VARIETIES OF CORONAL MASS EJECTIONS AND THEIR RELATION TO FLARES

ZDENĚK ŠVESTKA
CASS UCSD, La Jolla, California, U.S.A. and SRON Utrecht, The Netherlands

Abstract. Most coronal mass ejections (CMEs) start as coronal storms which are caused by an opening of channels of closed field lines along the zero line of the longitudinal magnetic field. This can happen along any zero line on the Sun where the configuration is destabilized. If the opening includes a zero line inside an active region, one observes a chromospheric flare. If this does not happen, no flare is associated with the CME in the chromosphere, but the process, as well as the response in the corona (a Long Decay Event in X-rays) remains the same. The only difference between flare-associated and non-flare-associated CMEs is the strength of the magnetic field in the region of the field line opening. This can explain essentially all differences which have been observed between these two kinds of CMEs. However, there are obviously also other sources of CMEs, different from coronal storms: sprays (giving rise to narrow, pointed ejections), erupting interconnecting loops (often destabilized by flares), and growing coronal holes. This paper tries to summarize and interpret observations which support this general picture, and demonstrates that both CMEs and flares must be properly discussed in any study of solar-terrestrial relations.

1. Introduction

For several decades solar physicists believed that all nonrecurrent disturbances of the terrestrial magnetic field were caused by solar flares. I remember a discussion which I had with K. O. Kiepenheuer during a meeting in Varenna in 1960. Sitting on the beach of Lago di Como, Kiepenheuer tried to convince me about the importance of activated dark filaments on the Sun, even without flares (the so-called *disparition brusques)*, and I resolutely disagreed with him.

Then, thirteen years later, OSO–7 and *Skylab* discovered *coronal mass ejections* (first called *coronal transients*) which were clearly related to magnetic disturbances at the Earth. For most of these ejections one could not find any flare source on the Sun, and quite a few were clearly related to erupting filaments, out of well-developed active regions (e.g., Munro *et al.*, 1979). Thus, Kiepenheuer was obviously right, and I (together with the vast majority of solar physicists at that time) was wrong.

Many more observations of coronal mass ejections (CMEs) were carried out in the years following the *Skylab* mission, and gradually another extreme view began to appear: that, from the point of view of geomagnetic disturbances at the Earth, flares have very little significance, and that the only phenomenon which is of real

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importance are the CMEs (Kahler, 1992; Gosling, 1993; Webb, 1996). According to Gosling, terrestrial effects of solar flares are a 'myth'.

As is often the case in science, one should not insist on extreme interpretations. As I was wrong in 1960, not seeing any importance in filament disappearances on the Sun, so are those who presently do not see any importance in the appearance of solar flares. The energy sequence of the phenomena which are associated with CMEs peaks with major eruptive flares, and γ-ray flares provide a proof that nuclei can be accelerated in flares to 1 GeV energies. As Sakai and de Jager (1996) said, Gosling's statement about the 'flare myth', decoupling flares from CMEs, is in its general form incorrect. And, as both Hudson *et al.* (1994) and the present author (Švestka, 1995) mentioned, this statement could have the unfortunate consequence of discouraging research in an area of fundamental significance.

Let me quote from a recent review by Miroshnichenko, de Koning, and Peres-Enriquez (2000): "The problem reduces not only to 'reconsidering' the perceived 'importance' of flares vs. CMEs, but rather to trying to understand the underlying physics involved in each case. Apparently, much can be learned from studying them both and exploring their relationship to one another." This is, what I try to do briefly in this paper.

