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SOLAR FLARES AND CORONAL MASS EJECTIONS

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1. INTRODUCTION

Attempts to clarify the nature of the terrestrial effects of solar activity and variability continue at an increasing pace. While mechanisms relating possible changes in terrestrial weather patterns to changes in solar luminosity remain elusive, it has long been thought that intense geomagnetic storms and interplanetary disturbances can be traced directly to large solar flares. To describe the basic scenario in simple terms, a large release of energy first occurs in a region of strong magnetic field. The energy release results in a rapid heating of coronal and chromospheric material, which expands outward into the interplanetary medium. In the case of the most energetic events the expanding material produces an interplanetary shock wave. The most energetic aspect of the flare, the impulsive phase, is characterized by the production of energetic ($E > 1$ MeV) electrons and protons, some of which can be observed as a solar energetic particle (SEP) event at 1 AU.

Over the past half century attempts have been made to identify the solar flares and their particular properties that result in geomagnetic storms and SEP events. These extensive studies, of interest to both solar physicists and forecasters of effects on the terrestrial environment, seemed to lay a solid foundation for the idea that the flare itself was the cause of the subsequent activity observed in the interplanetary medium and at the Earth.

About two decades ago large coronal eruptions, now known as coronal

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mass ejections (CMEs), were discovered in coronagraph observations on the *OSO-7* (Tousey 1973) and *Skylab* (Gosling et al 1974) spacecraft. At first they were thought to be driven by large flares. Today, although the general perception continues that large flares are the primary sources of both energy release in the corona and disturbed interplanetary flows, the observational evidence indicates that it is the CMEs themselves, and not large flares, that are the sources of both the energy release and interplanetary disturbances. Flares, the objects of extensive studies for decades, are not required to produce a CME and are probably only secondary phenomena when they occur with CMEs.

This review addresses two basic questions. First, how did we form such a fundamentally incorrect view of the effects of flares after so much observational and theoretical work? Second, what is the observational and theoretical evidence to support a primary role for CMEs, and what can we say about the relationship between flares and CMEs? In Section 2 we present flare and CME observations in a historical context to show the changing perspective between the two phenomena. In Section 3 we discuss the coronal phenomena that bear on the relationship between flares and CMEs. Interplanetary effects are discussed in Section 4.

2. HISTORICAL PERSPECTIVE

2.1 *The Flare as the Source of Geomagnetic Disturbances*

The first suggestion that geomagnetic disturbances were solar in origin was the observation that frequencies of both geomagnetic storms and sunspots followed the eleven-year cycle (Sabine 1852). Later, Maunder (1904) and Greaves & Newton (1928a,b) showed that the "great" geomagnetic storms were usually accompanied on the sun by groups of spots with large projected areas. By noting that the most probable spot position was one day west of central meridian and that large storms last about a day, Greaves & Newton (1928a,b) deduced a time of one and a half days for the disturbance to travel from the sun to the Earth. The smaller storms, however, did not show a strong correlation with sunspots.

The first step in associating geomagnetic storms with flares rather than with the associated spot regions was the memorable observation by Carrington (1860) of the 1 September 1859 white-light flare that was followed about 17 hrs later by a large geomagnetic storm. Hale (1931) reviewed the spectrohelioscope observations of large flares and drew a connection between some of those events and subsequent geomagnetic storms. A solid foundation for the statistical association of large flares and storms was provided by Newton (1939, 1943) who surveyed all the large flares observed since 1892 and found a significant correlation between those flares and subsequent geomagnetic storms. The result that the probability of a subsequent geomagnetic storm depends on the occurrence of a type IV radio burst (McLean 1959) and on the complexity of the magnetic field in the spot group associated with a flare (Bell 1961) further strengthened the tie between flares and storms.

Dellinger (1937) associated flares with another geomagnetic disturbance known as a shortwave radio fadeout or sudden ionospheric disturbance (SID). This kind of disturbance, in which an increase in atmospheric ionization and a geomagnetic disturbance occur nearly simultaneously with the flare brightening, had been tentatively associated with flares as early as the 1 September 1859 flare, but Dellinger (1937) provided the statistical foundation for the association. SIDs were attributed to ultraviolet radiation (e.g. Dellinger 1936) rather than to X rays, but the electromagnetic nature of the disturbance was correctly understood at the time.

A third kind of terrestrial disturbance, the increase of cosmic-ray intensity at the Earth, now known as a ground-level enhancement (GLE), was associated with flares by Forbush (1946). These events result when ions of energies exceeding about 1 BeV strike the Earth's atmosphere to produce secondary particles measured by detectors on the Earth. In a subsequent work Forbush et al (1949) discussed the acceleration and escape of BeV protons in terms of variable magnetic fields of sunspots. The detection of $E < 100$ MeV proton events by riometers (Reid & Leinbach 1959) also suggested flare sources for those events. Early efforts to understand particle acceleration considered the source to lie in or near the flare plasma (e.g. Smith & Smith 1963, Kundu 1965).

Thus, we see that by about 1960 there appeared little reason to doubt that all three solar-terrestrial disturbances—large geomagnetic storms, SIDs, and SEP events—were directly caused by the flare itself. It is the thesis of this review that although these disturbances are usually well associated with flares, only SIDs and some aspects of SEP events can be causally related to flares.

Since it was appreciated that the expulsion of a stream of high-velocity charged particles had to accompany the flare to cause the subsequent geomagnetic storm, a mechanism was required to effect the expulsion. Milne (1926) discussed a radiation-pressure mechanism in which outwardly moving atoms see a Doppler-shifted spectrum in which the resonant radiation lies on the violet side of the absorption line of the atom and is more intense than that in the absorption line itself. He calculated a maximum velocity of 1600 km/s for the escaping atoms, similar to that required for the expelled stream. Hale (1931) suggested that the flare emission could provide increased radiation to drive the particle stream in Milne's model, but Chapman & Bartels (1940) acknowledged that the solar phenomena giving rise to the particle stream had yet to be observed. Parker (1961) used a hydrodynamic calculation to show that a large solar flare with a temperature of 4×10^6 K could drive a hydrodynamic blast wave to the Earth in 1–2 days. Chapman (1964) and Akasofu & Chapman (1972) adapted Kahn's (1949) ad hoc treatment of a shell of gas expelled from the Hα flare region with a particle speed profile decreasing during the course of the flare. Again, no association with observed flare phenomena was claimed. However, by examining six major flare events observed in August 1972, Lin & Hudson (1976) provided observational support for the idea that the energy of $E > 10$ keV flare electrons can be sufficient to provide the energy and mass for interplanetary shock waves by heating the atmospheric gas to energies sufficient to escape the solar gravitational and magnetic fields. They found that shock waves were associated only with those flares for which the $E > 20$ keV electron energy exceeded 10^{31} erg.

The numerical integration of the time-dependent hydrodynamic equations for interplanetary disturbances with shock waves was carried out by Hundhausen & Gentry (1969), who obtained solutions for piston-driven and blast waves. Although they explicitly assumed flare-driven disturbances, Hundhausen (1972a,b), in reviewing these results, expressed reservations about associating flares with interplanetary shock waves, the agents causing geomagnetic storms. He noted 1. the imperfect correlation between large or energetic flares and interplanetary shocks, 2. the large masses and energies of the shocks compared with the flare energies, and 3. the occurrence of flares in closed magnetic field regions unrelated to solar wind flow. Thus, at the time of the *Skylab* mission in 1973 the basic physics of interplanetary shocks was understood, but the shocks were not yet directly related to any coronal events by observations.

Solar prominences were well known and easily observed by early investigators. These cool coronal structures have typical lengths of 2×10^5 km and heights of 5×10^4 km. They appear as bright features on the limb and as dark ribbons called filaments when seen on the disk. We may ask why prominence eruptions were not thought to play any role in geomagnetic storms. Greaves & Newton (1928b) suggested a relationship between prominences and geomagnetic storms, but Hale (1931) pointed out that erupting prominences generally fall back to the sun, and Newton (1939) dismissed erupting prominences as the sources of high-speed streams because they rarely achieve escape velocity. An additional factor may have been that the angular extents of the streams, correctly perceived to be up to 90° wide (Newton 1943), were thought to be much larger than prominence eruptions.

