigms, there is a third view for filament equilibrium given by *Martin and McAllister* [1997]. According to these authors, prominences are not actually supported at all (there are no dips) but are just

material flowing along field lines. In this scenario, filament eruption occurs when reconnection detaches the filament barbs from their photospheric roots.

How does the magnetic configuration control the stability of the prominence? *Filippov and Den* [this issue] have predicted that there is a critical height at which a prominence (a filament when seen on the solar disk) will become unstable and erupt. The critical height of a filament in the inverse-polarity configuration is related to the filament electric current such that the stronger the current the greater the height. According to these authors, the critical height is related to the vertical gradient of the photospheric magnetic field above the neutral line. This model has important implications for space weather applications. By observing a large number of prominences using an instrument such as the Nobeyama radioheliograph, it is possible to derive a critical height, which can be compared with the theoretical value obtained by *Filippov and Den*.

2.2. Sigmoidal Structures and CMEs

Eruptions from active regions are known to be more energetic, which increases their importance for geoeffectiveness. Active-region vector magnetic fields are routinely measured by the Marshall Space Flight Center vector magnetograph. Combining these magnetograms with the Yohkoh soft X-ray images, *Falconer* [this issue] has identified two characteristics of active regions that may be useful in discriminating CME-productive active regions: the length of the strong-field, strong-shear main neutral line and the global net current in the active region. In addition, there may be threshold values of the length and current above which the production of CMEs is likely and hence may aid CME prediction. *Falconer* also shows that these characteristics are better indicators of CME production than the sigmoidal structure seen in X-ray images. Sigmoidal structures in active regions are probably the coronal manifestations of the photospheric shear and might mark regions of solar eruptions [*Canfield et al.*, 1998] when certain caveats such as geometrical projection are taken into account [*Glover et al.*, 2000]. In an effort to link the field structure in sigmoids to the global field of the Sun, *Pevtsov and Canfield* [this issue] studied 18 coronal sigmoids observed in soft X-rays by Yohkoh. They found that during 1991-1998, sigmoids of one particular orientation were associated with strong geomagnetic storms while the sigmoids with opposite orientation were associated with weaker storms. Thus these

authors are of the view that magnetic field structure of individual eruptive regions plays a significant role in the geoeffectiveness of eruptions and that no simple solar-cycle-dependent generalizations could be made. This study contradicts the recent results obtained by *Crooker* [2000] and *Mulligan et al.* [1998] who suggest that the large-scale solar dipole magnetic field controls the orientation of the interplanetary magnetic clouds.

3. Onset of Solar Eruptions

Traditionally, H- α pictures were the primary source of information for near-surface manifestations of CMEs. H- α flares and filament/prominence eruptions are the two types of events often observed in association with CMEs. Moreton waves are the chromospheric response of the solar eruption, in the form of shock waves. Eruptive prominences were later identified as the innermost substructure of CMEs, the other components being the bright frontal structure and the coronal cavity [see, e.g., *Hundhausen*, 1999]. One difficulty with the H- α observations is that they provide information solely on the coolest portions of CMEs. The cavity and frontal structures are purely coronal with a temperature exceeding 10^6 K and hence cannot be probed in H- α light. Soft X-ray images made by the Skylab mission revealed some new details of the early phase of CMEs in the form of transient coronal holes [*Rust*, 1983] and posteruption arcades [see, e.g., *Kahler*, 1977]. The Yohkoh mission confirmed all the results of the Skylab mission and provided additional clarity. After the advent of SOHO's extreme-ultraviolet imaging telescope (EIT), a closer link between CMEs and early related activity near the surface has been established [see, e.g., *Thompson et al.*, 1999; *Gopalswamy and Thompson*, 2000; *Gopalswamy*, 1999; *Hudson*, 1999]. Coronal dimming and EIT wave transients have become common expressions in identifying the solar source of CMEs. Two recent additions to this suite of spaceborne noncoronagraphic instruments are the two ground-based radio telescopes: the Nobeyama radioheliograph and the Nancay radioheliograph. The Nobeyama Radioheliograph was built primarily to study flares, but it turned out to be an excellent source of information on filaments and prominences because radio emission can occur in a variety of ways and plasmas of wide-ranging temperatures can be probed [*Gopalswamy*, 1999]. An added advantage of microwave observations is that one need not worry about cloudy skies. The Nancay radioheliograph ob-

