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The Solar Flare Myth

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Many years of research have demonstrated that large, nonrecurrent geomagnetic storms, shock wave disturbances in the solar wind, and energetic particle events in interplanetary space often occur in close association with large solar flares. This result has led to a paradigm of cause and effect - that large solar flares are the fundamental cause of these events in the near-Earth space environment. This paradigm, which I call "the solar flare myth," dominates the popular perception of the relationship between solar activity and interplanetary and geomagnetic events and has provided much of the pragmatic rationale for the study of the solar flare phenomenon. Yet there is good evidence that this paradigm is wrong and that flares do not generally play a central role in producing major transient disturbances in the near-Earth space environment. In this paper I outline a different paradigm of cause and effect that removes solar flares from their central position in the chain of events leading from the Sun to near-Earth space. Instead, this central role is given to events known as coronal mass ejections.

SOLAR FLARES AND NONRECURRENT GEOMAGNETIC STORMS

In 1859, R. Carrington, a solar astronomer, observed an intense, short-lived brightening of the surface of the Sun in the vicinity of a sunspot [*Carrington*, 1860]. Figure 1 shows the sketch that Carrington made of this event based upon his white light observations. Such brightenings on the surface of the Sun are now known as solar flares and have been the objects of extensive research during the present century. Carrington noted that a particularly large geomagnetic storm began within a day of the flare he observed, and he very tentatively suggested that a causal relationship might exist between the solar and geomagnetic events. This observation and suggestion, together with Sabine's observation that geomagnetic activity appeared to track the 11-year sunspot cycle [*Sabine*, 1852], mark the beginning of the study of solar-terrestrial physics, which is concerned with the physical links between phenomena that occur on the Sun and phenomena that occur in the near-Earth space environment.

In the years since Carrington's discovery of solar flares numerous examples of apparent associations between flares and large, nonrecurrent geomagnetic storms have been noted [e.g., *Hale*, 1931; *Newton*, 1943]. The apparent association between flares and large nonrecurrent storms is, however, far from one-to-one. Many large, nonrecurrent geomagnetic storms have no obvious association with solar flares, and many large solar flares are not followed by large geomagnetic storms. Nevertheless, the occurrence frequency of large, nonrecurrent geomagnetic storms does wax and wane roughly in phase with the ~11-year solar activity cycle [e.g., *Greaves and Newton*, 1928]. *Hale* [1931] and (later) *Chapman* [1950] suggested that these relationships could be explained if large, nonrecurrent geomagnetic storms result from the interaction of the Earth's magnetic field with streams of plasma emitted into interplanetary space from large solar flares. Since then, this suggestion has dominated much of the thinking on the relationship between solar activity and nonrecurrent geomagnetic storms and has provided much of the modern impetus for the study of the solar flare phenomenon. (It is interesting to note that *Chapman and Ferraro* [1931*a*, *b*, 1932] are often given credit for this suggestion [e.g., *Parker*, 1963; *Hundhausen*, 1972*b*; *Hargreaves*, 1992]; however, Chapman and Ferraro did not directly relate the ejection of material from the Sun to the flaring process. Further, the original suggestion that a plasma ejection from the Sun is responsible for nonrecurrent geomagnetic storms seems to be due to *Lindemann* [1919], who places the ejections into the context of overall solar activity without mentioning solar flares explicitly.)

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SOLAR FLARES AND ENERGETIC PARTICLE EVENTS

A particularly large flare occurred on the western hemisphere of the Sun on February 23, 1956. As shown in Figure 2, intense fluxes of energetic ions (with energies up to 10-15 GeV) were detected by ground-based neutron monitors within minutes of the flare onset. The particle radiation was also detected indirectly in the polar regions of Earth by the fade-out of cosmic radio noise. Such fade-outs, commonly called polar cap absorption (PCA) events, are caused by enhanced ionization in the *D* region of the ionosphere associated with the influx of protons with energies of approximately 20 MeV and above. Figure 2 shows that at these lower energies the February 1956 particle event persisted for a number of days. The detailed study of energetic particle events associated with solar activity began with this event, although several ground level events, apparently associated with flares, had been noted prior to the February 1956 event [*Forbush*, 1946].

With the development of more sophisticated measurement techniques and the advent of satellite measurements, many more energetic particle events with durations of several days or more were observed in the years immediately following 1956 [e.g., *Webber*, 1962]. Most of these events appeared to be associated with large solar flares. However, it was noted that prompt arrival of energetic particles was generally restricted to flare events occurring in the western solar hemisphere where one would expect good magnetic connection between the flare site and the Earth along the interplanetary magnetic field spiral; the delay could be as much as several hours to a day or longer for events originating in the eastern solar hemisphere. Moreover,

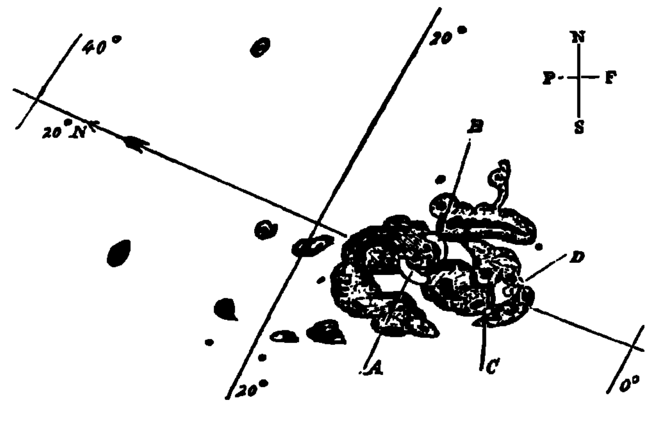

Fig. 1. Carrington's sketch of a solar flare observed in white light on September 1, 1859. The flare is the pair of crescent-shaped objects labeled A and B. During the course of the event, which lasted for just a few minutes, the flare ribbons migrated to positions C and D before fading from view. The dark regions in the sketch are sunspots [from *Carrington*, 1860].

many large solar flares did not produce energetic particle events at Earth even when they occurred in the western solar hemisphere. Some energetic particle events had no obvious associations with flares on the visible solar disk; such events were thought to arise from flares on the back side of the Sun. These events came to be called solar flare energetic particle events or solar energetic particle events (SEPs), with "flare" being understood. It was generally believed that the energetic particles in these events were accelerated at or directly above the flare site, the energy for the acceleration being derived from the strong magnetic fields in the flaring region. Observations of SEPs gave further strong impetus to the study of the flare phenomenon.

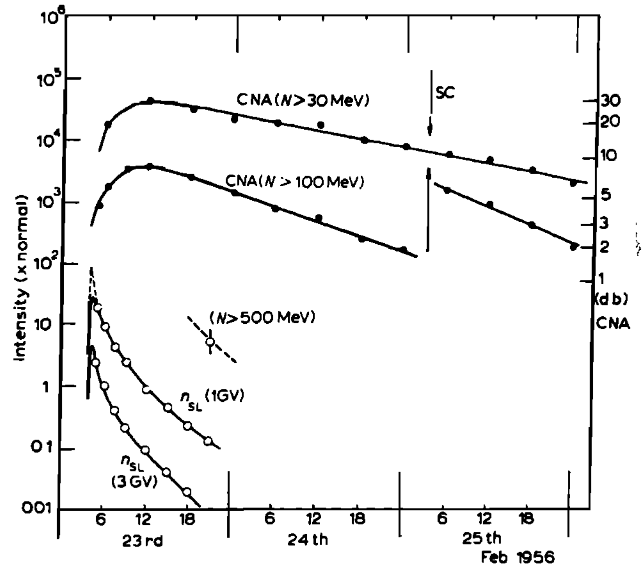

Fig. 2. The great energetic particle event of February 1956 as measured at different energies. The open circle points are from ground-based neutron monitors and the solid circle points are particle fluxes inferred from cosmic noise absorption measurements. The event began within minutes following a large solar flare that reached maximum intensity at 0342 UT on February 23, 1956. The sudden commencement of a large geomagnetic storm early in the day on February 25, 1956, is indicated by arrows; note the increase in cosmic noise absorption associated with the sudden commencement [from *Webber*, 1962].