There are two types of geomagnetic storms, which are due to different kinds of high-speed streams (e.g. Feynman & Gu 1986). The first type arises from magnetically open, long-lived solar coronal holes and usually results in small storms with gradual commencements. Twenty-seven-day recurrences of these storms (Hundhausen 1977) were first discovered by Maunder (1905) and analyzed by superposed epoch analysis by Chree & Stagg (1927). The second type of geomagnetic storm begins with a sudden commencement—a sharp increase in the horizontal component of the geomagnetic field. These storms are relatively large and are due to interplanetary shocks preceding high-speed streams arising from the transient eruption of closed-field solar regions. Thus, if one wishes to find an association between prominence eruptions (or flares) and geomagnetic storms, it is necessary to deal only with the largest storms. The connection between prominence eruptions and geomagnetic storms was not appreciated until the work of Joselyn & McIntosh (1981). In reviewing the history of work on associations between prominences and storms, they showed how the recurrent storms confused earlier investigators and provided one more reason that prominences, an integral part of many CMEs (Webb & Hundhausen 1987), were not linked to storms.

2.2 *Flares as Drivers for CMEs*

The first summary of *Skylab* CMEs (Gosling et al 1974) left little doubt that CMEs were the long-sought eruptions of coronal material required to produce the high-speed transient flows of solar wind which, in turn, produce geomagnetic storms. Gosling et al (1974, 1976) found that although few CMEs were accompanied by Hα flares, those CMEs were generally much faster than CMEs without flares and were nearly always accompanied by type II or type IV metric radio bursts. They suggested two classes of nonrecurrent interplanetary disturbances: 1. those due to fast CMEs associated with flares and type II or type IV bursts, and 2. a larger class due to slower CMEs but not associated with flares or type II or type IV bursts. Their results and those of Stewart et al (1974a,b) reporting on flare-associated CMEs observed on *OSO-7* left little reason to doubt that the fastest CMEs originated in the explosive phases of flares.

The idea that CMEs are propelled by pressure forces resulting from associated flares was the basis of several kinds of CME models. The first approach used pressure pulses, usually based on associated flare X-ray flux profiles, to drive the ejections (Dryer 1982). The results of numerical codes were compared with CME observations (e.g. Wu et al 1983b), but disagreement arose about the success of this approach in matching the appearances of CMEs (Sime et al 1984, 1985; Dryer & Wu 1985). A serious problem for this model is that parametric studies of potential fields show that reasonable pressure pulses in those fields cannot result in CMEs

(Hildner et al 1986). The neglect of solar magnetic fields in the early hydrodynamic calculations (e.g. Kahn 1949, Parker 1961) allowed modelers to provide support for the idea of expulsion of flare-heated plasma into the interplanetary medium.

A second approach to modeling CMEs assumed that magnetic reconnection occurs in the fields below an erupting prominence. Anzer & Pneuman (1982) suggested that flaring loops are the lower loops rooted to the solar surface and that the upper disconnected loops provide the driving force for the CME. The driving force can occur only as the flare takes place.

These early models assumed that the CME directly overlay the associated flare and that the flare had to begin at or before the CME onset. In Sections 3.2–3.4 we review the recent observational results on the sizes, locations, timings, and energetics of flares relative to CMEs which have undermined the crucial assumptions of these models. The rejection of models linking CME propulsion to associated flares eliminates the physical connection which had long been supposed to exist between flares and interplanetary shocks.

2.3 *Observability and Energetics of Flares and CMEs*

A factor contributing to the presumption of a direct association between flares and interplanetary shocks appears to be the relative ease with which flares are observed. Worldwide Hα patrol observations of the sun were begun about 1934, providing a large body of flare data. Optical observations must be spatially resolved to detect flares, but in the radio and X-ray ranges flare signals are frequently several orders of magnitude above their quiet solar backgrounds, so unresolved full-sun observations in both wavelength ranges are quite adequate to detect rather small flares. The white-light coronagraph, on the other hand, detects only changes in the line-of-sight brightness which correspond to the addition or subtraction of coronal material. It is sometimes necessary to subtract coronagraph images pixel by pixel (Figure 1) to detect these brightness changes (Howard et al 1985), which rarely exceed 20 to 30% of the background signal.

The occurrence of flare radiation in the radio and X-ray wavebands clearly established the presence of heated plasmas and nonthermal particles arising from the rapid release of energy. In contrast, the coronal material of CMEs observed in white-light coronagraphs is assumed not to be substantially heated above the ambient coronal temperature. In fact, coronagraph observations in the Hα line have established that cool prominence material is often observed in the cores of CMEs (Athay & Illing 1986).

The first white-light coronagraph observations of CMEs followed the first radio and X-ray observations of flares by over 20 years, by which

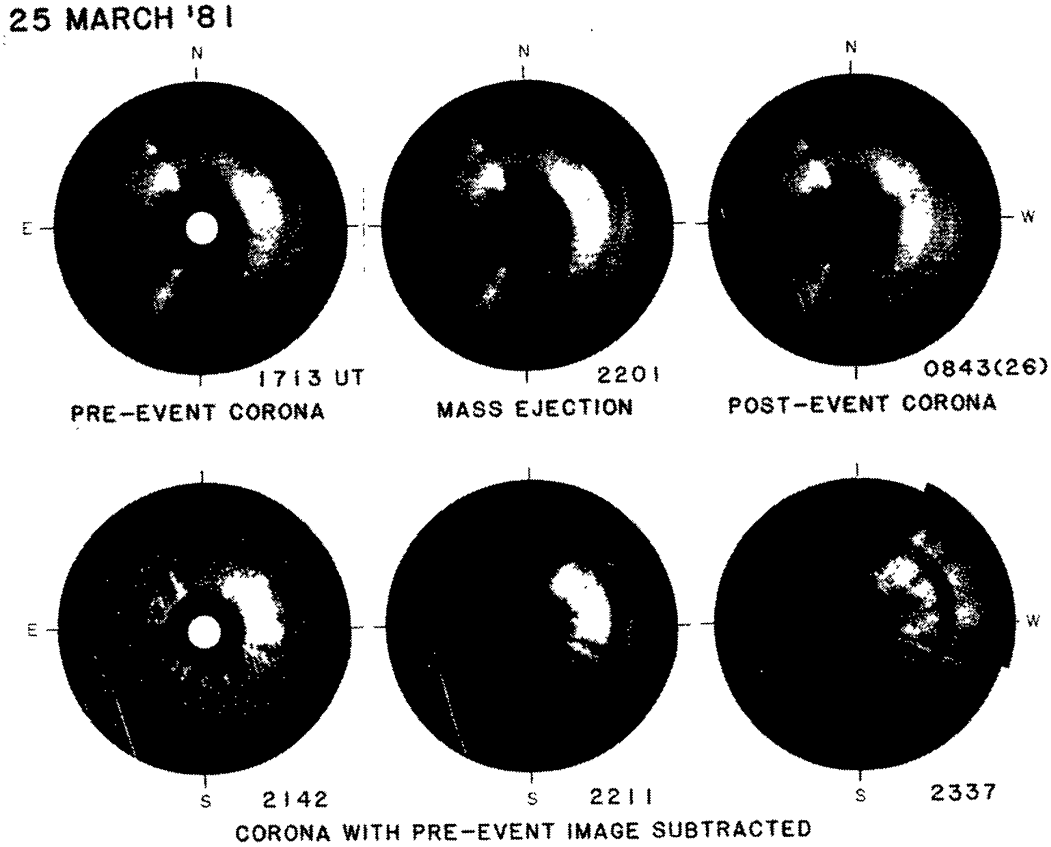

Figure 1 The CME of 25 March 1981, observed with the *Solwind* coronagraph. The top images are direct images, but the bottom images are difference images formed by subtracting a base image from the CME image. The solid white circles in the images on the left side indicate the solar disk. From N. R. Sheeley, Jr.

time the flare event itself had been firmly established as the source of SEP events and of transient high-speed wind streams causing geomagnetic storms (e.g. Smith & Smith 1963). The CME energies are due to mass motions of large-scale structures, while those of flares result from energized particles in small-scale structures. With the solar research community observationally and historically focused on flares as the sources of transient interplanetary phenomena, the concept of CMEs, rather than flares, as those sources is only now gaining credibility.