2. Eruptive Flares and Coronal Storms

In the past years, many authors tried to find and discuss differences between CMEs associated with flares and those without flares (e.g., Gosling *et al.*, 1976; MacQueen and Fisher, 1983; Dryer, 1996; Sheeley *et al.*, 1999; and also in this issue Andrews and Howard, 2000). I tried to demonstrate, first at the SacPeak 1985 SMM Symposium (Švestka, 1986), that in both these cases the cause of the CME is the same: an opening of magnetic field lines, previously closed in the form of arcades or helmet streamers, along the zero line of the longitudinal magnetic field; the only difference between flare-associated and non-flare-associated CMEs is the strength of the magnetic field in the region where the opening takes place (see also Švestka and Cliver, 1992 and Švestka, 1995). St. Cyr and Webb (1991) arrived at a similar conclusion when studying 73 CMEs observed by the SMM. Thus, when looking at the Sun in the Hα line, one can see as the source of a CME a two-ribbon flare, if the opening occurred in the strong field of an active region, an activated filament without any chromospheric flare, if the opening took place in weak fields surrounding a quiescent filament, or simply nothing, if field lines opened along a zero line where no dark filament was embedded.

Sheeley *et al.* (1975) were the first to show that sources of white-light coronal transients (later called CMEs) are characterized by unusually long soft X-ray bursts, and Kahler (1977) introduced for these events the term Long Decay Event (LDE). He found this characteristic X-ray feature common to both the flare-associated and non-flare associated CMEs, and suggested that 'the main difference between the two kinds of events may be simply due to the energy available for heating to coronal temperatures.' Thus, in X-rays one can see an atmospheric response to the field-line opening in all cases, but chromospheric images are very misleading.

This variety of chromospheric situations at the sites of CME origins has led to a lot of confusion for more than two decades. At the SacPeak Symposium (Švestka, 1986) I introduced a classification of flares as *confined* and *dynamic*, the dynamic flares being those associated with CMEs. This classification was based on the earlier one proposed by Pallavicini *et al.* (1977). Later on, the term *eruptive* instead of *dynamic* was introduced (due, I believe, to Eric Priest). As all such dynamic or eruptive events cause a coronal X-ray brightening, hence a *coronal flare*, I included under the term 'eruptive flare' all events which led to field-line openings, irrespective of their response in the chromosphere. However, for most solar physicists the term 'eruptive flare' is associated only with 'real' *chromospheric flares*, and they did not understand, or refused to accept the idea, that also a *disparition brusque*, or no effect in the chromosphere at all, might be called an 'eruptive flare'. It was clearly a big terminological mistake.

Among those who refused to accept this term was Harrison (1996), who tried to introduce instead the term *coronal storm*. I believe that this is indeed a better term and I will use it here instead of the earlier *eruptive flare*, leaving this latter term in use only for the case of coronal storms associated with chromospheric flares.

Thus the basic questions about CMEs should be rephrased as follows:

(A) Are there differences between CMEs caused by a coronal storm originating in strong magnetic fields (i.e., associated with chromospheric flares) and those where the coronal storm originates in weak fields (i.e., without chromospheric flares)?

(B) Are there any CMEs which originate in a process which is different from the coronal storm?

3. Coronal Storms Associated with Flares

Those who believe in the 'flare myth', use several arguments why flares are unimportant for understanding solar-terrestrial relations.

3.1. Flares do not Cause CMEs

First, they say that flares cannot cause CMEs, because there are many CMEs without any flare. Indeed, Munro *et al.* (1979) found from *Skylab* observations only 40% of CMEs associated with flares, and St. Cyr and Webb (1991), from SMM observations, only 34%.

I suppose that this is well explained by the *coronal storm* concept. Flares clearly do not *cause* CMEs. CMEs are caused by an instability which leads to the opening of previously closed field lines along a zero line of the longitudinal magnetic field. If this opening includes a zero line inside an active region (strong magnetic field), then another response of the opening is an *eruptive flare*, characterized by two bright flare ribbons, and 'post'-flare loops. As Harrison (1995) said: 'Flares and CMEs do not drive one another, but are closely related.'

3.2. Larger extent of CMEs

Another argument is that the opening of loops closed across a zero line often comprises a much larger teritory than that of a flare inside an active region (e.g., Kahler *et al.*, 1989; Harrison *et al.*, 1990; Harrison, 1995; Dere *et al.*, 1997; Wiik *et al.*, 1997).