Solar Flares and Interplanetary Shock Wave Disturbances

In 1955, T. Gold suggested that high-speed plasma ejected from the Sun during a solar disturbance would produce a collisionless shock in the interplanetary plasma as it forced its way outward into interplanetary space [*Gold*, 1955]. This shock would run in front of the ejected plasma and would initiate the compression and deflection of the ambient interplanetary plasma away from the path of the newly ejected material. Gold suggested that the sudden commencements of geomagnetic storms were caused by the impact of such shocks on the Earth's magnetosphere.

The first direct observations of a shock wave disturbance in interplanetary space were made with instruments aboard Mariner 2 in 1962 [*Sonett et al.*, 1964]. That particular shock disturbance was apparently not related to a solar flare; however, several interplanetary shocks observed shortly thereafter by other spacecraft apparently were [*Gosling et al.*, 1968]. Subsequent attempts at relating observed interplanetary shock disturbances with solar flares met with mixed success [e.g., *Hundhausen*, 1972*a*, *b*]. No flare associations were obvious for some shock disturbances, and many observed solar flares did not produce shock disturbances in the solar wind near the Earth, even when they occurred near the central meridian of the Sun. Nevertheless, it was generally thought that transient shock wave disturbances in the solar wind near 1 AU were predominantly a flare-related phenomenon. The sketch of an interplanetary shock disturbance driven by a flare ejection shown in Figure 3 is representative of this line of thought. Further, most (but not all) geomagnetic sudden commencements were associated with Earth passage of shock disturbances, as first suggested by Gold [e.g., *Smith et al.*, 1986].

An Historical Paradigm of Cause and Effect

Despite some of the troubling uncertainties noted above, the apparent relationship between solar flares and interplanetary and geomagnetic events was sufficiently strong

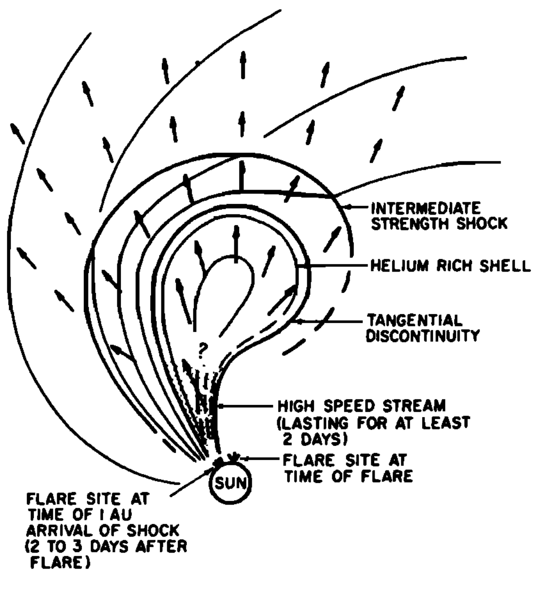

Fig. 3. A sketch of an interplanetary shock disturbance in the ecliptic plane driven by an ejection of material from a solar flare. Except for the emphasis on solar flares, this sketch is still relevant today [from *Hundhausen*, 1972*a*].

to have led to a paradigm of cause and effect that I believe still dominates much of the popular perception of the relationship between solar activity and these events (for example, see book articles by *Rust* [1987], *Dryer* [1987], and *Sakurai* [1987] and books by *Bone* [1991] and by *Hargreaves* [1992]). In its most elementary form the paradigm might be stated: large solar flares are the prime cause of large, nonrecurrent geomagnetic storms, transient shock wave disturbances in the solar wind, and major energetic particle events. This paradigm is what I call "The Solar Flare Myth."

Figure 4 outlines the major elements of the paradigm. As already noted, the paradigm originated in the suggestions of Hale and Chapman and others with regard to observed associations between solar flares and nonrecurrent geomagnetic storms and was modified as associations between flares and energetic particle events and shock wave disturbances also became apparent. Most of the elements of the paradigm have been in place since at least the early 1960s (for example, see *Parker* [1963] and *Webber* [1962]). A (perhaps oversimple) elaboration of the paradigm might proceed somewhat as follows in this and the following paragraph: Solar activity is associated with the evolution of the solar magnetic field. Large solar flares occur in magnetically complex regions where the field is often strongly sheared. The actual energy release mechanism associated with flaring activity is uncertain but is usually thought to include some form of magnetic reconnection. During the flare process some fraction of the charged particles present in the vicinity of the flare site are accelerated to high energy (right-hand branch in Figure 4). Some of these accelerated particles escape quickly into space along the interplanetary magnetic field; others are trapped in closed field regions at the Sun, diffuse slowly across field lines in the solar atmosphere, and leak out into interplanetary space over a period of several days. When the energetic particles arrive at 1 AU (or at a spacecraft) they cause a solar particle event; when they impinge upon the upper atmosphere in the polar regions of the Earth they cause a PCA event.

The flare process also substantially heats the chromosphere and the corona in the region immediately surrounding the flare site (left-hand branch in Figure 4). This heating, in possible

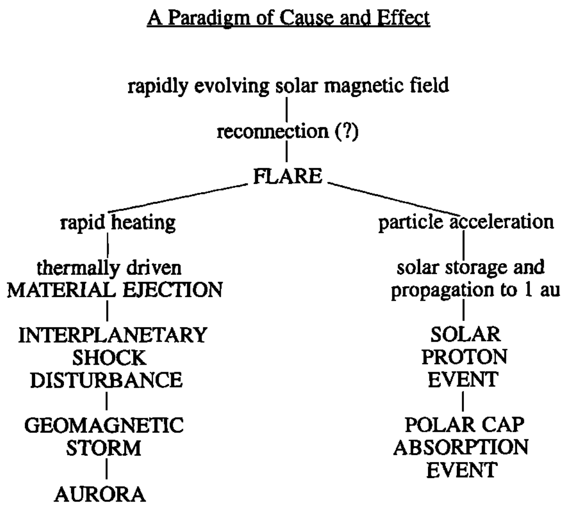

Fig. 4. The solar flare myth, a paradigm of cause and effect illustrating the supposed central position of solar flares in solar-terrestrial phenomena. Capital letters indicate observational phenomena and lowercase letters indicate physical processes or descriptive characteristics.

conjunction with magnetic forces, produces a rapid expansion of the chromosphere and corona around the flare site. When the speed of the rapidly expanding corona and/or chromosphere material is sufficiently high, a shock disturbance is produced in interplanetary space. A large geomagnetic storm and auroral disturbance results when this interplanetary disturbance impinges upon the Earth's magnetosphere.

Some form of the foregoing paradigm is often either stated explicitly or implied in scientific articles and books, in presentations at scientific meetings and colloquia, in posters and other material released for educational purposes, and in the popular press. Unfortunately, there is good evidence that this paradigm, which has grown to almost mythical proportions, is wrong. Here I will attempt to outline the rationale for a different paradigm of cause and effect in solar-terrestrial physics that removes solar flares from their central position in the chain of events leading from solar activity to interplanetary and geomagnetic disturbances. Certain aspects of this new paradigm have been apparent since the mid-1970s and have been championed elsewhere [e.g., *Joselyn and McIntosh*, 1981; *Gosling et al.*, 1981; *Cliver et al.*, 1983; *Mason et al.*, 1984; *Cane et al.*, 1986; *Lin*, 1987; *Hundhausen*, 1988; *Kahler*, 1992; *Reames*, 1992*a*, *b*, 1993; *Svestka and Cliver*, 1992; *Webb*, 1993; *Mandzhavidze and Ramaty*, 1993]; however, it is my experience that this new paradigm in its entirety is usually not fully appreciated even by those directly involved in studying solar and interplanetary events and their geomagnetic effects, and it does not yet seem to have caught the attention of the larger solar-terrestrial physics community or the popular press. One motivation of this paper is to help bring this modern paradigm to the general attention of these communities.