3. FLARE/CME RELATIONSHIPS

3.1 *Flare/CME Statistics*

The *Skylab* mission in 1973–1974 provided the first large data base of CMEs which could be compared with other solar phenomena to look for spatial and temporal associations. The first studies were based on the EUV and soft X-ray images of *Skylab* flares. Sheeley et al (1975) studied spatially resolved *Skylab* observations obtained during long-duration (>4.5 hr) soft X-ray events (LDEs) seen with the *SOLRAD* spacecraft. Their observations suggested that all LDEs are accompanied by CMEs and that most LDEs were accompanied by filament eruptions. Kahler (1977) studied the X-ray structures of LDEs and found them to consist of arcades of high (10^5 km) loops which he argued were the X-ray analogs of Hα post-flare loop prominence systems. The post-flare loop prominences had been modeled earlier by Kopp & Pneuman (1976), and Kahler suggested that their model was also applicable to the LDE structures.

Pallavicini et al (1977) surveyed X-ray limb-flare images in the *Skylab* data and concluded that all flares consist of two classes. The first class are compact flares with small volumes (10^{26}–10^{27} cm^3), low heights ($<10^4$ km), and short durations (tens of minutes). The second class consisted of large volumes (10^{28}–10^{29}cm^3), great heights ($>10^4$ km), and long time scales (hours). The second class were well associated with CMEs, but the first class were not. These results suggested that when CMEs are associated with flares, those flares are LDEs. These early results said nothing about CMEs not associated with flares.

A correlation between the average sunspot number of each longitudinal quadrant of the sun and the number of CMEs arising from that quadrant was found by Hildner et al (1976). In their view, this correlation suggested that strong magnetic fields provided the forces required to propel CMEs. Munro et al (1979) carried out the first comprehensive survey to associate CMEs with various forms of solar activity. Of those CMEs with some kind of association, about 40% were associated with flares, but more than 70% were associated with eruptive prominences or disappearing filaments. A similar result was obtained by Webb & Hundhausen (1987) for the CMEs observed on the *SMM* spacecraft at solar maximum in 1980. In addition, they found that most of the soft X-ray events associated with the *SMM* CMEs were LDEs.

The *Skylab* studies linking LDEs to CMEs and the model of reconnecting field lines in LDE flares (Kopp & Pneuman 1976, Anzer & Pneuman 1982) led to the scheme of one class of confined, compact flares of short duration with no associated CME and a second class of eruptive flares with associated CMEs and long durations due to the reconnection of open magnetic field lines (Svestka 1986). Sheeley et al (1983) examined the durations of the soft X-ray bursts associated with CMEs observed with the *Solwind* coronagraph. They found that the longer the duration of an X-ray event, the higher the probability of an associated CME. These probabilities ranged from 26% for the shortest durations (~ 1 hr) to 100% for the longest (>6 hr). No sharp distinction was found between short-duration and long-duration X-ray bursts in terms of their associations with CMEs. Such a distinction would have been expected, based on the existence of the two classes of flares. The broad range of durations of X-ray flares associated with CMEs was confirmed in subsequent studies of *Solwind* CMEs by Kahler et al (1989) and in *SMM* CMEs by Harrison (1991).

The reality of these two classes of flares has been challenged by Harrison (1991) on the grounds that no substantial difference in the range of soft X-ray durations is found between flares associated with CMEs and random samples of all flares. Kahler et al (1989) argued that the simple two-class scheme is complicated by the possibility that compact, noneruptive flares may occasionally occur as by-products of CMEs. Thus, the basic distinction between the two classes of flares still holds, but a flare of either class may be associated with a CME. Kahler et al (1989) also found a correlation between the CME angular width and the duration of the associated X-ray flare. In their view this implies a correlation between the spatial size scale of the CME and that of the associated flare, but they offer no convincing explanation of this result.

3.2 *Flare/CME Spatial Relationships*

The statistical studies of Munro et al (1979) and of Webb & Hundhausen (1987) confirmed the earlier report of Gosling et al (1974) that most CMEs were not accompanied by Hα or X-ray flares. The first studies relating the detailed positions and timings of X-ray flares to associated CMEs were those of Harrison and colleagues. In a statistical analysis of 48 flare/CME events Harrison (1986) found a tendency for flares to lie below one leg of the CME rather than below the center of the CME. In more recent studies of *SMM* CMEs, Harrison et al (1990) and Harrison (1991) found flare locations rather broadly distributed with regard to the CME spans, matching similar results of Kahler et al (1989) using *Solwind* CMEs. Hundhausen (1988), Kahler et al (1989), and Harrison et al (1990) have emphasized the fact that the characteristic angular sizes of CMEs exceed those of the associated Hα flares and active regions by factors of 3 to 10. In a detailed study of four cases of flares and associated filament eruptions, Kahler et al (1988) found that the Hα region which brightened in the impulsive phases of the flares were much smaller than the overall span of the erupting filaments. To generalize, the flare regions are much smaller and usually not centered under the erupting CMEs.

3.3 *Flare/CME Temporal Relationships*

Coronagraphs occult the inner coronal field of view in which a CME is formed. To find the time at which a CME began to leave the sun it is necessary to plot the height of the CME as a function of time and then extrapolate the trajectory backward in time to the limb. Three unknowns (Harrison & Sime 1989) must be dealt with in this process: 1. the accelerations of CMEs at low heights (MacQueen 1985); 2. the altitude at which the CME was formed; and 3. the position, i.e. longitude and latitude, of the CME source region on the disk. One can assume a constant speed and calculate the extrapolated departure time for a CME from the solar limb. The comparison of this time relative to the onset of the associated flare can show whether the CME onset precedes or follows the flare onset. Harrison's work using this basic assumption with *SMM* CMEs has consistently shown (Harrison 1986,1991; Harrison et al 1985, 1990) that CME onsets usually precede associated X-ray flare onsets.

If substantial acceleration occurs early in the development of a CME, it can only be observed close to the solar limb. The ground-based K-coronameter at Mauna Loa Observatory provides observations of CMEs from 1.2 to 2.0 solar radii ($R_{\odot}$) from sun center. It operated during the *SMM* mission, allowing some CME trajectories to be tracked from 1.2 to 5 $R_{\odot}$ by combining the Mauna Loa and *SMM* observations (Figure 2). Hundhausen & Sime (1992) have found many CMEs from the large number observed in 1988 and 1989 in which the CME initiations are directly observed within the field of view of either the Mauna Loa or the *SMM* instrument. The launch times for such events can be determined with uncertainties of a few to ten minutes, with no need for extrapolation of observed trajectories; they once again tend to occur before the onset of associated hard or soft X-ray emissions (Figure 3).

In a related study Kahler et al (1988) examined the development of four Hα filament eruptions during the impulsive phases of flares for evidence of how the eruptions are driven. In each case they found that the eruption began before the onset of the impulsive phase and that the eruptive motion was consistent with a smooth evolution through the impulsive phase, showing no new acceleration attributable to the impulsive phase.

3.4 *Flare/CME Energetic Relationships*

Besides the spatial and temporal relationships discussed above, we can ask whether the energetics of flares and CMEs supports the view that flares drive CMEs. MacQueen & Fisher (1983) examined the kinematic properties of 12 inner coronal (1.2–2.4 $R_{\odot}$) CMEs observed with the Mauna Loa K-coronameter. When the radial speeds were plotted as a function of distance from sun center, a clear difference between flare- and prominence-associated CMEs was found. Flare-associated CMEs showed generally higher speeds with little evidence of acceleration in the coronameter field of view while the prominence-associated CMEs were slower and exhibited

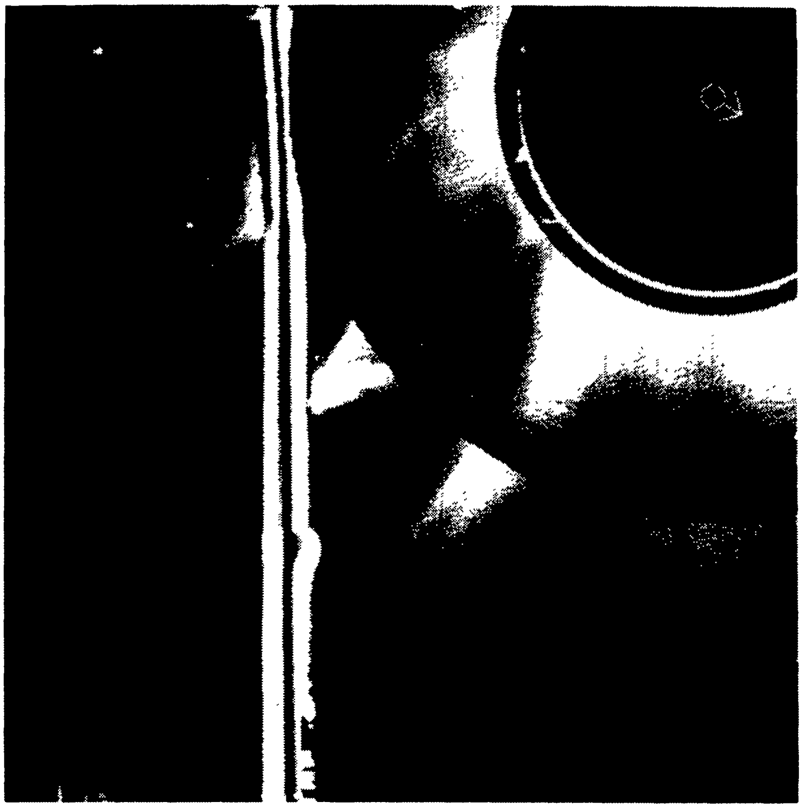

Figure 2 Composite image of a CME on 17 August 1989 observed with the Mauna Loa Observatory prominence monitor (inner field of view) and coronameter (middle field of view) and *SMM* coronagraph (outer field of view). The bright vertical structure is a detector artifact. From Hundhausen & Sime (1992).