Indeed sometimes, e.g., in *Yohkoh* SXT images, one observes very extensive arcades associated with CMEs. But this does not contradict our interpretation. The field opening may involve a very long portion of the zero line. As long as it avoids any active region, we do not see any chromospheric flare. However, if the opening extends into an active region, the subsequently closing field lines are seen as bright loops of an eruptive flare.

3.3. Sequence of events

A third argument is that there is no fixed relationship between the onset of CMEs and the onset of flares: in most cases it is the CME that appears first, but there are also many events when we see the flare first, and only afterwards a CME is formed (e.g., Harrison, 1991, 1995).

It is true that the above model of a coronal storm should produce a coronal mass ejection first (when the field opens) and a flare thereafter (when the open field begins to close). Flare appearance prior to a CME clearly contradicts this model. However, a coronal storm needs a trigger, and in many cases this trigger is a *confined flare* (cf., e.g., Harrison *et al.*, 1983; Jordan *et al.*, 1997; Innes *et al.*, 1999). More such cases (unpublished) were observed by the SMM, and one can recognize them best in GOES X-ray records, where a shorter impulsive event precedes a long-lasting burst of the eruptive flare.

Confined flares are much more frequent than eruptive flares, usually are of much smaller dimensions, and, with few exceptions (see Section 6.1), are not associated with CMEs. However, their appearance can destabilize configurations along zero lines, which subsequently leads to coronal storms. Thus observers see first a confined flare and only later the beginning of a CME. But they may not (and in the vast majority of events do not) realize that the flare seen prior to the CME (the confined flare) and the flare continuing after the appearance of the CME (the eruptive flare) are two different flare phenomena caused by quite different instabilities. They just see first a small flare, which grows in size after the CME appeared.

3.4. Different speeds

Further, many authors have found that CMEs associated with flares differ in several aspects from those without flares. While the flare-associated CMEs propagate with constant speed, those without flares tend to show constant acceleration during their rise (e.g., MacQueen and Fisher, 1983; Gosling, 1993; Tappin and Simnett, 1997; St. Cyr *et al.*, 1999; Sheeley *et al.*, 1999; Andrews and Howard, 2000). And those with constant speed are generally brighter and faster than those which show acceleration (e.g., Webb and Hundhausen, 1987; Tappin and Simnett, 1997; Andrews and Howard, 2000). Gosling *et al.* (1976) found that flare-associated CMEs were not only faster, but also more likely to produce shocks at 1 AU. Tappin and Simnett (1997) and St.Cyr *et al.* (1999) find larger height of launch for those CMEs which show an acceleration.

However, these authors never claim that all flare-associated CMEs are without any acceleration, faster, and brighter – only that *preferably* flare-associated events show these properties. Although some authors (like MacQueen and Fisher, 1983 and Andrews and Howard, 2000) speak about two distinct classes of CMEs, it seems more likely that there is a continuous spectrum of CMEs of different speeds and accelerations, which simply depend on the strength of the magnetic field where the field opening occurred. In strong fields one can expect a larger energy input into the ejection, thus a brighter event with higher speed and, because of the high speed, no further acceleration occurs in the upper corona. If the speed also depends on the altitude where the field opens – and in eruptive flares the initial heights of ‘post’-flare loops can be quite different in different events – some non-flare CMEs with low-lying onset may easily have higher speeds than flare-associated CMEs originating high, thus creating the ‘spectrum’ of speeds which I mentioned above. From this one would expect that flares with widely separated bright Hα ribbons at their onset (and therefore with high post-flare loops) should produce slower CMEs.

4. Coronal Storms without Flares

4.1. Triggers of coronal storms

While associations of flares with CMEs are quite common, there are more events where a CME occurs without any chromospheric flare as we mentioned in Section 3.1. We do not know well what destabilizes closed structures along zero lines and leads to their opening, but several triggers have been suggested:

(i) Emerging magnetic flux (e.g., Feyman and Martin, 1995; Plunkett *et al.*, 1997; Tang *et al.*, 1999; Wang and Sheeley, 1999).