CORONAL MASS EJECTIONS CLOSE TO THE SUN

Observations made with white light coronagraphs flown on OSO 7 and Skylab in the early 1970s convincingly demonstrated that large quantities of material (10^{+15} - 10^{+16} g) are sporadically ejected from the Sun into interplanetary space [e.g., *Tousey*, 1973; *Gosling et al.*, 1974]. Figure 5 shows two snapshots of an event observed by the Skylab coronagraph. Such transient ejections of material are now known as coronal mass ejections (CMEs). These events have been extensively studied not only with the coronagraphs flown on OSO 7 and Skylab but also with ground-based coronagraphs and with coronagraphs flown on the P78 and SMM satellites (see, for example, reviews by *Hundhausen* [1988] and *Kahler* [1988]) and with photometers flown on Helios [e.g., *Jackson*, 1985; *Webb and Jackson*, 1990]. The probable connection between CMEs, interplanetary disturbances, nonrecurrent geomagnetic storms, and the ideas of Lindemann, Hale, Chapman, and others has long been recognized by many of those involved in these measurements (for example, see *Gosling et al.* [1974]). However, it has been obvious since the first observations of CMEs that these events are not fundamentally a flare-related phenomenon (see below).

Table 1 summarizes some of the important characteristics of CMEs as observed by satellite-borne coronagraphs. As illustrated by the distribution of CME speeds observed by the Skylab coronagraph and shown in Figure 6, individual CMEs exhibit a wide range of outward speeds, with the average CME leading edge speed being close to that of the average solar wind at 1 AU [e.g., *Gosling et al.*, 1976; *Howard et al.*, 1985]. Like other forms of solar activity, CMEs occur with a frequency that

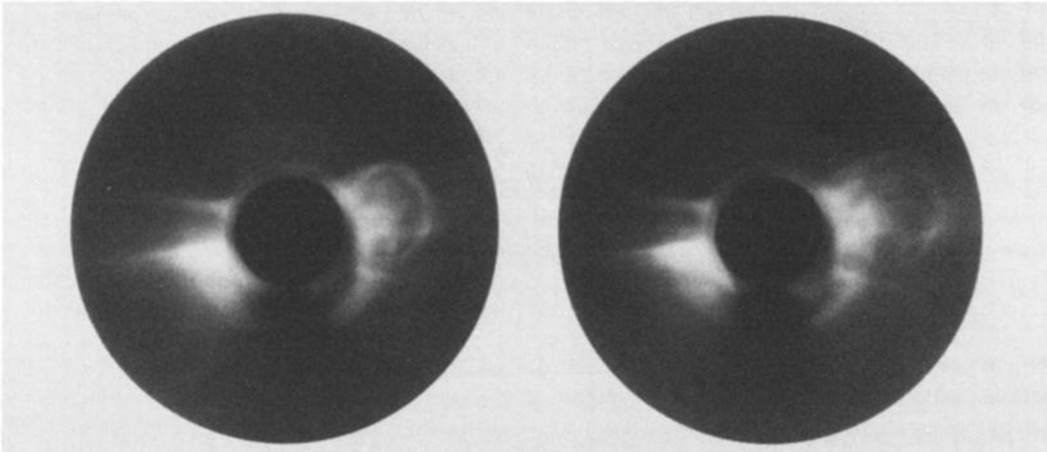

Fig. 5. Two snapshots of a coronal mass ejection event observed above the west limb of the Sun with the white light coronagraph on Skylab on August 10, 1973. The field of view of the photographs is 6 solar diameters, and the snapshots are separated in time by 24 mins. As is common in many of these events, the August 10, 1973, CME was not associated with a solar flare (adapted from *Gosling et al.* [1974]).

varies in a cycle of ~11 years; the occurrence frequency varies by roughly an order of magnitude between solar activity minimum and solar activity maximum [*Webb*, 1991]. CMEs originate in closed field regions in the corona not previously participating in the solar wind expansion [e.g., *Gosling*, 1976; *Hundhausen*, 1988]. Typically, these closed field regions are found in the coronal streamer belt that encircles the Sun and that underlies the heliospheric current sheet.

CMEs are frequently, but not always, observed in association with other forms of solar activity such as solar flares and eruptive prominences. Of these, the most common association is with eruptive prominences, which often lie well away from active regions [e.g., *Gosling et al.*, 1974; *Munro et al.*, 1979] (see also the review by *Webb* [1992]). As illustrated in Figure 7, CMEs often occur at much higher solar latitudes than do active regions or solar flares [*Hundhausen*, 1993], another good indication that CMEs are not uniquely related to solar flares. Because of their common association with the base of the heliospheric current sheet, CMEs tend to be concentrated at low solar magnetic latitudes rather than at low heliographic latitudes; by way of contrast, solar active regions where flares generally originate are found almost entirely at low heliographic latitudes, as shown in Figure 7. The Skylab observations indicated that even though some of the prominence-associated events had quite high outward speeds, on the average flare-associated events had higher outward speeds than did prominence-associated events. On the other hand, such speed differences are less apparent in the more recent SMM observations (A. J. Hundhausen, private communication, 1993).

On those occasions when CMEs and flares do occur in close temporal association with one another, the CMEs usually begin to lift off from the Sun before any substantial flaring activity has occurred [e.g., *Harrison*, 1986; *Hundhausen*, 1988; *Harrison et al.*, 1990]. The upper panel of Figure 8 illustrates schematically the relative timing between CME lift off and flare onset documented in the *Harrison et al.* [1990] study. Moreover, as illustrated in the lower panel of Figure 8, any associated flaring that does occur often lies to one side of the much broader (typically many tens of degrees wide) CME span. This clearly indicates that CMEs are not generally caused by solar flares even though these different aspects of solar activity can occur together. It seems likely that both CMEs and solar flares arise from instabilities connected with the temporal and spatial evolution of the magnetic field in the solar atmosphere, with CMEs resulting more from changes in the large-scale magnetic field that permeates the solar corona [e.g., *Low*, 1993] and flares resulting more from changes in the stronger, but smaller scale, fields associated with solar active regions.

CMEs often (~1/3 of all events) occur in conjunction with long-duration (many hours), soft X ray events that commonly begin near the time that CMEs lift off from the Sun [e.g., *Sheeley et al.*, 1975, 1983]. These long-lived X ray events seem to be associated with a restructuring of the solar corona

TABLE 1. Characteristics of Coronal Mass Ejection Events Near the Sun

Characteristic	Value
Mass ejected	10^{+15} - 10^{+16} g
Speed of leading edge	<50 km s^{-1} to > 1200 km s^{-1}
Average speed of leading edge	~400 km s^{-1}
Average heliocentric width	~45 deg
Occurrence frequency	~3.5 events d^{-1} (solar activity maximum)
	~0.2 events d^{-1} (solar activity minimum)
Site of origin	closed field regions in corona (typically underlying heliospheric current sheet)
Associated solar activity	eruptive prominences (common)
	long duration soft X ray events (~1/3 of all events)
	impulsive X ray events and optical flares (some of the time)
	type II and IV radio bursts (the faster events)
	nothing (some of the time)

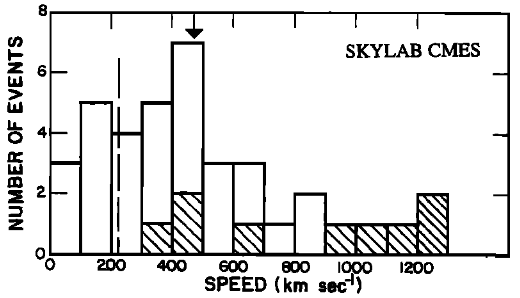

Fig. 6. The number distribution of measured speeds of the leading edges of coronal mass ejection events observed by Skylab on the declining phase of the solar activity cycle from June 1973 through January 1974. Cross hatching indicates events where the assigned speed is only a lower limit estimate. The arrow indicates the average speed of all the events and the vertical dashed line indicates the gravitational escape speed for material at a heliocentric distance of six solar radii (adapted from *Gosling et al.* [1976]).

following the ejection of the CMEs and commonly involve the formation of new loops of hot material low in the corona. These newly formed loops are probably a result of the pinching off (reconnection) of some of the closed field lines embedded within the outward moving CMEs [e.g., *Kopp and Pneuman,* 1976]. It is unlikely, however, that the "legs" of the magnetic loops ever interconnect with themselves to form fully detached plasmoids in interplanetary space, as is often surmised from two-dimensional drawings. Rather, as illustrated in Figure 9, reconnection should preferentially occur between the legs of neighboring loops; such reconnection produces CMEs with a flux rope topology in interplanetary space [*Gosling,* 1990].