substantial acceleration. MacQueen & Fisher suggested a fundamental difference between the two classes of CMEs, with flare-associated CMEs produced in impulsive accelerations acting over small spatial (0.2 $R_{\odot}$) and temporal (<10 min) regimes. While this may be taken as evidence for flare-driven CMEs, there is some ambiguity in distinguishing between flare and prominence-associated CMEs, so an extension of their work to later periods should be carried out before their results are accepted.

In general, the estimated energies of interplanetary shocks can exceed 10^{32} erg, about a factor of 10 larger than the energies of big flares (Hundhausen & Gentry 1969, Hundhausen 1972a, Lin & Hudson 1976). Hundhausen (1992) has found a poor correlation between flare X-ray intensities and associated CME energies, contrary to what is expected if CMEs are flare-driven and if X-ray intensity is a measure of the flare energy. In addition, Cane et al (1986), Heras et al (1988), and Sanahuja et al (1991) discussed 14 cases in which interplanetary shocks and SEP events arose from eruptions of filaments lying outside active regions. Despite the lack

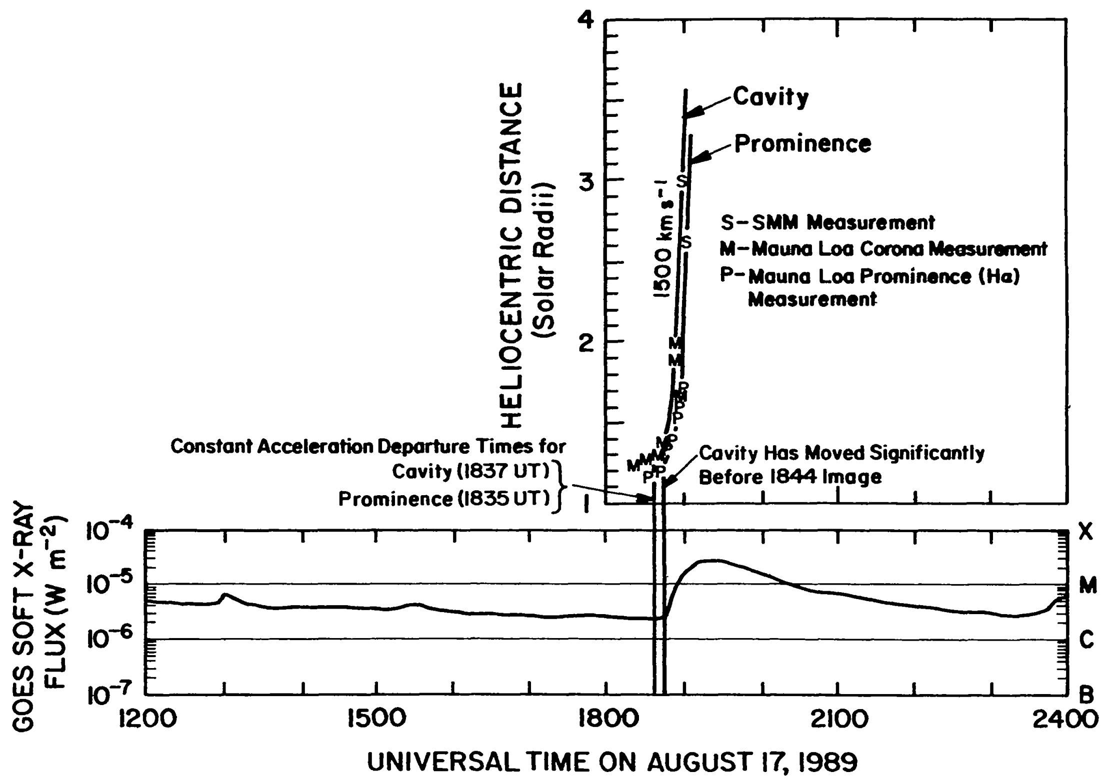

Figure 3 (*Top panel*) Height-time profiles of the CME cavity (the dark region behind the CME loop) and prominence. The best fits for constant acceleration give limb departure times of 1837 UT and 1835 UT for the cavity and prominence, respectively. (*Bottom panel*) The time profile of the *GOES 1–8A* X-ray flux. The onset of the CME components precedes the onset of the X-ray flare. From Hundhausen & Sime (1992).

of accompanying flares, these apparently innocuous solar events resulted in quite energetic interplanetary phenomena, including one case of an $E > 50$ MeV proton event (Figure 4; Kahler et al 1986). These recent studies have shown that flare energies are poorly correlated with associated CMEs or interplanetary SEPs.

During the 1987–1989 rise in solar activity the sunspot latitudes gradually moved equatorward in the familiar butterfly pattern while the latitudes of the coronal helmet streamers moved poleward. Hundhausen (1992) found that the CME latitudes tracked the helmet streamer latitudes rather than the latitudes of sunspots, active regions, or flares. In addition, the widths and speeds of CMEs during this period showed no variation with latitude—a result suggesting that CMEs lying at active region latitudes, and possibly associated with flares, are not qualititively different from those associated with high-latitude filament eruptions. Thus, contrary to the implications of the earlier MacQueen & Fisher (1983) result, these later

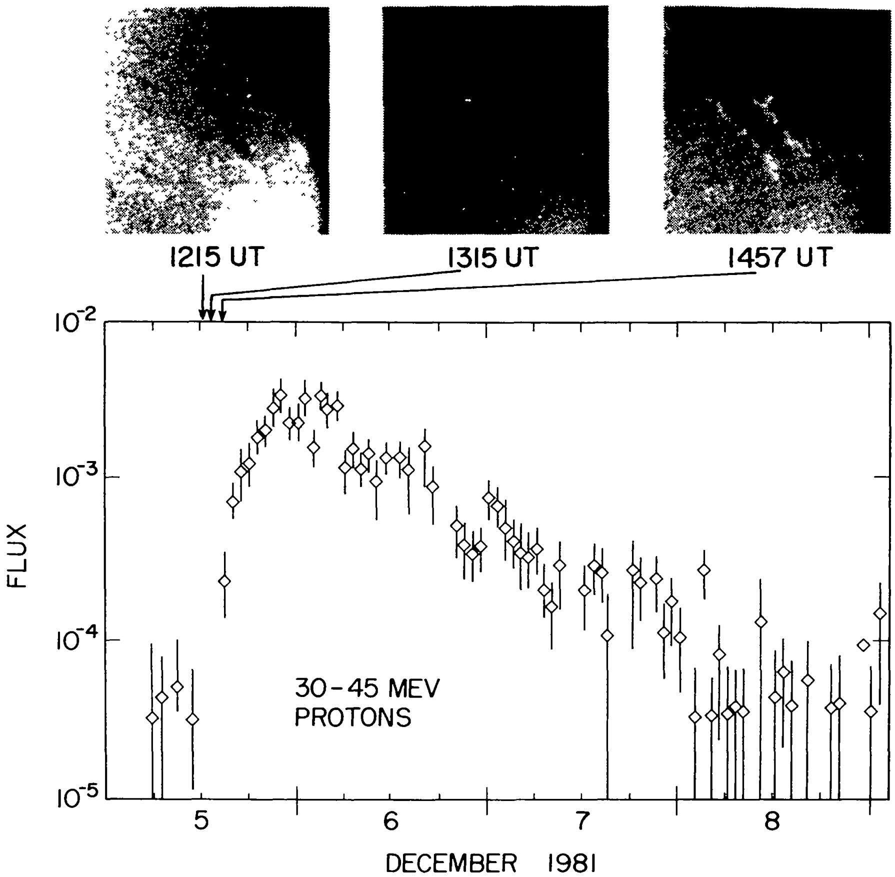

Figure 4 (*Top*) Hα images of the disappearing quiescent filament. The 1457 UT image shows a double-ribbon structure characteristic of active region flares, although the filament was far removed from any active region. (*Bottom*) The flux-time profile of 30–45 MeV protons observed at 1 AU following the filament eruption and CME. From Kahler et al (1986).

studies do not support the idea that the presence of an associated flare has some effect on the characteristics of a CME.