serves the Sun at meter wavelengths and is capable of observing thermal and nonthermal phenomena associated with CMEs. Thermal emission from CMEs arises due to free-free emission, providing an opportunity to directly image CMEs, as first reported by *Gopalswamy and Kundu* [1992]. *Hudson and Cliver* [this issue] review the current status of the noncoronagraphic observations of CMEs with major emphasis on X-ray imaging. They show that there is enormous benefit in cross calibrating CME signatures from a wide variety of observations for a better understanding of the eruptive process.

EIT proved to be an extremely useful instrument for unambiguously identifying the solar source of CMEs. The only drawback is the poor cadence, resulting in an incomplete picture of the eruption. However, it is the best inner coronal imager available to probe the early evolution of CMEs in coronal layers not accessible to coronagraphic observations. *Neupert et al.* [this issue] have used EIT data to study a number of coronal loops and filaments before and during CME-related flares and identified them as substructures in the white-light images of the CMEs. They were able to discern the first hints of CMEs at a height of about 100,000 km. They also demonstrated that EUV dimming occurs at the location of EUV loops in the preeruptive phase. *Sterling and Moore* [this issue] examine a series of morphologically homologous solar flares using EIT images in conjunction with magnetograms. They find that each of the flares began with the formation of a crinkle pattern in EUV outside of the emerging flux region. Reconnection inside the emerging flux region and in the overlying corona is suggested to be the cause of the homologous flares and the associated CMEs: Internal reconnection results in the primary energy release of the eruption, while the external reconnection causes the EIT crinkle pattern and restores the region to the preeruptive phase. In a case study, *Bagalá et al.* [this issue] describe an eruptive event using multiple data sets (Yohkoh X-ray data, H- α data, and Fe XIV green-line data from the Mirror Coronagraph for Argentina (MICA)) that cover a wide range of temperatures (in a hot jet and in cool surges) in the eruptive event. Some of these observed features could be interpreted as signatures of magnetic reconnection in the eruptive region.

4. Solar Eruptions, Shocks, and Type II Radio Bursts

Type II radio bursts occur at metric wavelengths (below $1.5 R_{\odot}$) to kilometric wavelengths (close to Earth) and hence are an important diagnostic for solar disturbances over the entire Sun-Earth connected space [*Reiner et al.* this issue; *Leblanc and Dulk*, this issue] and beyond [*Thejappa and MacDowall*, this issue]. Type II radio bursts are produced by fast mode MHD shock waves resulting from solar eruptions. There is a long-standing controversy regarding the shock driver [*Gopalswamy et al.*, 1998; *Cliver et al.*, 1999]. Flare blast waves, chromospheric evaporations, reconnection jets, hot plasmoids, and CMEs are some of the candidate shock sources. Of these, CMEs are confirmed sources of interplanetary (IP) shocks [*Sheeley et al.*, 1985]. It is not clear if the the same applies to the coronal shocks responsible for metric type II bursts. Historically, type II bursts were observed in the near-Sun and near-Earth domains by ground-based and spaceborne radio instruments, respectively. Lack of observations connecting these two domains was a major hurdle to understanding the relations between the coronal and interplanetary shocks. The Wind/WAVES experiment essentially removed this hurdle by providing observations in the decameter-hectometric (DH) wavelength domain (1-14 MHz). The new observations have confirmed a number of previous results on IP type II bursts and led to new results such as the discovery of radio signatures of interacting CMEs [*Gopalswamy et al.*, 2001]. However, the controversy regarding the relation between coronal and IP shocks is not yet resolved: *Gopalswamy et al.* [1998] compared coronal shocks inferred from metric type II bursts with the IP shocks detected in situ by Wind and found little correspondence between the two and hence concluded that the shocks in the two domains were of independent origin. Unfortunately, no type II radio burst was observed in the DH domain in the study period of *Gopalswamy et al.* [1998]. Since then, a large number of DH type II bursts have been observed starting in 1997 April, all of which are associated with CMEs [*Gopalswamy et al.*, 2000]. In addition, a large number of IP shocks have also been observed in situ. Using the expanded data set, *Gopalswamy et al.* [this issue] explore the relation between coronal and IP shocks and confirm their earlier result that there is very little correspondence between these two shock populations. Unlike the previous study, *Gopalswamy et al.* [this issue] find that in a number of events, both coronal and IP shocks are observed, but