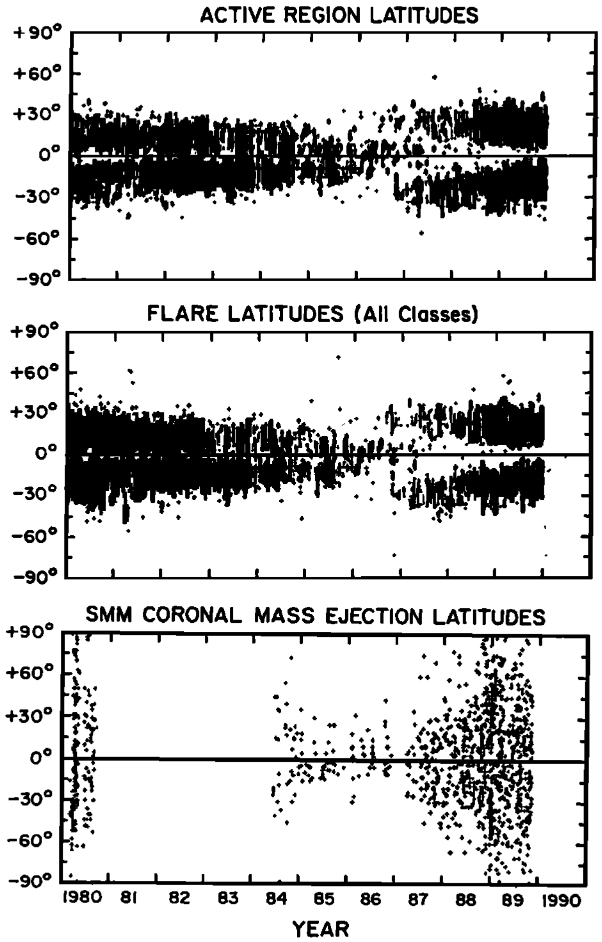

Fig. 7. Scatterplots of the latitudes of solar active regions, optical flares, and coronal mass ejections (as observed with the coronagraph experiment on SMM) as a function of time. No CME observations were available from late 1980 until early 1984 and after late 1989. This plot illustrates that CMEs tend to occur at different latitudes than do active regions and flares, and helps emphasize that CMEs are not fundamentally a flare-related phenomenon (adapted from *Hundhausen* [1993]).

CORONAL MASS EJECTIONS IN INTERPLANETARY SPACE

The leading edges of the faster CMEs have outward speeds considerably greater than that associated with the normal solar wind expansion and should drive shock wave disturbances in the solar wind [e.g., *Gosling et al.,* 1975, 1976]. Indeed, studies reveal that virtually all transient (as opposed to corotating) shock wave disturbances in the solar wind are driven by CMEs [e.g., *Sheeley et al.,* 1985; *Cane et al.,* 1987]. The identification of CMEs in solar wind plasma and field data is still something of an art. In this regard, shocks serve as useful fiducials for identifying fast CMEs. A number of plasma and field signatures have been recognized in solar wind data that qualify as unusual compared to the normal solar wind but that are commonly observed a number of hours after shock passage (where one would expect to encounter a fast CME) and that are often used to identify CMEs. These signatures have been reviewed elsewhere [*Gosling,* 1990, 1992] and include the following: (1) counterstreaming (along the field) halo electrons, (2) counterstreaming energetic protons (>~20 keV), (3) helium abundance enhancements (He^{++}/H^{+} > ~.08), (4) ion and electron temperature depressions, (5) strong magnetic fields (>~8nT), (6) low plasma beta (<1.0), (7) low magnetic field strength variance, (8) anomalous field rotations (flux ropes), and (9) unusual plasma ionization states (e.g., Fe^{+16}, He^{+}). Most of these anomalous signatures are also often

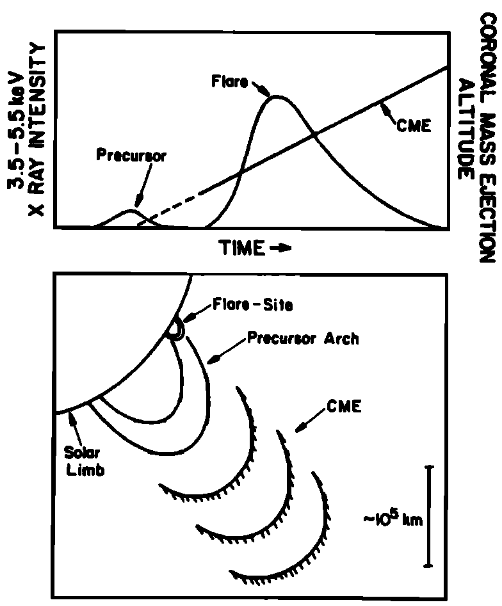

Fig. 8. Sketches illustrating the temporal and spatial relationships between X ray flares and coronal mass ejections inferred from the study by *Harrison et al.* [1990, p. 917] and summarized as follows: "Our findings confirm recent suggestions that CME onsets precede any related flare activity and that the associated flaring commonly lies to one side of the CME span. The CME launch appears to be associated with minor X ray (flare precursor) activity." This study clearly showed that even when flares and CMEs occur in conjunction with one another the flares are not, in general, the cause of the CMEs [from *Hundhausen,* 1988].

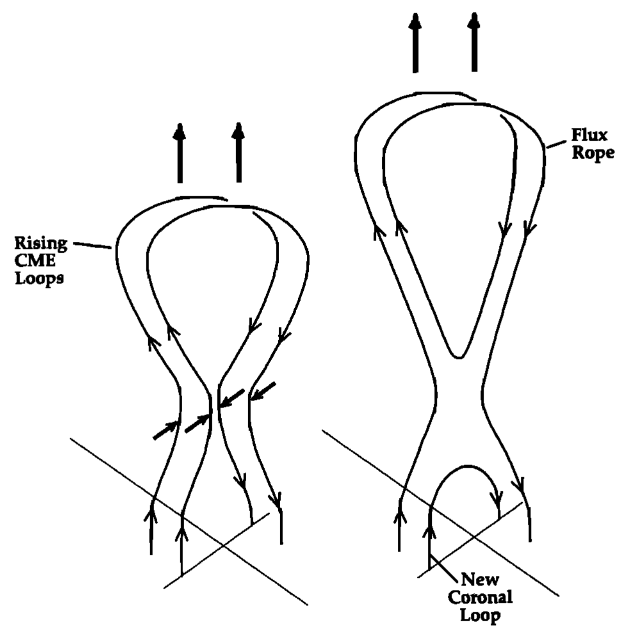

Fig. 9. Sketches illustrating the pinching off (reconnection) of the magnetic loops in a rising CME whose legs are sheared relative to one another. When the force pushing the legs together is at an angle relative to the original planes of the loops, new magnetic interconnections are made (the individual magnetic loops do not reconnect with themselves) and a rising flux rope is formed as well as new closed magnetic loops low in the corona. Observations of long-duration X ray events and post-CME loops in the corona and of flux ropes in interplanetary space suggest that magnetic reconnection occurs in ~1/3 of all CME events.

observed in the absence of shocks where, presumably, they serve to identify those numerous relatively low speed CMEs that do not drive shock disturbances. Few CMEs at 1 AU exhibit all of the characteristics noted above, and some of these characteristics are more commonly observed than are others. Present experience indicates that a counterstreaming flux of suprathermal solar wind halo electrons above ~80 eV probably provides the most reliable means of identifying a CME in the solar wind at 1 AU. As illustrated in Figure 10, the relative reliability of the counterstreaming electron signature is related to the closed magnetic field topology typical of most CMEs, which contrasts with the "open" topology of field lines within the normal solar wind.