(ii) Slow-mode wave propagating from another solar disturbance (Bruzek, 1952; Yajima, 1971; Rust and Švestka, 1979; Lyons and Simnett, 1999; see also Khan and Hudson, 2000).

(iii) Excessive sheer in an arcade (e.g., Antiochos *et al.*, 1999); sigmoid shapes are good indicators of non-potentiality and thus large free magnetic energy (Canfield *et al.*, 1999). Many CMEs have the form of a magnetic flux rope, a helical current-carrying coil extending from the Sun but attached at its footpoints to its surface (see, e.g., Rust and Kumar, 1994, 1996; Chen *et al.*, 1997; Sterling and Hudson, 1997). These twisted magnetic ropes are often S-shaped, forming sigmoids. Priest *et al.* (1989) showed that solar prominences (filaments) must be supported by a large-scale curved and twisted magnetic flux tube. When the flux tube is not twisted, it cannot support dense plasma against gravity.

(iv) A catastrophic loss of mechanical equilibrium (Lin *et al.*, 1998, and references therein).

Most of these processes can occur equally well in the quiet Sun as in an active region, and there are far more zero lines separating weak fields than strong fields. Thus it is not surprising to find that a higher number of CMEs originate outside active regions.

4.2. CMEs WITHOUT ANY OBVIOUS SOURCE

As CMEs are best observed over the solar limb and their angular extensions are large, one should expect that about one half of all observed CMEs have their sources hidden behind the limb. For these CMEs even the soft X-ray LDE associations are missing, unless the source was located quite close to the limb, so that the upper parts of the X-ray-emitting structures could be seen to emerge above it. However, even some CMEs originating on the visible hemisphere may not show any recognizable source in chromospheric images, because of the absence of any dark filament at that part of the zero line of the longitudinal magnetic field where the closed field lines disrupted and opened. Dark filaments require a transport of material towards the zero line, and enough time to cool this material to a temperature that makes it visible in Hα images. Thus dark filaments become visible only along some sections of the zero lines. Moreover, once a filament has erupted, it may take quite some time to build another at its place. Therefore, some field openings, both inside and outside active regions, may involve no filament activation and eruption, although the basic process of the CME origin is still the same.

Examples of such events were shown, e.g., by Dryer *et al.* (1998). Wood *et al.* (1999) compare two CMEs, one following a filament (prominence) eruption and another one without it. Both these CMEs were quite similar in appearance, the main difference being the speed (900 and 300 km s^{-1}, respectively). Wiik *et al.* (1997) observed a CME which appeared before the filament (prominence) eruption. Apparently, in this case the CME originated elsewhere along the zero line, where no filament had been formed, and only later extended to a region marked by the prominence which subsequently erupted. The CME had an angular extent of 85 deg and the prominence was at its southernmost edge.

5. Complexity

One should expect that only few CMEs show the expected ‘classical’ forms of solar eruptions. Most events, as LASCO has now demonstrated very clearly, reveal large complexity and diversity of forms. One reason for this is, as shown by Gibson and Low (1998), that the orientation of the three-dimensional CME structures relative to the line of sight can give rise to a variety of different geometrical appearances. However, the main reason is the complexity of the underlying situations in the CME source on the Sun. The zero lines of the longitudinal magnetic field are rarely straight, and often, in particular in active regions, several zero lines may be involved in an eruption. Tang (1985) demonstrated Hα images of flares with very strange forms, one of them in the form of a circle, others with three or four bright ribbons. Naturally, eruptions from such structures have little resemblance to an eruption along a straight, or sigmoidal zero line.

Howard *et al.* (1985) classified CMEs in nine different categories. The most complex ones, *complex* and *multiple spikes*, appeared in their vast majority only in the maximum phase of solar activity, when one can expect the largest complexity in the surface magnetic configurations. Contrary to that, streamer blowouts were observed mainly during the period of solar minimum (Howard *et al.*, 1986). Thus complexity of magnetic situations on the Sun obviously plays a very significant role in the observed shapes and forms of CMEs.