these events involve large-scale CMEs. In a related study, *Reiner et al.* [this issue] find a close relationship between the speeds of IP shocks inferred from DH type II bursts and CMEs, while there is no such correlation between shock speeds inferred from metric type II bursts and CME speeds. In a different statistical study, *Vrsnak* [this issue] finds a positive correlation between flare importance and inferred shock speed. Furthermore, after examining a number of observed parameters of metric type II bursts, such as starting frequency and delay with respect to the flare onset, he concludes that flare blast waves are the most likely source of coronal type II bursts.

Leblanc and Dulk [this issue] compare the onset times of several DH type II bursts from the time of the impulsive phase of the associated flares and the CME liftoff times. They suggest that the type II shock in the corona and IP medium out to $30 R_{\odot}$ is a blast wave resulting from the impulsive energy release and deduce that the type II burst position is behind the CME leading edge. They also find some events in which the type II burst is produced by a CME-driven shock from the Sun all the way to 1 AU.

5. Solar Eruptions and Energetic Particles

Solar energetic particles (SEPs) are high-energy particles from the Sun that play an important role in space weather. The largest SEP events can enhance the radiation intensity in the near-Earth space by several orders of magnitude. Relativistic particles arrive within tens of minutes after an eruptive event and can last for many days. The long-lasting SEPs are thought to be due to CME-driven shocks. In addition to the prompt SEPs, the IP shocks also carry enhanced levels of energetic particles that arrive in the vicinity of Earth along with the shock. These are known as the energetic storm particles. Unlike electrons, which can be readily detected by the electromagnetic waves produced by various radiation mechanisms, the SEP ions are difficult to detect. Recently, instruments flown on Wind and ACE have been detecting SEPs with unprecedented accuracy, allowing detailed studies on the temporal evolution of composition and spectra over a wide range of energies and species. *Tylka* [this issue] describes how this new information has shaped our views on the SEP generation in CME-driven shocks and their interplanetary transport (including wave-particle interaction) and helped constrain theoretical models.

Both electrons and ions are accelerated in CME-driven shocks. Energetic electrons are responsible for most of the radio radiation observed from the Sun, accelerated either at the flare site near the Sun or at the shock front. Energetic electrons at the shock front are responsible for the type II bursts, while those escaping from the shock front are responsible for the complex type III bursts known as shock-associated (SA) events [*Cane*, 1981; *Bougeret et al.*, 1998; *Reiner et al.*, 2000; *Gopalswamy et al.*, 2000]. Electrons escaping from the shock front are easily detected in situ. The SA events typically start when the CME is in the outer corona and last for about 30 min. SA events are also known to have good association with SEPs [*Kahler*, 1994]. The new information about the CME height at the time of the SA event onset is consistent with that (5 -15 R_{\odot}) when SEPs were released near the Sun [*Kahler*, 1994]. Thus there are indications that electrons and ions may be injected roughly at the same time when the CME is within several solar radii of the Sun.

6. Conclusions

Most of the aspects of solar eruptive events have been addressed in this special section: their origin at the Sun, interplanetary propagation, and 1 AU manifestations. Two missing topics are CME statistics and interplanetary scintillation (IPS) observations of CMEs. Fortunately, there are recent publications on these topics: *St. Cyr et al.* [2000] have provided information on LASCO CMEs observed until June 1998. *Tokumaru et al.* [2000] have reported on the three-dimensional propagation of interplanetary disturbances associated with CMEs.

This special section is a testament to the benefits of coordinated data analysis, especially in enhancing the scientific return from space missions and enabling collaboration between diverse groups. By pooling data from space- and ground-based instruments and analyzing them collectively, it has been possible to piece together information from different spatial and temporal domains related to the eruption and hence gain a better understanding of the CME phenomenon. It is hoped that the link established between groups working on near-Sun and near-Earth manifestations of CMEs will be strengthened by this special section.

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