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The Solar Flare Myth In Solar-Terrestrial Physics

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Abstract

Early observations of associations between solar flares and large non-recurrent geomagnetic storms, large 'solar' energetic particle events, and transient shock wave disturbances in the solar wind 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. However, research in the last two decades shows that this emphasis on flares is misplaced. In this paper I outline briefly the rationale for a different paradigm of cause and effect in solar-terrestrial physics that removes solar flares from their central position as the 'cause' of major disturbances in the near-Earth space environment. Instead, this central role of 'cause' is played by events now known as coronal mass ejections, or CMEs.

In 1859, R. Carrington observed an intense, short-lived brightening of the surface of the Sun in the vicinity of a sunspot [*Carrington*, 1860]. 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. Major transient shock wave disturbances in the solar wind, energetic particle events in interplanetary space, and large non-recurrent geomagnetic storms often occur in close association with large solar flares such as the one Carrington observed. Over the years such observed associations led to a paradigm of cause and effect - that large solar flares are the fundamental cause of these major events in the near-Earth space environment [e.g., *Hale*, 1931; *Chapman*, 1950; *Parker*, 1963]. This paradigm, which I call 'The Solar Flare Myth', not only dominates the popular perception of the relationship between solar activity and interplanetary and geomagnetic events, but also provides much of the pragmatic rationale for the study of the solar flare phenomenon [e.g., *Haisch et al.*, 1991].

Figure 1 provides an outline of this paradigm of cause and effect whose major elements have all been firmly in place since at least the early 1960's. A simple elaboration of the paradigm follows. 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 the figure). 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 energetic particle event; when they impinge upon the upper atmosphere in the polar regions of the Earth they cause a polar cap absorption event. The flare process also substantially heats the chromosphere and the corona in the region immediately surrounding the flare site (left hand branch in the figure). This heating, in possible 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.

The foregoing paradigm appears reasonable in the light of observational knowledge available by the early 1960's, but today there is good evidence that this paradigm is wrong and that solar flares do not generally play a fundamental role in producing major transient disturbances in the near-Earth space environment [e.g., *Kahler*, 1992]. The evidence, which is elaborated upon more fully elsewhere [*Gosling*, 1993] consists primarily of the following:

1. No one-to-one relationship exists between solar flares and either transient shock disturbances in the solar wind at 1 AU or major solar energetic particle events or large non-recurrent geomagnetic storms. Indeed, all of these phenomena can and do occur in the absence of any substantial flaring activity [e.g., *Newton*, 1943; *Joselyn and McIntosh*, 1981; *Hundhausen*, 1972; *Gosling et al.*,

1980; *Domingo et al.*, 1979; *Cliver et al.*, 1983].

2. Although the Sun does commonly and often somewhat impulsively eject large quantities of material (10^{+15} - 10^{+16} g) into interplanetary space in events now known as coronal mass ejections, CMEs, [e.g., *Tousey*, 1973; *Gosling et al.*, 1974], solar flares are not fundamentally responsible for these ejections. Many CMEs, including some of the more spectacular ones, occur in the absence of any substantial flaring activity [e.g., *Munro et al.*, 1979; *Webb*, 1992]. Even when they occur in conjunction with flares the CMEs generally lift off from the Sun before any substantial flaring activity has occurred. Moreover, any associated flaring that does occur often lies to one side of the much broader (typically many 10's of degrees) CME span [e.g., *Harrison*, 1986; *Hundhausen*, 1988; *Harrison et al.*, 1990]. All of which indicates that CMEs are not generally the result of 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.

3. Virtually all transient shock wave disturbances in the solar wind at 1 AU are driven by fast CMEs [e.g., *Sheeley et al.*, 1985; *Cane et al.*, 1987]; however, as noted above, solar flares play no fundamental role in producing CMEs.

4. Large, non-recurrent geomagnetic storms are produced almost exclusively by Earth-passage of interplanetary disturbances driven by fast CMEs [*Gosling et al.*, 1990; 1991]; however, again as noted above, solar flares play no fundamental role in producing CMEs.