6. Other Kinds of CMEs

Nevertheless, some CMEs indeed seem to be different from the *coronal storms* which we have discussed so far.

6.1. Confined Flares and Sprays

Several authors have found that also *confined flares* can be sources of CMEs, which basically contradicts our understanding of the coronal storms (Kahler *et al.*, 1989; Kahler, 1992). However, according to Kahler *et al.* the CMEs associated with compact flares are narrow, while those with LDEs are broad.

This strongly indicates that one encounters here another kind of CMEs, not associated with extensive field-line openings, but with pointed mass ejections. Indeed, some individual observations seem to confirm this. For example, McCabe (1985) described a limb flare associated with a CME which looks like a spray. And sometimes both a spray-associated CME and a coronal storm can occur. This might have happened in the major flare of 21 May 1980, in which the active region filament did not erupt, although flare loops formed above it: apparently, the field opened only at altitudes above the filament. In addition to it, a spray formed at one end of the filament and a narrow CME appeared in extension of this spray (McCabe *et al.*, 1985; de Jager and Švestka, 1985). The flare was far from the limb, so that a CME rising radially might not have been observed. However, the spray was ejected at a small angle to the surface and thus could be recorded above the limb.

Thus *sprays* (defined as 'ejections with speeds that are in excess of the escape velocity from the Sun') obviously are another source of CMEs, which differ from the coronal-storm CMEs mainly in two aspects: they are narrower, and can also be associated with confined flares. Whether also other ejections (surges and jets) are associated with CMEs is doubtful. Shibata *et al.* (1995) reported several confined flares which were associated with X-ray plasma ejections that 'looked like miniature versions of CMEs'. But obviously these jet-associated events were quite different from coronal-storm CMEs.

6.2. Interconnecting loops

When Kahler (1991) studied CMEs associated with the appearance of the high-altitude, new-cycle active regions at the beginning of cycle 22, he found that these CMEs appeared to arise from magnetic connections between the high-altitude regions and low-latitude, old-cycle regions, or between high-latitude regions of the new cycle on opposite hemispheres. At that time, there were no spacecraft capable of seeing loops that interconnect such active regions. However, such connections were seen in X-rays by *Yohkoh* at the beginning of the present cycle (Fárník *et al.*, 1999). Thus Kahler's observations indicate that those CMEs at the beginning of cycle 22 were due to *eruptions of interconnecting loops*, a very different process from coronal storms originating in closed loop configurations along zero lines.

This really has been confirmed by Khan and Hudson (2000), who found disappearances of several transequatorial interconnecting loops closely associated with major flares and CMEs. In all cases the flarings preceded the interconnecting loop disappearance and the CME, and Khan and Hudson suggest that shock waves from nearby flares could destabilize the interconnecting loops.

Švestka *et al.* (1995) observed on April 27–28, 1992 another event of rising transequatorial interconnecting loop (although they could not prove its relation to a CME) and one event quoted by Gosling (1993), on August 10, 1973, not associated with a solar flare, might have been an interconnecting loop eruption. Thus it seems to be confirmed beyond any doubt that erupting interconnecting loops, often crossing the solar equator, are another, different source of CMEs. However, they seem to represent only a small fraction of the CME events.

6.3. Coronal hole boundaries

Very recently Lewis and Simnett (2000) found sources of CMEs coinciding with a coronal hole. They suggest that magnetic reorganization at the hole boundaries could act as trigger for the destabilization of other structures. It may be that we encounter here also coronal storms of the same kind as described above, and that the restructuring of coronal hole boundaries is only another trigger to be added to those mentioned in Section 4.1. However, it may be that subsequent collapses of borders of coronal holes create another kind of CMEs which may differ in some aspects from the main source of the CMEs, the coronal storms.

7. CMEs, Flares, and Particle Acceleration

Lin (1970) and Švestka and Fritzová-Švestková (1974) found very good association between solar energetic particle (SEP) events and metric Type II radio bursts on the Sun. As Type II bursts are closely linked to CMEs, it is not surprising that later on a good association was also found between SEP events and CMEs (e.g., Kahler *et al.*, 1984). However, Kahler *et al.*'s (1986) discovery of a quiescent filament eruption, without any flare, as a source of energetic particles in space, became another contribution to the belief that not solar flares, but CMEs are producers of all powerful disturbances of the Earth's environment.