3.5 *Preflare Phenomena and CMEs*

If the CME involves the release of a large amount of coronal energy and begins minutes to tens of minutes before an associated flare, we might expect to find a preflare signature of the CME in the soft X-ray, microwave, or optical wavebands. It has long been known (Martin & Ramsey 1972) that distinct stages of filament activity precede the eruption of the filament itself. Since the erupting filament provides the bright core for many CMEs (Webb & Hundhausen 1987), the pre-eruptive filament activity provides one kind of pre-CME signal. Do we find early coronal signatures of CMEs in other wavebands? Harrison et al (1985) and Harrison (1986) found evidence for soft X-ray enhancements near the times of projected onsets of CMEs and about 20 min before the onsets of several associated flares.

In a recent study of 16 flare-associated CMEs Harrison et al (1990) found some X-ray emission preceding most of the flares, but positional information was lacking for many of those events. Tappin (1991) has also found that nearly all X-ray flares observed with the HXIS instrument on the *SMM* spacecraft were preceded by weak soft X-ray bursts. Thus, we have an indication that weak soft X-ray emission may arise during CME onsets, but this result should be considered tentative.

3.6 *Post-flare Phenomena and CMEs*

Post-flare loop prominence systems (LPS) are magnetic loops observed to overlie the magnetic inversion line for some hours following major flares. Following the detailed description of their properties by Bruzek (1964) and the description of CMEs as eruptions of closed magnetic field lines (MacQueen et al 1974), Kopp & Pneuman (1976) proposed that an LPS forms from magnetic reconnection of oppositely directed field lines. Each newly formed loop is first observable in soft X rays (Sheeley et al 1975, Kahler 1977) and then in Hα after it cools sufficiently. Cargill & Priest (1982) suggested that the rising neutral point trails a pair of slow MHD shocks which heat the upflowing plasma to temperatures as high as 10^7 K (Figure 5). The angular size of an associated CME is much larger than that of the post-flare LPS, which are observed only in active regions at flare sites. Perhaps such a reconnection scenario occurs throughout the open fields associated with the CME, and the LPS can be seen only where the fields are sufficiently strong and the reconnection sufficiently energetic to produce observable loops. Forbes et al (1989) have extended the model of Cargill & Priest (1982) to predict temperatures and maximum heights of flare loops in terms of the coronal vector field (Figure 6).

Cliver et al (1986) and Kosugi et al (1988) have found a type of post-flare event, the gradual hard X-ray burst, which is closely associated with CMEs and major flares. These events follow the occurrences of CMEs by 5 to 60 minutes and are characterized by a hardening of the $E > 30$ keV X-ray spectrum and a high ratio of microwave to hard X-ray fluxes. They are strongly associated with type IV or continuum radio bursts and were interpreted in terms of acceleration and trapping of electrons in a post-flare LPS following a CME (Cliver et al 1986). This interpretation is supported by the observation that the bursts occur in the late phases of flares and are not accompanied by significant changes in Hα flare brightness or area.

Another kind of coronal structure, known as a giant arch, was discovered by Svestka (1983) in images from the *SMM* Hard X-ray Imaging Spectrometer. These large ($> 10^5$ km) structures lie over active regions and appear to brighten in association with double-ribbon flares. Since giant

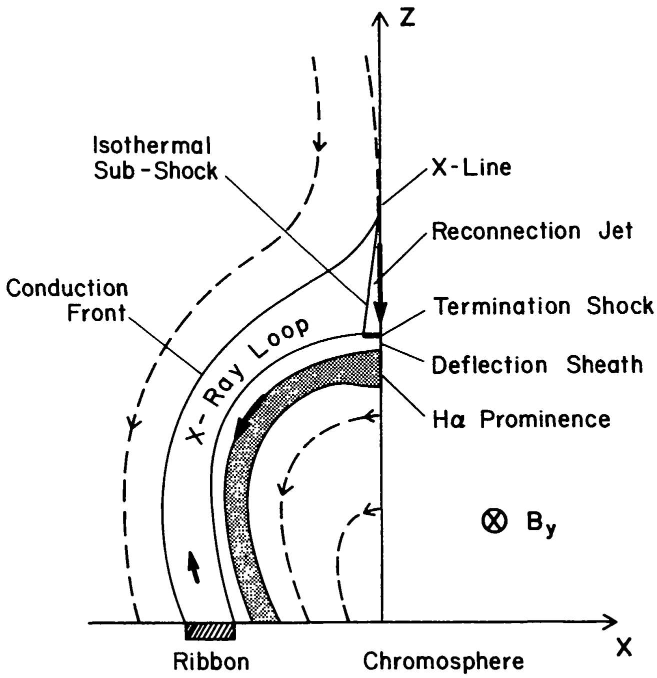

Figure 5 The flow pattern in the reconnection model of flare loops. Magnetic field reconnection at the isothermal subshocks provides the energy to heat the chromosphere. As higher field lines are reconnected, the loops grow in size. From Forbes et al (1989).

arches appear to be quasi-stationary and long-lived, it is difficult to understand how they can be associated with flares normally involved with CMEs (Svestka et al 1989). Two different interpretations of the arches have been suggested (Poletto & Svestka 1990). The first (Hick & Svestka 1987) is that there is a basic long-lived structure which is not disrupted in the double-ribbon flare. However, the reconnection process following the flare adds additional structure to the arch. This view is supported by the apparent long-lived nature of the arches and the lack of any evidence that they are disrupted during the flares. The second interpretation (Poletto & Kopp 1988) is that the arches result from the reconnection of opened field lines in a manner similar to that creating the smaller and underlying post-flare LPS. The Hα footpoints of a series of giant arches observed in November 1980 were detected at the periphery of the active region (Martin et al 1989). Since these footpoints lay at the positions predicted by the current-free modeling of Kopp & Poletto (1990), this would appear to favor the Poletto & Kopp (1988) interpretation.

3.7 *Type II, III, and IV Metric Radio Bursts*

Type II metric radio bursts are interpreted as plasma emission from coronal shocks. The super-Alfvenic speeds ($v > 400$ km/s) of the faster CMEs

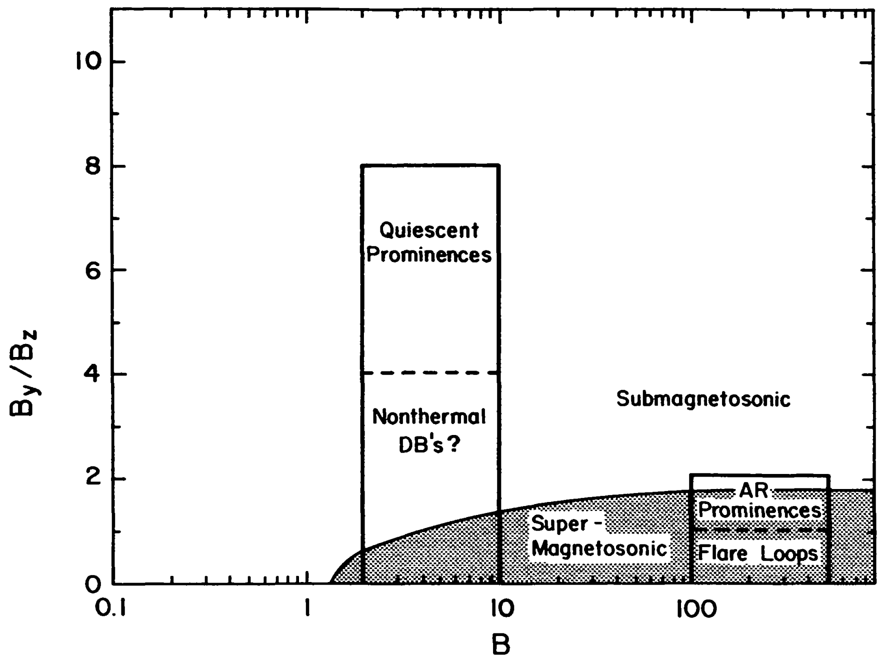

Figure 6 Ratio of B_y, the magnetic field component along the neutral line, to B_z, the vertical magnetic field, versus the total field B. Shaded area indicates where the reconnection jets of Figure 5 are supermagnetosonic. In the model of Forbes et al (1989) post-flare loops can form only in regions such as active regions, which lie in the shaded area.