5. There are at least two fundamentally different types of solar energetic particle events: impulsive events and gradual events [e.g., *Cane et al.*, 1986; *Lin*, 1987; *Mason et al.*, 1989; *Reames* 1992a,b] . Impulsive events are common (~1000 events yr^{-1} near solar activity maximum), are usually weak events with durations of several hours, are rich in electrons, ^3He, and Fe, have

ionization states characteristic of flare temperatures, are commonly observed in association with impulsive optical and X-ray flares, and are detected almost exclusively in association with solar events that are relatively well connected to the observer along the interplanetary magnetic field spiral. It is clear that such events are a direct product of the same process that produces flares and that the energetic particles in these events are accelerated near the flare site. But these events are usually not major events in terms of particle intensity or event duration [e.g., *Reames*, 1993]. By way of contrast, gradual events occur infrequently (~10 events yr^{-1} near solar activity maximum), are often intense events that last for several or more days, are rich in protons and have elemental abundances and ionization states characteristic of the solar corona and solar wind [e.g., *Mason et al.*, 1984], are strongly associated with CMEs that drive interplanetary shock disturbances [e.g., *Kahler et al.*, 1984], have spectra that emerge smoothly from the solar wind thermal population [e.g., *Gosling et al.*, 1981] , and are observed primarily on field lines that connect the observer to an interplanetary shock [e.g., *Cane et al.*, 1988]. All presently available evidence indicates that gradual events are the product of the shock acceleration of coronal and solar wind particles in interplanetary space. That is, gradual events are not related in a fundamental way to solar flares. Most of the major (that is, intense and long-lasting) solar energetic particle events observed in interplanetary space are gradual events or composites of gradual and impulsive events.

The foregoing indicates that the paradigm of cause and effect in solar-terrestrial physics outlined in Figure 1 is incorrect, primarily with regard to the central importance given to solar flares. Figure 2 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 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 energetic particle events in interplanetary space. Impulsive events are observed near Earth only for flares in the western solar hemisphere [e.g., *Reames*, 1992a,b], 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 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 [e.g., *Gosling et al.*, 1976]; 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, 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 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, energetic particle events 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* [1992a,b], most major solar energetic particle events observed in the vicinity of the Earth are gradual events associated with fast CMEs, although some fraction of major particle events are composites of the gradual and impulsive types because of the overall association between CMEs and flaring activity.

In conclusion, over the last twenty years a major change in paradigm has occurred concerning the solar 'cause' of major transient disturbances in the near-Earth space environment. This change appears to be based firmly upon present observational knowledge from a wide variety of sources. Yet it is clear to me that this new paradigm has not yet caught the attention of many members of the solar-terrestrial physics community and that 'the solar flare myth' continues to propagate widely 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. It is my belief that the time has come to lay the myth to rest, and it is my hope that the present paper will play some small role in achieving its burial.

Acknowledgments

This paper is based upon a considerably more detailed paper submitted to the *Journal of Geophysical Research*. A large American Geophysical Union exhibit, prepared for the Smithsonian Air and Space Museum and titled 'Electric Space: Our Sun-Earth Environment' provided the original impetus for the paper. In its original form this exhibit, which highlights connections between solar events and events in the near-Earth space environment, made no mention of CMEs. Further inspiration for the paper has come from statements made and not made in a variety of scientific papers and books, in scientific presentations, seminars, and colloquia, in casual conversations, in educational materials released for popular consumption, and in the popular press. The author has profited from discussions on this topic with a number of individuals, including E. Cliver, N. Crooker, D. Hamilton, A. Hundhausen, S. Kahler, G. Mason, D. Reames, and D. Webb among others. He thanks N. Crooker for help in the preparation of Figure 2. This work was performed under the auspices of the U.S. Department of Energy with partial support from NASA.

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Figure Captions

Fig. 1. The solar flare myth - a paradigm of cause and effect illustrating the supposed central position of solar flares as a 'cause' of major disturbances in the near-Earth space environment. Capitol letters indicate observational phenomena and lower case letters indicate physical processes or descriptive characteristics.