It really seems to be true that gradual particle events, i.e., those which do not start immediately after a flare, or which form a second, long-lived part of a SEP event, are accelerated in shocks associated with CMEs. However, the majority of SEP events are impulsive events which are clearly produced in flares. Their origins coincide in time with the flare impulsive phase, and particles from them arrive at the Earth almost exclusively from sources on the western solar hemisphere (Reames, 1992). The same is true for ^{3}He-rich events (Kahler *et al.*, 1985). Also nonrelativistic electrons are accelerated in flares (Kahler *et al.*, 1994). On the other hand, long-lasting SEPs do not show any dependence on the source position on the solar disk, which clearly indicates acceleration in extensive shocks far from the Sun (Reames, 1992). Because most of the major (i.e., intense and long-lasting) SEP events are gradual or impulsive-plus-gradual events, Gosling (1993) added it as another reason why one should not believe in the 'flare myth'. However, Guzik *et al.* (1995) found in two large SEP events the ^{3}He/^{4}He ratio orders of magnitude greater than the solar wind (coronal) value. Thus the seed population for large SEP events cannot be interplanetary solar wind particles which the CME-driven shock accelerates, but the seed population must come from the flare regions. Therefore, it seems that while small SEPs can be produced by CMEs themselves, without any flare, strong SEP events either originate in flares, if they are of impulsive nature, or - probably the largest of them - form in a 'cooperation' between the flare and the CME creating a long-lasting burst with an impulsive onset. According to Torsti *et al.* (1999), the proton production starts with less intense but hard-spectrum injection in the flare and then moves to the more intense but soft-spectrum flux farther from the Sun.

Another proof that one cannot neglect flares as SEP sources are the γ-ray observations, which show that protons can be accelerated to energies of 1 GeV or higher during the flare impulsive phase (Chupp, 1990). And also the appearance of high-energy neutrons during the ground-level events shows that they are produced in regions of high densities. Thus, one cannot escape the conclusion that – in spite of the very important role of CMEs in solar-terrestrial physics – the most energetic events are the proton and cosmic-ray flares, and this is the reason why the question of the ‘flare myth’ has caused such big problems.

8. The Importance of Flare Observations

Therefore, as I tried to demonstrate in the preceding sections, it is misleading to claim that flares are not important in solar-terrestrial relations. Although they do not cause the CME phenomenon that propagates from the Sun eventually hitting the Earth, they are excellent indicators of coronal storms and actually indicate the strongest, fastest and most important storms. According to Webb (1995), the largest geomagnetic storms are caused by fast CMEs and strong shocks which often have associated energetic flares on the Sun, but most storms are of moderate to small size, and majority of those has no association with flares. Flares are also sources of short-wave radiation that affects the ionosphere, and produce a significant fraction of accelerated particles that cause disturbances at the Earth.

Apart from these cause-and-effect reasons, flares remain important simply from the observational point of view. Let me quote Cane (1998): “Even if the flare does not produce the CME, nevertheless it provides a very useful diagnostic data, in particular, for determining the position on the Sun at which a CME originates.” And one can add to it that before 1973 nobody observed CMEs, but for many decades prior to that time people observed flares and associated them (successfully in most cases) with disturbances at the Earth. Thus, also for the sake of continuity of data, one should still pay full attention to flares as co-sources of geomagnetic disturbances.

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References

Andrews, M. D. and Howard, R. A.: 2000, *Space. Sci. Rev.* **95**, 147 (this issue).
Antiochos, S. K., DeVore, C. R. and Klimchuk, J. A.: 1999, *Astrophys. J.* **510**, 485.
Bruzek, A.: 1952, *Z. Astrophys.* **31**, 111.
Cane, H. V.: 1998, *Proc. 25th Int. Cosmic Ray Conf.* **8**, 135.
Canfield, R. C., Hudson, H. S. and McKenzie, D. E.: 1999, *Geophys. Res. Lett.* **26**, 6.
Chen, J., *et al.*: 1997, *Astrophys. J.* **490**, L191.