in the corona suggest that type II bursts are piston-driven coronal shocks. Several studies (Sheeley et al 1984, Robinson et al 1986, Kahler et al 1984b, Sawyer 1985) show that from 60% to more than 80% of all type II bursts are associated with CMEs. Sheeley et al (1984) explained the type II bursts without CMEs as blast wave shocks. Wagner & MacQueen (1983) proposed the more radical idea that all type II bursts, those with and without associated CMEs, are due to blast waves. In their view the blast wave is generated in the flare impulsive phase and then moves through and perhaps ahead of any accompanying CME. The preflare onset times of CMEs and the close association of type II bursts with flares and with impulsive phase radio bursts (Cane & Reames 1988a) supports the blast-wave case. However, the positional associations of type II bursts with filaments and streamers rather than with flares (Stewart 1984) and the fact that type II bursts are rarely associated with slow ($v < 400$ km/s) CMEs (Kundu et al 1989) argues for piston-driven shocks. In addition, most looplike CMEs are preceded by deflections of preexisting coronal features ahead of the CME flanks, suggesting driven waves or shocks running well ahead of the CME fronts (Sime & Hundhausen 1987). Obviously, the relationship between type II shocks and CMEs remains undefined.

Type III radio bursts result from plasma emission and indicate the coronal trajectories of fast ($v \sim 0.15c$) electrons (Dulk 1990). Since the electrons are guided by coronal magnetic fields, their presence may provide a diagnostic of coronal conditions during the CME/flare onset. Strong type III bursts occur preferentially with impulsive (Cane & Reames 1988a) and bright (Poquerusse & McIntosh 1990) flares and may therefore not be a good diagnostic of CMEs. However, Leblanc et al (1983) and Leblanc & Hoyos (1985) found that most type II bursts are associated with U bursts, a kind of type III burst due to electrons streaming along closed magnetic loops. When U bursts accompany type II bursts, the turning frequencies of successive U bursts drift lower, suggesting that the loops are expanding to higher altitudes. Since the expansion rates are similar to characteristic speeds of CMEs, Leblanc & Hoyos (1985) interpret these expanding loops as manifestations of CMEs.

Type IV metric radio bursts consist of broad-band emission usually seen only in conjunction with type II emission (Cane & Reames 1988b). The emission mechanism may be either gyrosynchrotron emission or plasma emission. The two broad classes of type IV bursts consist of moving type IV bursts and stationary type IV bursts, the latter sometimes called storm continuum (Pick 1986). A CME may be a necessary condition for stationary type IV bursts (Robinson et al 1986, Cane & Reames 1988a). Robinson et al (1986) found that nearly half of all CMEs with $v > 400$ km/s were associated with type IV sources located within the CMEs, well behind the leading edge. Other observations (Kerdraon et al 1983) also find stationary type IV bursts in the bright structures at the bases of CMEs. A plausible explanation (Cliver 1983) is that the energetic electrons giving rise to the burst are produced during magnetic reconnection at neutral sheets in newly formed streamers following CMEs.

Because of their outward motion through the corona, we can expect some association between moving type IV bursts and CMEs. Gergely (1986) used several assumptions about the statistics of CMEs and type IV bursts to conclude that the mean speed of moving type IV bursts is less than that of associated CMEs and that the burst regions move behind or along with the CME leading edges. Multifrequency radioheliograph observations have shown that moving type IV bursts are confined to loops and blobs of CMEs (Kundu et al 1989, Gopalswamy & Kundu 1990). The usual association of moving type IV bursts with only fast ($v > 400$ km/s) CMEs (Gosling et al 1976) may be a matter of detection thresholds due to the limitations of radio instrument sensitivities. Kundu et al (1989) reported the observation of a moving type IV burst associated with a slowly moving ($v \sim 200$ km/s) CME. They suggested that a flare may not have been necessary for the production of the energetic electrons in the type IV burst. It is possible that moving type IV bursts arise only from CMEs rather than from flares, but it is not clear that all moving type IV bursts are associated with CMEs (Gergely 1986).

4. INTERPLANETARY EFFECTS

4.1 *Shocks and Shock Driver Gas*

The composition of the interplanetary plasmas and SEPs associated with an observed eruptive solar event can provide the clues we need to distinguish between flares and ambient coronal material as the sources of the eruptions. The signature of a major interplanetary disturbance resulting from such an eruptive event consists of the arrival at the Earth of an interplanetary shock causing a geomagnetic storm and Forbush decrease. The first observations of the elemental composition of the high-speed driver-gas plasmas behind interplanetary shocks showed a He abundance enhancement (HAE) which was presumed to be flare plasma (Hirshberg et al 1972).

Borrini et al (1982, 1983) analyzed the 103 forward shocks and 73 cases of solar wind HAE events (He/H $>$ 10% for $>$2 hr) observed during 1971–1978 with the Los Alamos plasma instruments on *IMP 6*, *7*, and *8*. They found that 44% of the HAE events followed an interplanetary shock within 2 days. Borrini et al (1982, 1983) cited several observational arguments that the HAEs were interplanetary signatures of CMEs. First, the HAEs were well associated with solar type II and type IV radio bursts and varied in frequency of appearance with the solar activity cycle. Second, the high magnetic fields and low proton temperatures suggested a solar origin in strong coronal magnetic fields with closed topologies resulting in adiabatic cooling. While these arguments are certainly consistent with a solar source in CMEs, they could also be used to argue for a source in expelled flare plasma.

Another kind of solar wind He ion enrichment, that of the He^+ ion relative to the normal He^{++} ion, also appears promising as a signature of the cool filamentary material known to be ejected in many CMEs (Illing & Hundhausen 1985). Enhanced He^+ ion abundances have been observed in the solar wind on a number of occasions (Gosling et al 1980, Schwenn et al 1980, Bame 1983). The He^+/He^{++} ratio in these events reaches 0.1, about four orders of magnitude above that expected at coronal temperatures (Ahmad 1977). Cane et al (1986) found that at least 6 of the 15 or so reports of He^+ (Bame 1983) can be associated with solar filament eruptions, suggesting that in these cases some prominence material has reached 1 AU without being raised to coronal temperatures.

The amount of cool filamentary material can be substantial. In one

CME, on 18 August 1980, Illing & Hundhausen (1986) and Athay & Illing (1986) found a prominence mass of $\sim 10^{16}$ g, comparable to that of the rest of the CME. It should be noted, however, that most CMEs do not show the bright cores indicative of prominence plasmas (Webb & Hundhausen 1987) and that many of the features showing prominence-like structures are nearly fully ionized (Illing & Athay 1986). The lack of high instrumental sensitivity to the He^{+} ion may have precluded routine detection of the 1 AU passage of cool filamentary material.

Observations of high ionization states of solar-wind heavy ions have been made with electrostatic analyzers on the *Vela 5* and *6* and *ISEE–3* satellites. Bame et al (1979), Fenimore (1980), and Ipavich et al (1986) compared their heavy ion charge distributions with calculated equilibrium ionization states to deduce that some particle spectra had been heated to temperatures of $2.5\text{–}10 \times 10^6$ K, well above the normal solar-wind ionization temperatures. The association of these heated plasmas with post-shock flows, HAEs, and large solar flares led the authors to invoke flare-heated driver gases as the sources, as Hirshberg et al (1972) had done earlier.

What evidence do we have for flare-heated plasmas as constituents of CMEs? Before we can address that question, we have to be more specific about the term "flare-heated plasma." Three possibilities (Kahler 1988) are 1. hot ($T > 10^7$ K) X-ray emitting flare plasma from the lower corona (Wu et al 1986); 2. coronal plasma in the CME which is radiantly heated by the lower-lying flare plasma; and 3. CME plasma which is heated to temperatures above those of the normal corona. Case 1 involves the flare source responsible for producing X-ray events observed in full-sun detectors. Case 2 corresponds to the model proposed by Mullan & Waldron (1986) in which the 10^7 K flare plasma heats the overlying corona to produce the high ionization states observed in solar energetic particle events. In case 3 some local heating occurs within the CME as energy is released. As discussed above, the white light coronagraph observations do not provide temperature diagnostics for coronal plasmas.