Table 2 summarizes some of the important characteristics of CMEs as observed in the solar wind at 1 AU, derived primarily from observations of counterstreaming solar wind halo electron events. CMEs have variable radial thicknesses, but the average is close to 0.2 AU. Observed flow speeds within CMEs range from less than 300 to greater than 1000 km s^{-1}, with the average speed being close to that of normal solar wind (~400 km s^{-1}). Approximately 1/3 of all CMEs have sufficiently high speeds relative to the ambient solar wind ahead to drive shock disturbances; the remainder simply ride along with the rest of the solar wind. Approximately 1/3 of all CMEs at 1 AU (not necessarily the same 1/3 as above) appear to have the internal field topology characteristic of twisted flux ropes [*Gosling*, 1990] as might be expected if reconnection close to the Sun occurs in ~1/3 of all CME events (see previous section). Interplanetary flux ropes are commonly known as magnetic clouds when the field strength at 1 AU exceeds approximately 10 nT [e.g., *Burlaga*, 1991]. On the average, the Earth intercepts approximately six CMEs every month near solar activity maximum, but less than one CME per month near solar activity minimum. Averaged over the solar activity cycle, CMEs account for about 7% of all solar wind measurements in the ecliptic plane at Earth's orbit.

CORONAL MASS EJECTIONS AND LARGE NONRECURRENT GEOMAGNETIC STORMS

Numerous studies have shown that large geomagnetic storms are stimulated by high solar wind flow speeds and prolonged intervals of a strong southward directed interplanetary magnetic field (IMF) (see, for example, *Rostoker and Falthammar* [1967], *Burton et al.* [1975], and the review by *Baker et al.* [1984]). These associations reflect the fact that energy from the solar wind is transferred to the Earth's magnetosphere primarily by means of reconnection between the IMF and the terrestrial magnetic field at the dayside magnetopause, which favors such interplanetary conditions. Because high flow speeds and strong magnetic fields, often with strong southward components, are features common to many interplanetary disturbances driven by fast CMEs, these disturbances can be very effective in stimulating geomagnetic activity, as illustrated by the March 22, 23 1979 event shown in Figure 11. The particularly strong fields in such disturbances are primarily the result of compression in interplanetary space. The orientation of the field within the compressed ambient plasma ahead of the CMEs is affected by field line draping about the CMEs in interplanetary space [e.g., *Gosling and McComas*, 1987; *McComas et al.*, 1989], whereas the orientation of the field within the CMEs themselves probably is determined by conditions back at the Sun. As demonstrated below, CME-driven interplanetary disturbances such as that shown in Figure 11 are the cause of virtually all large, nonrecurrent geomagnetic storms.

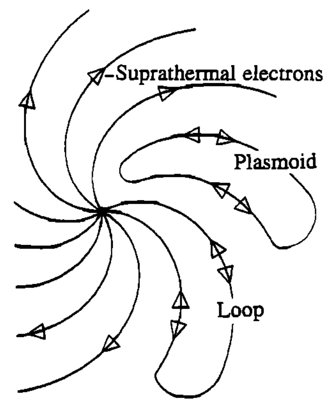

Fig. 10. A sketch illustrating several possible magnetic field topologies in interplanetary space and the corresponding types of suprathermal electron streaming that is observed. Field lines in the normal solar wind are "open" (in the sense that they connect to field lines of the opposite polarity only in the distant heliosphere very far from the Sun) and are thus effectively connected to a hot source (the solar corona) at only one end. This type of connection results in a unidirectional flux of hot, suprathermal electrons streaming outward from the corona along the field. CMEs, on the other hand, generally originate in closed field regions in the solar corona not previously participating directly in the solar wind expansion, and field lines threading CMEs thus are initially connected to the hot solar corona at both ends as illustrated here by the loop. Such a field topology results in suprathermal electrons moving outward from the corona from both footpoints, producing a counterstreaming flux of these electrons in interplanetary space. The counterstreaming fluxes are trapped on the field lines within the structure if the field lines reconnect with themselves to form a plasmoid (a limiting case of the more general three-dimensional reconnection situation illustrated in Figure 9) [from *Gosling*, 1993].

TABLE 2. Characteristics of Coronal Mass Ejections in the Solar Wind at 1 AU

Characteristic	Value
Average radial thickness	0.2 AU
Range of speeds	300 - 1000 km s^{-1}
Single point occurrence frequency	~72 events $year^{-1}$ (solar activity maximum) ~8 events $year^{-1}$ (solar activity minimum)
Magnetic field topology	predominantly closed magnetic loops, ~1/3 are twisted flux ropes
Fraction of events driving shocks	~1/3
Fraction of earthward directed events producing large geomagnetic storms	~1/6

Figure 12 summarizes the associations found between geomagnetic storms and Earth passage of interplanetary disturbances driven by CMEs (as identified by the counterstreaming halo electron signature) during the last solar maximum when ISEE 3 was making nearly continuous measurements directly upstream from the Earth [*Gosling et al.*, 1990, 1991]. The definition of storm categories, ranking from small to major, is indicated in the bottom panel of the figure. All 14 of the major storms during the 50-month interval studied (August 1978 through October 1982) were associated with Earth passage of shock disturbances, and in 13 of these storms the Earth also encountered the CME driving the shock. Of the 23 events in the large storm category, all but one were associated with Earth passage of a shock or a CME or both. If we make the reasonable assumption that the shock events lacking an associated observed CME were driven by CMEs that did not encounter ISEE3 or Earth (shock disturbances are considerably broader in extent than the CMEs that drive them), then all but one of the 37 largest geomagnetic storms in this time interval were caused by Earth passage of interplanetary disturbances driven by CMEs. Transient ejections of material from the Sun in the form of CMEs are therefore the prime link between solar activity and large, nonrecurrent geomagnetic storms, much as suggested by Lindemann, Hale, Chapman, and others many years ago. However, as already noted, solar flares are not fundamentally responsible for these ejections; indeed, many CMEs occur in the absence of any substantial flaring activity.