Fig. 2. A modern paradigm of cause and effect in solar-terrestrial physics emphasizing the central importance of coronal mass ejections, CMEs, in producing major events in the near-Earth space environment and deemphasizing the importance of solar flares in this respect. Capitol letters indicate observational phenomena and lower case letters denote processes or descriptive characteristics. This new paradigm appears to be consistent with a wide variety of observations.

<u>A Paradigm of Cause and Effect</u>

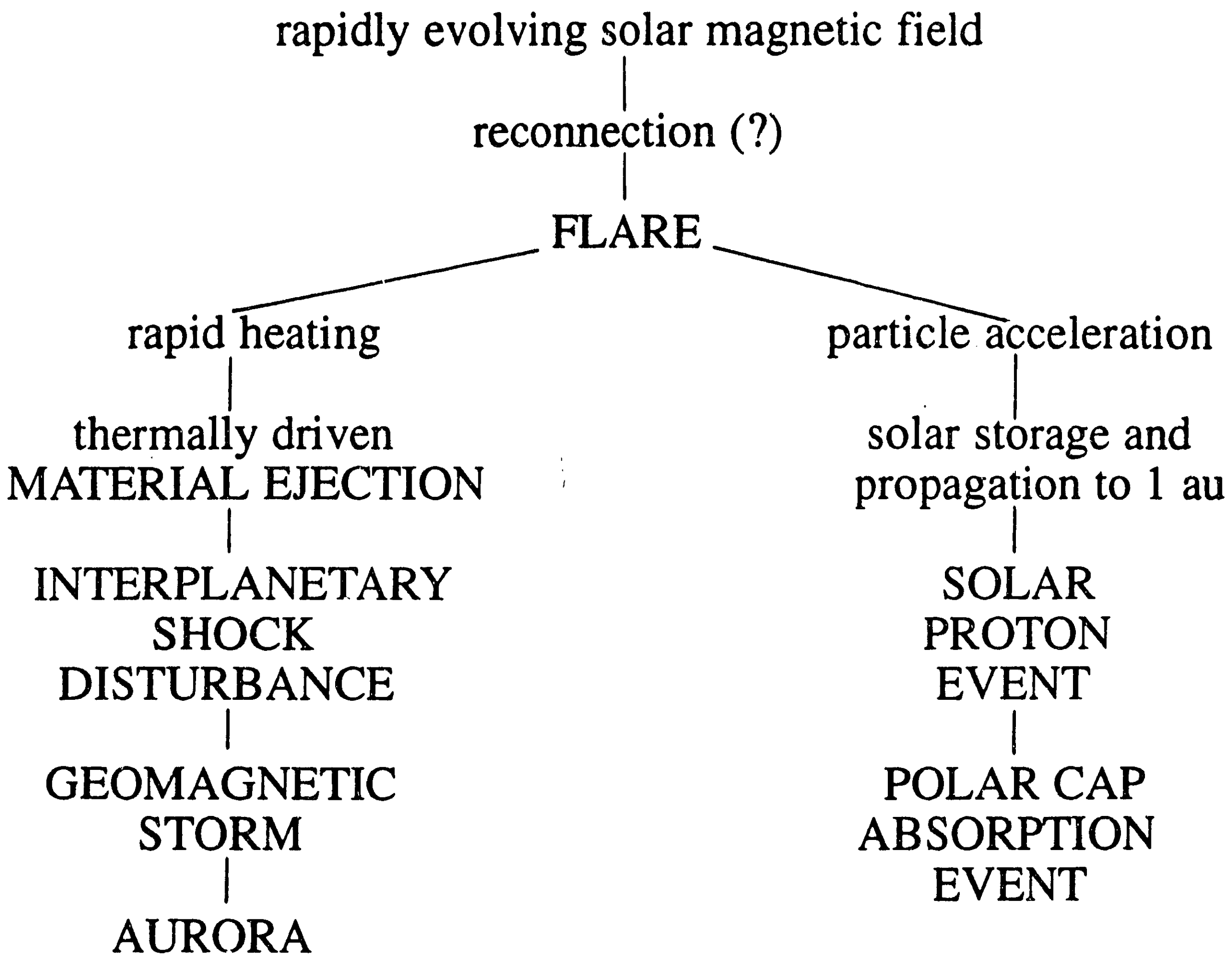

Fig. 1

CAUSE AND EFFECT IN SOLAR-TERRESTRIAL PHYSICS

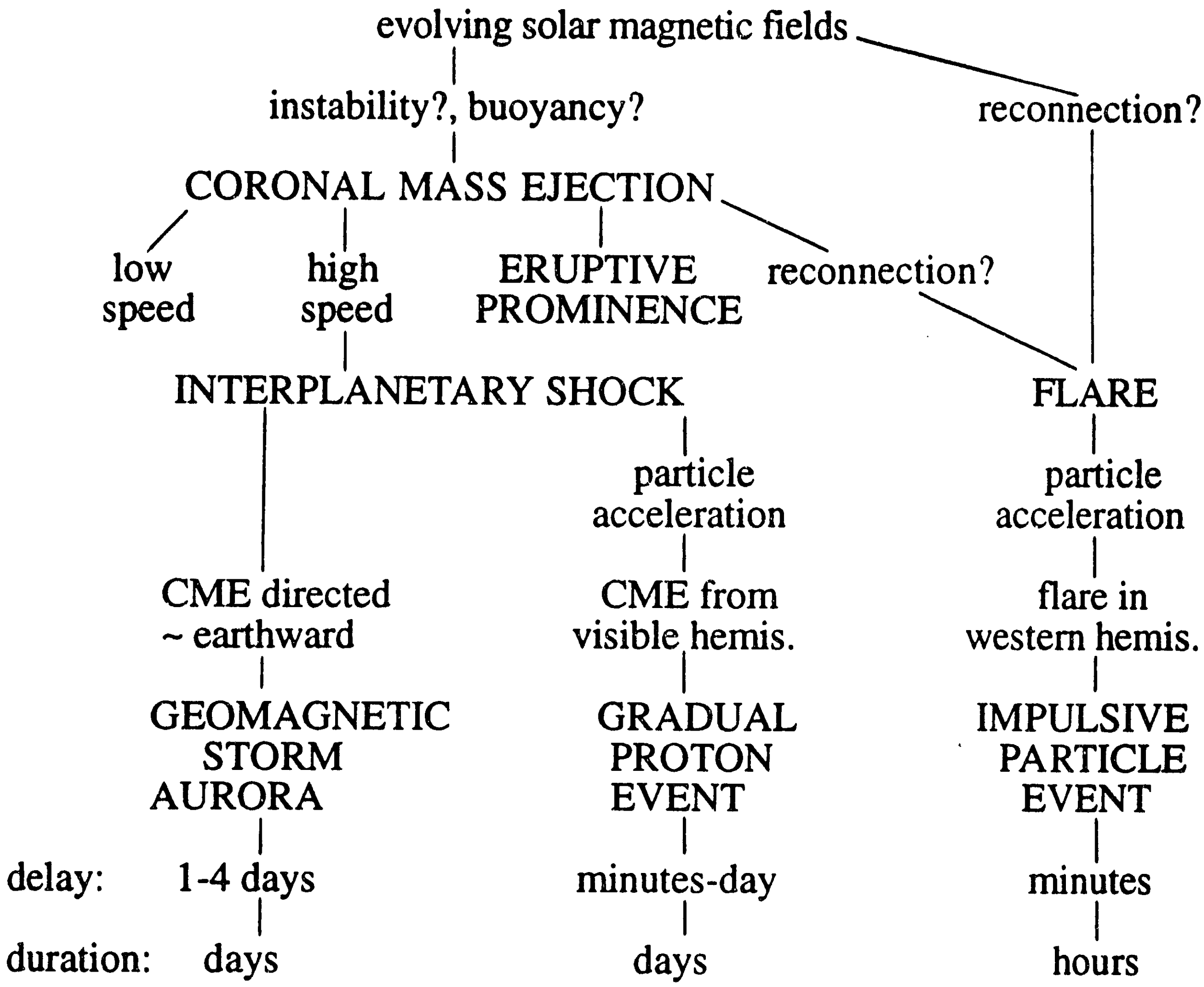

Fig. 2

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