Which of the three candidate flare-heated plasmas look best? Candidate 1, part of the flare plasma itself, seems very unlikely. *Skylab* and *SMM* observations have shown these plasmas to be confined to closed loops in the lower corona. In addition, the ionization temperatures of $\sim 2 \times 10^7$ K early in the flare are higher than what is observed in the solar wind data. Candidate 2, the plasma radiantly heated by flare X-ray emission and modeled by Mullan & Waldron (1986), seems a good choice. The ionization temperatures can differ significantly among the various solar wind ions and the enhanced temperatures should only be seen for CMEs with large X-ray flares. Both conditions are met in the few reported observations.

Candidate 3, heating within the CME, can not be ruled out, but the CME precursor observations of Harrison (1986) and the infrequent observation of moving type IV bursts and X-ray emitting blobs with CMEs suggests that the amount of heated material accompanying CMEs is small in most cases. To summarize, there is certainly evidence in the solar-wind observations for the escape of ions with high ionization temperatures, but it is only infrequently observed at 1 AU and is not likely to be escaping flare plasma.

A good statistical correlation has been found between interplanetary shocks and CMEs. Sheeley et al (1985) reported that 72% of 49 interplanetary shocks detected at the *Helios* spacecraft could be confidently associated with CMEs intersecting the ecliptic. Another 26% were possibly associated with CMEs. Only a few of the speeds of the CMEs producing shocks detected at the *Helios* spacecraft lay below 500 km/s. Cane et al (1987) studied the solar sources of interplanetary shocks fast enough to produce slow-drift kilometric type II radio bursts. They found that all 29 kilometric type II bursts with complementary *Solwind* observations were associated with fast ($v > 500$ km/s) and massive CMEs. A previous study by Cane et al (1986) showed that the eruptions of filaments lying outside active regions were the sources of six interplanetary shocks. Impulsive phases and metric type II bursts were absent in all six cases, showing that a rapid release of energy is not necessary for the formation of an interplanetary shock.

A very different and controversial view of the origin of interplanetary shocks was proposed by Hewish & Bravo (1986). In their study of transient events detected by interplanetary scintillation (IPS) observations at Cambridge they found that the projected solar source regions were always accompanied by coronal holes and suggested that transient activity at hole boundaries could produce interplanetary shocks. Noting the well observed association between coronal holes and high speed streams, they further argued that the 5 or 6 day duration of the high speed solar wind flow behind the shock was inconsistent with the short-lived flow expected from an explosive solar event. This view is not widely accepted for several reasons. First, the significance of the associations with holes is questioned because several holes are usually seen on the disk at any one time (Tsurutani & Gonzalez 1990). Second, the association between CMEs and IPS transients has not been established (Hewish 1990). However, assuming that CMEs are proxies for IPS events, Harrison (1990) found that active regions were far better associated with CME source regions than were coronal holes. Third, contrary to suggestions that large-scale ($>10^5$ km) eruptive events occur in coronal holes (Bravo et al 1991), Kahler & Moses (1990) found only small-scale ($\sim 2 \times 10^4$ km) changes at coronal hole boundaries. Fourth, although the long-duration high speed wind flow is inconsistent with a blast-wave model (Wu et al 1983a), as Hewish & Bravo (1986) point out, it is compatible with a piston-driven ejection corresponding to flows in newly opened coronal fields.

4.2 *Orientations of Flare and Interplanetary Magnetic Fields*

The strongest geomagnetic storms occur when the B_z component of the interplanetary magnetic field points southward (Tsurutani et al 1990). If the transient magnetic fields behind an interplanetary shock arise solely from the eruptive magnetic fields of a flaring region, and if those fields retain their coronal orientation in interplanetary space, perhaps as a magnetic bottle (Gold 1959), then a strong geomagnetic disturbance should be preceded by an eruptive flare in which the coronal fields generally point southward. Pudovkin & Chertkov (1976) found that flares with large-scale ($\sim 10^5$ km) southward fields were associated with intense storms, but flares with northward fields were rarely associated. This result suggested the importance of the solar flare magnetic field orientation for subsequent storm association.

Later work of Dodson et al (1982) and Lundstedt et al (1981) implied that the southward-field criterion for flares somehow selected more energetic flares which were more likely to be associated with geomagnetic storms. Although Pudovkin et al (1977) verified that daily averages of B_z observed several days after flares were rather well correlated with the flare field directions, the Dodson et al (1982) and Lundstedt et al (1981) results suggested flare energetics, rather than interplanetary B_z direction, was the dominant factor in producing geomagnetic storms.

The first contradiction to the idea that southward-field flares are significant for either flare energetics or geomagnetic storms came in a study by Wright & McNamara (1982). They examined the relationships between geomagnetic disturbances, flare energies, and flare-field directions for all large flares between 1968 and 1979. In contrast to Dodson et al (1982), no significant differences among northward, southward, and east-west flare fields in terms of average energies of flares were found. Wright & McNamara (1982) concluded that the sample of flares used by Pudovkin & Chertkov (1976) and Dodson et al (1982) was not typical. Later, Tang et al (1985, 1989) compared interplanetary events of large southward B_z values with associated flare fields and found that in three of five southward B_z events the photospheric fields had no dominant southward component.

The following problems in comparing the interplanetary B_z values with associated flare fields arose in the exchange of differences between Pudovkin & Zaitseva (1986) and Tang et al (1986): 1. uncertainties in making correct flare associations with geomagnetic storms (Neugebauer 1988); 2.

distinguishing the driver gas fields from those of the preceding compressed solar wind where B_z may also be large; and 3. differences in methodology of determining the flare field directions (Lundstedt 1982). In view of the fact that angular sizes of CMEs greatly exceed those of either flares or active regions, one might further expect that the flare fields used in these studies are not the appropriate coronal fields to use for correlation studies with interplanetary fields. The better choice of a coronal source field may be that over an erupting filament, but even that field may be only a part of the entire erupting field of the CME. A further problem is that the filament field generally lies at large angles to the overlying potential field and may be the dominant field of the CME driver. On the other hand, by the time the eruptive field reaches 1 AU, the dominant driver field of a CME may be only that from the associated active region containing most of the eruptive flux. To summarize, we don't know whether large-scale eruptive coronal fields maintain either their integrity or direction in the interplanetary medium, and if they do, we don't know the appropriate coronal source fields.

A common assumption in the preceding studies was that the solar origin of geomagnetic storms lay in flares or active regions. In a search for the solar sources of geomagnetic storms from 1976 to 1979 Joselyn & McIntosh (1981) found that many storms could be associated only with erupting filaments. Superposed epoch analyses have shown that geomagnetic (Wright & McNamara 1983) and interplanetary (Wright & Webb 1990) disturbances typically follow filament disappearances by 3 to 6 days. In view of our earlier discussion of the good correlation between filament eruptions and CMEs on the one hand and between CMEs and interplanetary shocks on the other, this association between filament eruptions and geomagnetic storms is not surprising and serves to diminish further the importance of flares as signatures of CMEs and interplanetary shocks.

4.3 *Interplanetary SEPs*

Solar energetic ($E > 1$ MeV) particle (SEP) events have traditionally been associated with large solar flares and type II and type IV metric radio bursts (e.g. Smith & Smith 1963). SEPs have been presumed to be accelerated at the flare site, probably during the impulsive phase, after which they diffuse through the coronal and interplanetary magnetic fields on their path to the Earth. The first evidence of trouble for this simple picture of SEPs diffusing through a static corona was presented by Kahler et al (1978). Working with SEP events observed during the *Skylab* mission, they found that nearly every SEP event could be associated with a CME or a proxy for a CME, such as an LDE X-ray event. This result was confirmed by comparisons of SEP events and CMEs observed with the *Solwind* coronagraph (Kahler et al 1984a, 1987) that showed a correlation between CME speed and the associated $E > 4$ MeV peak proton flux. The comparable size scales of the CMEs and the region of fast propagation of the SEPs ($\sim$50–90 degrees) suggested that the CMEs defined a dynamical coronal region over which the SEP injection occurred.