The association between geomagnetic activity and interplanetary disturbances driven by CMEs is less pronounced at lower levels of geomagnetic activity. For example, Figure 12 also demonstrates that 82% of the small geomagnetic storms during the interval studied were not associated with Earth passage of either CMEs or shocks. Further, many CMEs and shocks passing Earth are not particularly effective in

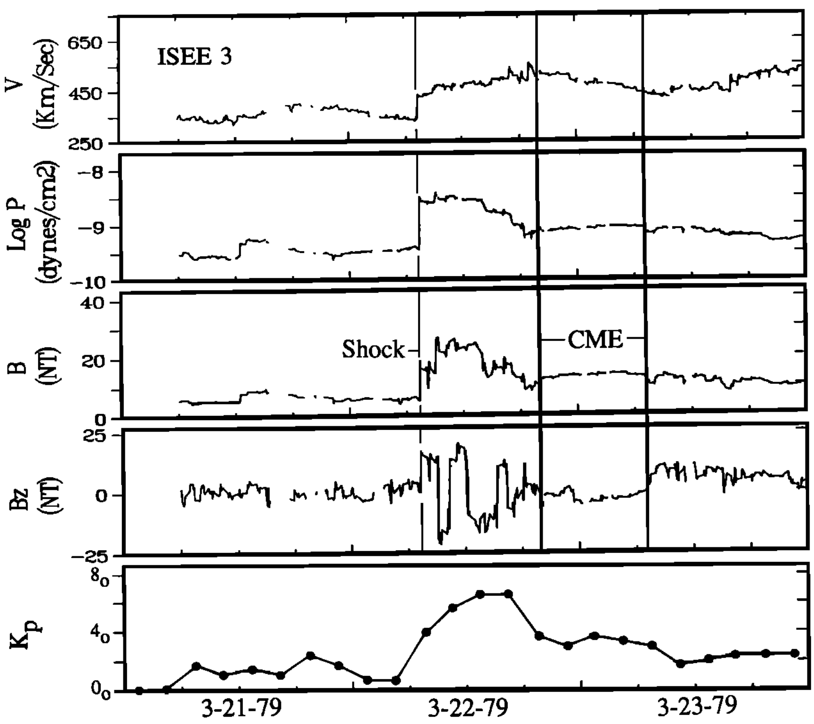

Fig. 11. Selected solar wind plasma and magnetic field parameters measured at ISEE 3 on March 21-23, 1979, and the geomagnetic index K_p. From top to bottom the parameters plotted are the bulk flow speed, the log of the combined ion, electron, and magnetic field pressure, the magnetic field strength, the out-of-the ecliptic component of the magnetic field, and K_p. The broken vertical line marks passage of a transient interplanetary shock, and the solid vertical lines bracket the CME (as distinguished by counterstreaming suprathermal electron fluxes) driving the shock. The lack of a significant field rotation within the CME indicates that the March 22, 23 CME was not a flux rope. A large, but relatively short-lived, nonrecurrent geomagnetic storm occurred during passage of this event, stimulated primarily by the moderately high speeds and strongly southward fields within the shocked plasma immediately ahead of the CME. The high flow speeds and strongly southward interplanetary fields responsible for stimulating large geomagnetic storms can be found within the compressed plasma ahead of the CME (as within this event), within the CME itself, or within both.

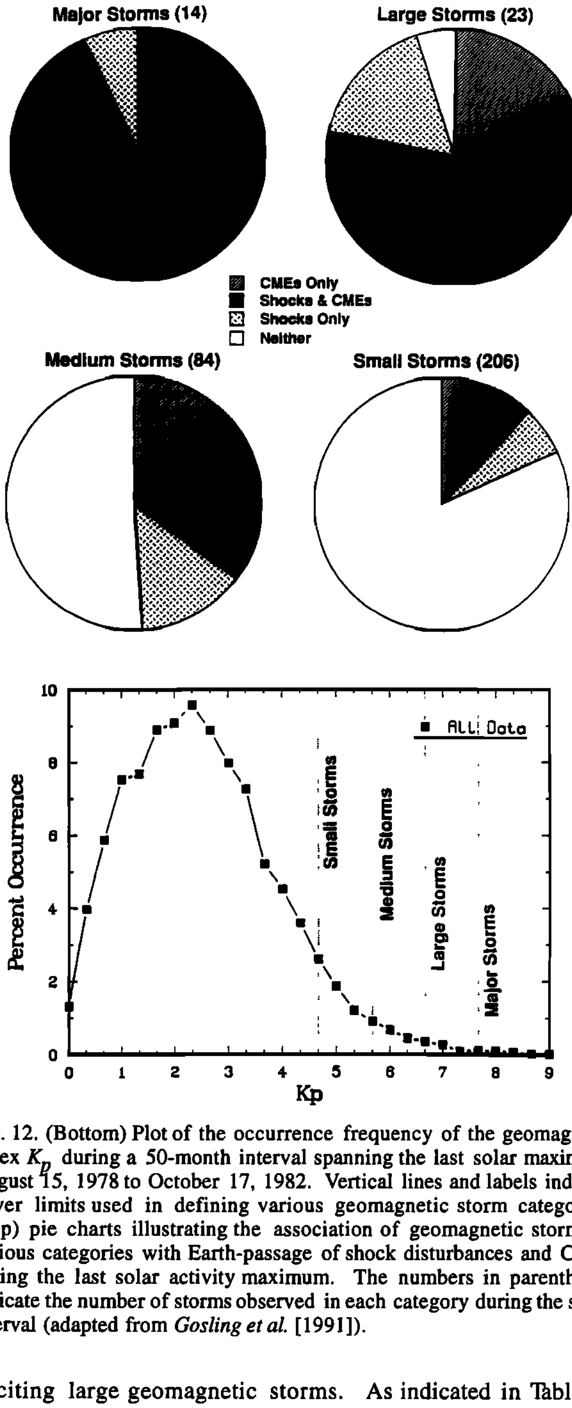

Fig. 12. (Bottom) Plot of the occurrence frequency of the geomagnetic index K_p during a 50-month interval spanning the last solar maximum, August 15, 1978 to October 17, 1982. Vertical lines and labels indicate lower limits used in defining various geomagnetic storm categories. (Top) pie charts illustrating the association of geomagnetic storms in various categories with Earth-passage of shock disturbances and CMEs during the last solar activity maximum. The numbers in parentheses indicate the number of storms observed in each category during the study interval (adapted from *Gosling et al.* [1991]).

exciting large geomagnetic storms. As indicated in Table 2, only about one out of six CMEs passing Earth in the 50-month interval studied produced a large or major geomagnetic storm as defined here. Slow CMEs and weak shock disturbances are generally ineffective in a geomagnetic sense because they lack the strong fields and high speeds necessary to provide a significant stimulation of the Earth's magnetosphere.

IMPULSIVE AND GRADUAL SOLAR PARTICLE EVENTS

During the last decade it has become apparent that there are at least two different types of solar energetic particle events: impulsive events and gradual events [e.g., *Cane et al.*, 1986; *Lin*, 1987; *Reames*, 1992*a*, *b*, 1993] (some SEPs appear to be composites of these basically distinct types [e.g., *Mason et al.*, 1989]). Figure 13 illustrates the contrasting temporal profiles of these different types of SEPs, while Figure 14 demonstrates their very different longitudinal distributions. In retrospect, because of the limited sensitivity of the instrumentation then available, early observations of SEPs were confined primarily to events that would now be classified as gradual or composite events. Table 3, adapted from *Reames* [1992*b*], summarizes and contrasts some of the important characteristics of these two fundamentally different types of SEPs.

Impulsive events reach maximum intensity quickly following many solar flares and typically decay over a period of several hours. Energetic particles in these events are rich in electrons, ^{3}He, and Fe, and the ions have high ionization states characteristic of flare temperatures (~10^7 K). Impulsive energetic particle events are commonly observed in association with optical and impulsive X ray flares; however, some events have no obvious flare associations [e.g., *Kocharov and Kocharov*, 1984; *Reames et al.*, 1988]. The upper panel of Figure 14 illustrates that impulsive (^{3}He-rich) particle events are observed almost exclusively in association with solar events in the western solar hemisphere. That is, these events are usually detected only when the observer is relatively well connected along the interplanetary magnetic field to the site of activity on the Sun. Most impulsive events produce only modest fluxes of energetic particles in interplanetary space; however, on relatively rare occasions impulsive events contain very energetic particles (> ~500 MeV) at sufficient intensities to register on ground level neutron detectors. At a fixed point in interplanetary space these short-lived events occur at a rate of ~1000 events/year near solar activity maximum. It seems clear that impulsive events are a direct product of the same process that produces flares and that the energetic particles in these events are accelerated near the flaring sites.