Chupp, E. L.: 1990, *Astrophys. J. Suppl.* **73**, 213.
de Jager, C. and Švestka, Z.: 1985, *Solar Phys.* **100**, 435.
Dere, K. P., *et al.*: 1997, *Solar Phys.* **175**, 601.
Dryer, M.: 1996, *Solar Phys.* **169**, 421.
Dryer, M., *et al.*: 1998, *Solar Phys.* **181**, 159.
Fárník, F., Karlický, M. and Švestka, Z.: 1999, *Solar Phys.* **187**, 33.
Feyman, J. and Martin, S. F.: 1995, *J. Geophys. Res.* **100**, 3355.
Gibson, S. E. and Low, B. C.: 1998, *Astrophys. J.* **493**, 460.
Gosling, J. T.: 1993, *J. Geophys. Res.* **98** (A1), 18937.
Gosling, J. T., Hildner, E., MacQueen, R. M., Munro, R. H., Poland, A. J. and Ross, C. L.: 1976, *Solar Phys.* **48**, 389.
Guzik, T. G., Chen, J. and Wefel J. P.: 1995, *24th Int. Cosmic Ray Conf.* **4**, 123.
Harrison, R.: 1991, *Adv. Space Res.* **11** (1), 25.
Harrison, R.: 1995, *Astron. Astrophys.* **304**, 585.
Harrison, R.: 1996, *Solar Phys.* **166**, 441.
Harrison, R. A., Simnett, G. M., Hoyng, P., LaFleur, H. and van Beek, H. F.: 1983, *Solar Phys.* **84**, 237.
Howard, R. A., Sheeley, N. R., Jr., Koomen, M. I. and Michels, D. J.: 1985, *J. Geophys. Res.* **90**, 8137.
Howard, R. A., Sheeley, N. R., Michels, D. J. and Koomen, M. I.: 1986, in R. G. Marsden (ed.), *The Sun and Heliosphere in Three Dimensions*, D. Reidel Publ. Co. Dordrecht, Holland, p. 107.
Hudson, H., Haisch, B. and Strong, K. T.: 1994, *J. Geophys. Res.* **100**, A3, 3473.
Innes, D. E., *et al.*: 1999, *Solar Phys.* **186**, 337.
Jordan, S., Garcia, A. and Bumba, V.: 1997, *Solar Phys.* **173**, 359.
Kahler, S. W.: 1977, *Astrophys. J.* **214**, 891.
Kahler, S. W.: 1991, *Astrophys. J.* **378**, 398.
Kahler, S. W.: 1992, *Ann. Rev. Astron. Astrophys.* **30**, 113.
Kahler, S. W., Sheeley, N. R., Jr. and Liggett, M.: 1989, *Astrophys. J.* **344**, 1026.
Kahler, S. W., *et al.*: 1984, *J. Geophys. Res.* **89**, 9683.
Kahler, S. W., Reames, D. V., Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J. and Michels, D. J.: 1985, *Astrophys. J.* **290**, 742.
Kahler, S. W., Cliver, E. W., Cane, H. V., McGuire, R. E., Stone, R. G. and Sheeley, N. R., Jr.: 1986, *Astrophys. J.* **302**, 504.
Kahler, S. W., Daibog, E. I., Kurt, V. G. and Stolpovskii, V. G.: 1994, *Astrophys. J.* **422**, 394.
Khan, J. I. and Hudson, H. S.: 2000, *Geophys. Res. Lett.* **27**, 1083.
Lewis, D. J. and Simnett, G. M.: 2000, *Solar Phys.* **191**, 185.
Lin, J., Forbes, T. G., Isenberg, P. A. and Démoulin, P.: 1998, *Astrophys. J.* **540**, 1006.
Lin, R. P.: 1970, *Solar Phys.* **12**, 266.
Lyons, M. A. and Simnett, G. M.: 1999, *Solar Phys.* **186**, 363.
MacQueen, R. M. and Fisher, R. R.: 1983, *Solar Phys.* **89**, 89.
McCabe, M. K.: 1985, *Solar Phys.* **98**, 127.
McCabe, M. K., Švestka, Z., Howard, R. A., Jackson, B. V. and Sheeley, N. R.: 1985, *Solar Phys.* **103**, 399.
Miroshnichenko, L. I., de Koning, C. A. and Perez-Enriquez, R.: 2000, *Space Sci. Rev.* **91**, 615.
Munro, R. H., Gosling, J. T., Hildner, E., MacQueen, R. M., Poland, A. I. and Ross, C. L.: 1979, *Solar Phys.* **61**, 201.
Pallavicini, R., Serio, S. and Vaiana, G. S.: 1977, *Astrophys. J.* **216**, 108.
Plunkett, S. P., *et al.*: 1997, *Solar Phys.* **175**, 699.
Priest, E. R., Hood, A. W. and Anzer, U.: 1989, *Astrophys. J.* **344**, 1010.
Reames, D. V.: 1992, *AIP Conf. Proc.* **264**, 213.