Elemental abundance measurements of SEP events have provided evidence for an ambient coronal source of the SEPs. Breneman & Stone (1985) showed that the elemental abundances of a given SEP event differ from the abundances averaged over all SEP events in a way which depends systematically on q/m, the ratio of the charge to the mass of the ions. The derived SEP source elemental abundances are essentially invariant and match the measured coronal abundances. Compared with photospheric abundances, the coronal abundances are known to be deficient in elements with a first ionization potential exceeding about 9 ev (Meyer 1985). Thus, the Breneman & Stone (1985) observations rule out a SEP source with photospheric abundances.

There is now some evidence to suggest that elemental abundances of flare plasmas more closely match the photospheric rather than the coronal abundances (Feldman & Widing 1990), perhaps because the photospheric material is the primary source of the heated flare plasma. The work of Widing & Feldman (1989) suggests a fundamental distinction in elemental abundances between closed and open magnetic structures, matching the nominal photospheric and coronal abundances, respectively. The implication is that the SEP sources lie in the open magnetic structures outside the closed-field structures of flares.

Mason et al (1984) studied the compositional variations of eight SEP events over broad ranges of heliolongitude separation angles between the optical flare sites and the footpoints of the interplanetary magnetic field at the Earth. The relative invariance of the elemental abundances with separation angles was difficult to reconcile with coronal propagation models but was more consistent with acceleration over a large volume of the corona by a shock wave.

A second kind of SEP event is that known as a He^3-rich event. These events are composed of relatively small ion fluxes, with high e/p ratios, scatter-free propagation, and enhanced abundances of He^3 and heavy ions (Reames 1990b, Klecker et al 1990). These events show a correlation of heavy element abundances with flare X-ray temperatures (Reames 1988) and are apparently produced in flares (Reames et al 1988) or in impulsive coronal energy releases (Cliver & Kahler 1991). They are not associated with CMEs or type II bursts (Kahler et al 1985) and are observed only from flares in the western hemisphere of the sun which are well connected to the Earth (Reames et al 1991). Murphy et al (1991) found that the elemental abundances they deduced for a well observed gamma-ray flare on 27 April 1981 differed significantly from those of large SEP events but resembled the abundances observed in the He^3-rich events, further suggesting a flare source for the He^3-rich events. In their survey of elemental abundances of 90 SEP events observed on *ISEE–3*, Reames et al (1990) found evidence for the two classes of events, with all the He^3-rich events having substantially higher Fe/C values than that of the corona (Figure 7).

Ionization state measurements of heavy ions in SEP events showed that the states were consistent with a source in ambient coronal temperatures of $\sim 2 \times 10^6$ K (Gloeckler et al 1981, Luhn et al 1985). The enhanced ionization of several elements such as Mg can be explained by photoionization from flare X-ray fluxes (Mullan & Waldron 1986). The biggest challenge in the SEP ionization states is to understand why the He^+/He^{++} is about 4 orders of magnitude larger than in the ambient corona (Hovestadt et al 1984), since this indicates a cool source of $T \sim 10^4$ K. Contrary to the situation for the relatively small-flux He^3-rich events, in which the SEP ionization states reflect flare temperatures of $\sim 10^7$ K (Klecker et al 1984, Luhn et al 1987), the ionization states of SEPs in large events provide further evidence for nonflare sources in the corona for those events.

More convincing evidence that the sources of SEPs lie outside flare regions would be SEP events associated either with flares lacking an impulsive phase or with a nonflare source. As examples of the former, Cliver et al (1983) discussed a number of SEP events with weak flare impulsive phases, including the GLE of 21 August 1979. They argued that in these

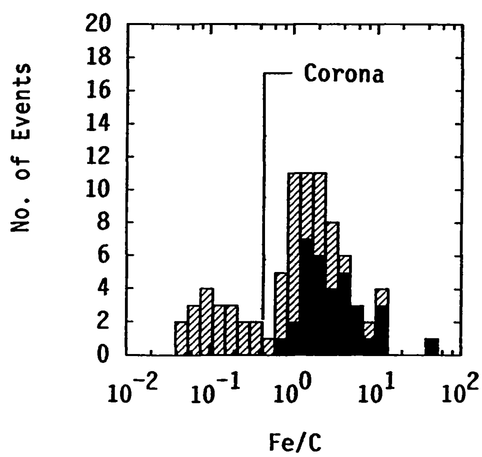

Figure 7 Distribution of Fe/C ratios of ~2 MeV/nucleon SEP events observed at 1 AU. The blackened events indicate the He^3-rich events, which are enhanced relative to average coronal abundances (*vertical line*). The bimodal distribution supports the interpretation of two classes of SEP events. From Reames et al (1990).

cases the explosive heating of the impulsive phase was not adequate to accelerate shocks to produce the SEP event and suggested that the shocks were produced by CMEs. Kahler et al (1986) discussed an example of a SEP event with both protons of $E > 50$ MeV and relativistic electrons which was clearly associated with a fast CME and the eruption of a quiescent filament which lay well away from any active region (Figure 4). A flare-like double ribbon was observed on the disk in Hα, but a weak interplanetary type II burst was the only radio emission detected from this event. These phenomena suggest that all the particle acceleration occurred in the high corona.

While the above results argue strongly for nonflare sources for the SEP events, there is also evidence that some SEP events may result from both flare and nonflare sources. Cliver et al (1989) examined 4–8 MeV gamma-ray line (GRL) fluences produced by $E > 10$ MeV protons in flares. They calculated the ratios of those fluences to the peak ~ 10 MeV proton fluxes in the SEP events associated with those flares. The ratios varied by over 4 orders of magnitude, but nearly every GRL flare was associated with a SEP event, suggesting that at least some of the 10 MeV protons in the flare region were escaping to interplanetary space. Reames (1990a) has discussed several examples of SEPs in which the Fe/O ratio was initially high, but then declined to values characteristic of coronal values. He suggested that the earliest part of the SEP event may have been dominated by SEPs produced in the impulsive phase of the flare, which was magnetically well connected to the Earth. Further, Cliver et al (1982) found that the onsets at 1 AU of the ~ 1 BeV protons in GLE events were well associated with signatures of the flare impulsive phases.

To summarize, the abundance and ionization state measurements of SEPs strongly suggest the ambient corona, rather than a flare-heated plasma, as the primary source for these particles. The situation is complicated by the fact that a class of SEPs do originate in flare plasmas, and hybrids of the two kinds of events may occur. It is clear, however, that the classical picture of all SEPs originating in flares is no longer valid.

5. CONCLUSIONS

The high temperatures and rapid energy release characteristic of eruptive flares led early investigators to assume that flares were the direct causes of interplanetary SEP events and shock waves causing the most intense geomagnetic storms. Until recently, CMEs associated with flares were assumed to be a consequence rather than a cause of flares. Hudson (1987), for example, in his list of 42 discoveries that have changed our understanding of the physics of solar flares, found no place for CMEs. In this review I have tried to show that a broad spectrum of evidence now supports a primary role for CMEs in the production of SEPs and shocks observed at 1 AU.

The recent trend in modeling CMEs is to assume a loss of equilibrium in the large-scale coronal magnetic field (Low 1990). One promising approach is to model the shear of a dipole configuration with azimuthal photospheric motions in opposite directions on each side of the magnetic neutral line (Biskamp & Welter 1989, Wu et al 1991, Steinolfson 1991). Observations of active regions have shown the importance of the shear angle for the occurrence of flares (Moore et al 1987). In addition, magnetic shear can lead to the loss of equilibrium which may also induce eruptions of prominences (Zweibel 1991), although the prominence eruption can not be the driver of the CME (Hundhausen 1988).

Despite substantial progress in understanding the relationships between flares, CMEs, and the interplanetary consequences of these phenomena, many problems remain. We still have not determined the exact boundaries of the eruptive coronal magnetic fields involved in CMEs. The development of the erupting closed fields of the CME into open fields in the interplanetary medium is not understood. The relationship of impulsive flares to CMEs (Kahler et al 1989) is still unknown, and the roles of flare-driven blast-wave shocks and CME-driven shocks have yet to be defined. Although flares appear as consequences of CMEs, it is possible that very energetic flares may still have some influence on the development of associated CMEs. In addition, source regions of SEPs and their relationships to flares and coronal shocks are only crudely known. Despite the apparent wealth of observations, some rather fundamental problems of coronal physics await solution.

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