By way of contrast, gradual events can have rise times as long as a day and typically persist at high intensity levels for several days or more. Energetic particles in these events are rich in protons and have elemental abundances and ionization states that are characteristic of the corona and solar wind [e.g., *Mason et al.*, 1984]. Some gradual events have no obvious associations with optical solar flares or impulsive X ray events

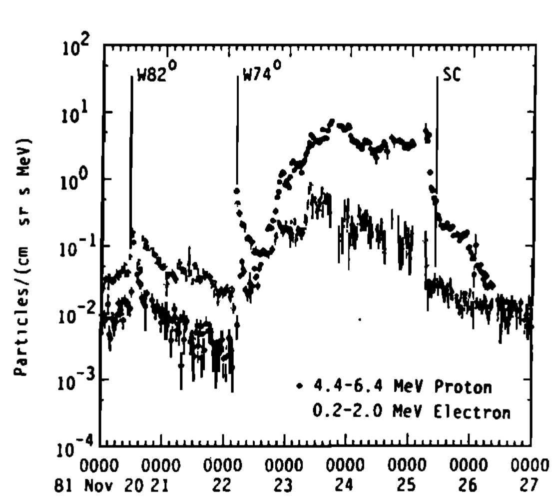

Fig. 13. Energetic particle time profiles from ISEE 3 in November 1981. This plot illustrates that there are two types of energetic particle events: impulsive and gradual events. Associated flare longitudes are indicated above the two impulsive events, while the sudden commencement of a geomagnetic storm is indicated near the end of the most intense portion of the gradual event [from *Reames*, 1992*a*].

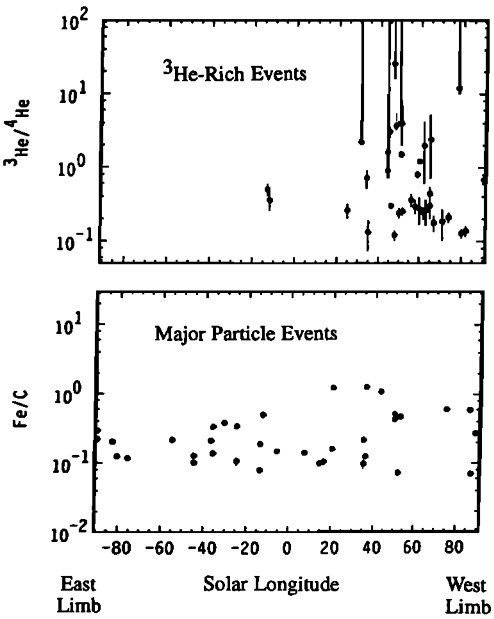

Fig. 14. Solar longitude distributions of the sites of origin for ^{3}He-rich (impulsive) energetic particle events and for major (gradual) energetic particle events. Impulsive events originate almost entirely in the western solar hemisphere where a good magnetic connection exists between the site of activity and the Earth along the interplanetary field spiral. In contrast, major particle events, which generally have Fe/C ratios considerably less than one, can originate anywhere on the visible solar disk (adapted from *Reames* [1992*b*]).

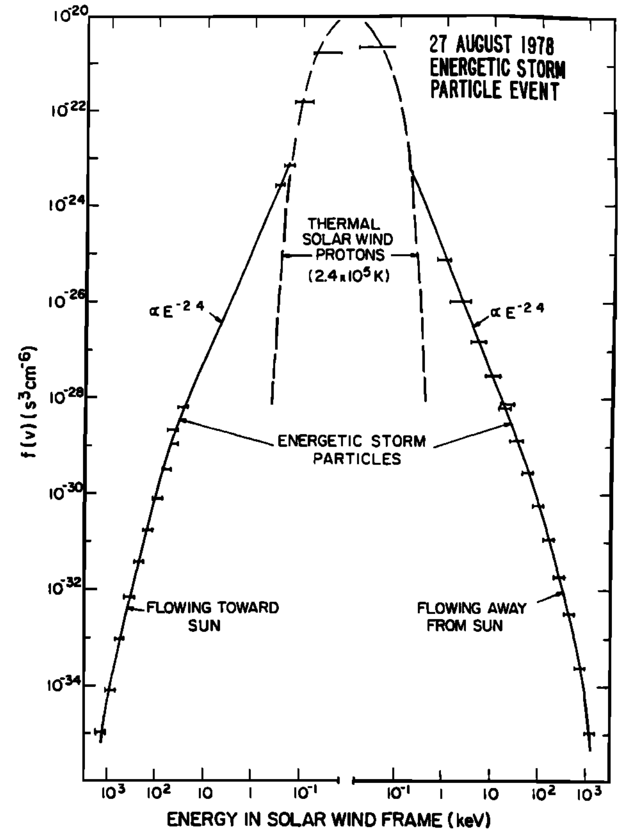

Fig. 15. Measured distribution of interplanetary ions from 10 eV to 1.6 MeV in the solar wind frame of reference shortly after shock passage during a gradual energetic particle event detected at ISEE 3 on August 27, 1978. This cut through the distribution function is along the Sun-satellite line. The dashed curve at the center is a Gaussian in velocity corresponding to the measured solar wind temperature of 2.4 x 10^5 K and density of 25 cm^{-3}. No solar flare was observed in association with this relatively intense energetic particle event, but both a shock and a CME were encountered at ISEE 3. Because the energetic particle spectrum emerges out of the solar wind thermal distribution and extends smoothly to the highest energies measured, this observation indicates that the shock accelerates the energetic particles out of the solar wind thermal distribution [from *Gosling et al.*, 1981].

[e.g., *Domingo et al.*, 1979; *Cliver et al.*, 1983; *Kahler et al.*, 1986]; on the other hand, almost all of these events are associated with CMEs that drive shock wave disturbances in the solar wind [e.g., *Kahler et al.*, 1984]. As illustrated in the lower panel of Figure 14, gradual events can arise from disturbances that originate anywhere on the visible disk of the Sun; energetic particles in these events are observed on or close to interplanetary magnetic field lines that connect to the shocks running in front of fast CMEs [e.g., *Cane et al.*, 1988]. In addition, as illustrated in Figure 15, the spectrum of energetic particles near interplanetary shocks during gradual particle events extends smoothly from MeV energies down to solar wind thermal energies (~10 eV) without an intervening break or peak. This is a clear indication that the solar wind thermal particles act as the seed population for gradual events [*Gosling et al.*, 1981]. Indeed, all of the available observational evidence indicates that gradual events are the product of the shock acceleration of coronal and solar wind particles in interplanetary space [e.g., *Mason et al.*, 1984; *Lockwood et al.*, 1990; *Reames*, 1993]. Such acceleration continues as the shocks propagate out to the Earth and beyond. Most of the major (that is, intense and long-lasting) SEPs observed in interplanetary space are gradual or composite events. On the other hand, these major events occur at a rate of only ~10 events/year near solar activity maximum.

TABLE 3. Properties of Impulsive and Gradual Solar Energetic Particle Events

Characteristic	Impulsive	Gradual
Particles	electron-rich	proton-rich
	^{3}He/^{4}He ~1	~ 0.005
	Fe/O ~ 1.0	~ 0.1
	H/He ~ 10	~ 100
Iron ionization	~ +20	~ +13
Delay	minutes	hours to days
Duration	hours	days
Longitudinal extent	< 60 deg	~ 180 deg
Radio bursts	III, V	II, IV
X rays	impulsive	gradual, long duration events
Coronal event	...	CME
Solar wind event	...	shock disturbance
Occurrence frequency (solar maximum)	~ 1000 events year^{-1}	~ 10 events year^{-1}

CAUSE AND EFFECT IN SOLAR-TERRESTRIAL PHYSICS: A MODERN PARADIGM

The foregoing brief summary of current knowledge concerning the relationships between solar and large interplanetary and geomagnetic events indicates that the paradigm of cause and effect outlined in Figure 4 is incorrect, primarily with regard to the central importance given to solar flares. Figure 16 outlines a more modern paradigm that is, I believe, far more consistent with present knowledge. The underlying cause of solar activity appears to be the evolution of

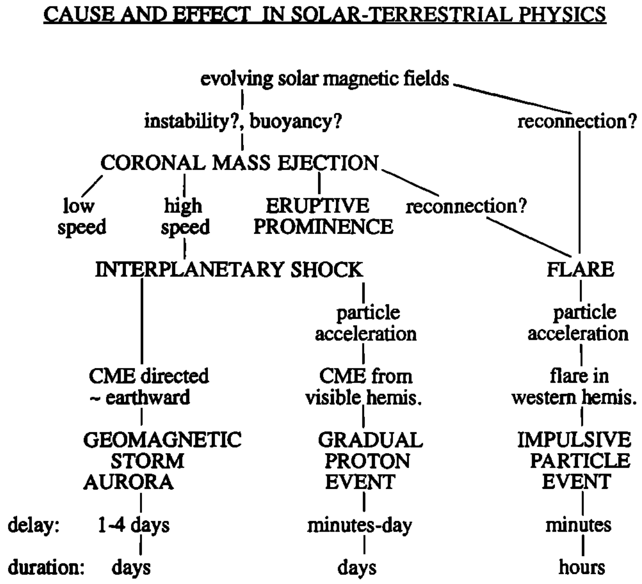

Fig. 16. A modern paradigm of cause and effect in solar-terrestrial physics emphasizing the central importance of CMEs in producing major events in the near-Earth space environment and deemphasizing the importance of solar flares in this respect. Capital letters indicate observational phenomena and lower case letters denote processes or descriptive characteristics. This new paradigm is consistent with a wide variety of observations.

the solar magnetic field. Solar flares occur in magnetically complex regions, perhaps as a result of magnetic reconnection. Energetic particles are often produced during the impulsive phase of solar flares; these particles escape from the Sun along field lines originating close to the flare sites to produce impulsive SEPs in interplanetary space. Impulsive SEPs are observed near Earth only for flares in the western solar hemisphere, indicating that there is little diffusion of the energetic particles in these events across the spiral interplanetary magnetic field. These events have characteristic durations at 1 AU of a few hours and, with a few exceptions, typically are weak events.

Coronal mass ejections also appear to be a result of the spatial and temporal evolution of the solar magnetic field, although the processes that trigger the release of CMEs and the factors that determine the timing, the size, and the speed of the ejections are still not well understood (see, for example, the review by *Low* [1993]). It does seem clear, however, that flares do not play a fundamental role in producing CMEs. CMEs may result from global instabilities in the coronal magnetic field [e.g., *Priest*, 1988], and buoyancy may be important in accelerating the plasma outward into interplanetary space, but this is uncertain. Solar prominence material or material ejected large geomagnetic storms and auroral disturbances usually result, the most crucial element being the presence of a strong southward directed field somewhere within the interplanetary disturbance [e.g., *Gonzalez and Tsurutani*, 1987; *Tsurutani et al.*, 1988; *Gosling et al.*, 1990].

The strong shocks driven by the fastest CMEs are also effective in accelerating a small fraction of the particles they intercept to very high energies [e.g., *Lee and Ryan*, 1986]. Only a small fraction of the solar wind particles encountering these shocks are accelerated to high energies, but the flux of these particles relative to the cosmic ray background is quite high, and the accelerated particles are found on all field lines intersecting the shocks. The largest number of accelerated

from a flaring region is often embedded within CMEs; however, most of the material within CMEs usually originates from the corona rather than from prominences or the chromosphere [e.g., *Hildner et al.*, 1975]. Further, there is no observational evidence to suggest that prominences or chromospheric material drive the CMEs outward from the Sun. CMEs exhibit a wide range of outward speeds; those that move at the same speed as or slower than the ambient solar wind ahead do not produce significant disturbances in the solar wind. The fastest CMEs, on the other hand, often produce very large interplanetary disturbances, characterized by high solar wind speeds and strong magnetic fields, often with strong southward components. The strong fields in these disturbances are primarily a result of compression in interplanetary space. An interplanetary shock usually, but not always, is an integral part of such disturbances, depending primarily on the relative speed between the CME and the ambient solar wind ahead. When these major interplanetary disturbances are directed earthward, particles probably are produced near the Sun where the CME-driven shocks are strongest and the ambient density is highest, but acceleration takes place over a prolonged period of time as the shocks propagate outward through the solar wind to the Earth and beyond. Throughout the outward journey of the disturbance accelerated particles continually leak away from the acceleration region near the shock along the interplanetary magnetic field. CMEs typically are large structures with broad latitudinal and longitudinal extents and the shocks they drive often spread over more than 90 deg in solar latitude and longitude. The gradual, but intense, SEPs produced by CME-driven shocks typically last for several days or longer and are found in association with disturbances originating from virtually anywhere on the visible solar disk. The detailed temporal intensity profiles that are observed depend sensitively on the longitude where the CMEs originate relative to the observer [e.g., *Cane et al.*, 1988]. According to *Reames* [1992*a*, *b*], most major solar proton events observed in the vicinity of the Earth are gradual events associated with fast CMEs, although some fraction of major SEPs are composites of the gradual and impulsive types because of the overall association between CMEs and flaring activity.

CONCLUSION

Early observations of apparent associations between solar flares and large transient interplanetary and geomagnetic disturbances led to a paradigm of cause and effect that gave flares a central position in the chain of events leading from solar activity to major transient disturbances in the near-Earth space environment. It is apparent to this author that this paradigm dominates the popular perception of the relationship between solar activity and these disturbances and is still being propagated in various forms within the solar-terrestrial physics community. As "cause"and "effect" lie at the heart of the science of solar-terrestrial physics, this paradigm has also provided much of the pragmatic rationale for study of the solar flare phenomenon. However, research in the last two decades shows that this emphasis on flares is misplaced. Although particles are often accelerated to high energies during the flaring process, in terms of intensity and temporal duration the impulsive particle events directly associated with the flaring process are not, in general, the major energetic particle events observed in the near-Earth space environment. The major energetic particle events are those produced by the shock acceleration of coronal and solar wind particles in interplanetary space. These shocks, in turn, are driven by fast CMEs that have no fundamental association (in terms of cause and effect) with solar flares. CME-driven interplanetary disturbances are also the prime cause of large, nonrecurrent geomagnetic storms, so that solar flares also play no fundamental role in producing large geomagnetic storms. Clearly, the time has come to lay the solar flare myth to rest.

On the other hand, our new paradigm of cause and effect speaks out for renewed interest and study of the CME phenomenon. The fundamental factors affecting the release of CMEs from the Sun are poorly understood, and it is not yet possible to predict with accuracy when and where these events will occur on the Sun or what their outward speeds will be. Nor do we fully understand global aspects of CMEs in interplanetary space [e.g., *McComas*, 1993]. Further, it is particularly difficult to detect and measure the speeds of the fast earthward directed events that provide the largest effects in the near-Earth space environment. We have noted elsewhere [*Gosling et al.*, 1991] that such detection would be routine with coronagraphs placed in orbit about the Sun well ahead of and behind the Earth in its orbit about the Sun, possibly at the L4 and L5 Lagrange points, but the immediate prospect for such measurements seems remote at the present time.

Finally, the foregoing should not be construed as a suggestion that solar flares are unworthy of study. From the standpoint of solar physics, flares are important energetic events where complex physical processes occur. Further, there is very good evidence that substantial particle acceleration occurs in the vicinity of the flare site involving processes that are not yet fully understood (see, for example the review by *Mandzhavidze and Ramaty* [1993]). When good magnetic connection exists between the flare site and the Earth, these energetic particles propagate out to Earth where they can produce significant, if short-lived, effects. Moreover, flares provide a diagnostic of overall activity on the Sun and often occur in conjunction with CMEs, even if they do not produce them. X ray fluxes from flares are also responsible for producing sudden, short-lived enhancements in the electron content of the ionosphere, known as sudden ionospheric disturbances. However, research on solar flares should not be justified, as it often is [e.g., *Haisch et al.*, 1991], on the basis of the solar flare myth.

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