Rust, D. M. and Kumar, A.: 1994, *Proceedings of the Third SOHO Workshop*, ESTEC, Noordwijk, p. 39.
Rust, D. M. and Kumar, A.: 1996, *Astrophys. J.* **464**, L199.
Rust, D. M. and Švestka, Z.: 1979, *Solar Phys.* **63**, 279.
Sakai, J.-I. and de Jager, C.: 1996, *Space Sci. Rev.* **77**, 1.
Sheeley, N. R., Jr., *et al.*: 1975, *Solar Phys.* **45**, 377.
Sheeley, N. J., Jr., Watters, J. H., Wang, Y.-M. and Howard, R. A.: 1999, *J. Geophys. Res.* **104** (A11), 24739.
Shibata, K., *et al.*: 1995, *Astrophys. J.* **451**, L83.
St. Cyr, O. C. and Webb, D. F.: 1991, *Solar Phys.* **136**, 379.
St. Cyr, O. C., Burkepile, J. T., Hundhausen, A. J. and Lecinski, A. H.: 1999, *J. Geophys. Res.* **104**, 12493.
Sterling, A. C. and Hudson, H. S.: 1997, *Astrophys. J.* **491**, L55.
Švestka, Z.: 1986, in D. F. Neidig (ed.), *The Lower Atmosphere of Solar Flares*, NSO/SacPeak Publ., p. 332.
Švestka, Z.: 1995, *Solar Phys.* **160**, 53.
Švestka, Z. and Cliver, E. W.: 1992, *Lecture Notes in Physics* **399**, 1.
Švestka, Z. and Fritzová-Švestková, L.: 1974, *Solar Phys.* **36**, 417.
Švestka, Z., Fárník, F., Hudson, H. S., Uchida, Y., Hick, P. and Lemen, J. R.: 1995, *Solar Phys.* **161**, 331.
Tang, F.: 1985, *Solar Phys.* **102**, 131.
Tang, Y. H., Mouradian, Z., Schmieder, B., Fang, C. and Sakurai, T.: 1999, *Solar Phys.* **185**, 143.
Tappin, S. J. and Simnett, G. M.: 1997, *ESA* **SP-415**, 117.
Torsti, J., Kocharov, L. G., Teittinen, M. and Thompson, B. J.: 1999, *Astrophys. J.* **510**, 460.
Wang, Y.-M. and Sheeley, N. R., Jr.: 1999, *Astrophys. J.* **510**, L157.
Webb, D. F.: 1995, *Rev. Geophys.*, Supplement July 1995, p. 577.
Webb, D. F.: 1996, *ASP Conference Series* **95**, 219.
Webb, D. F. and Hundhausen, A. J.: 1987, *Solar Phys.* **108**, 383.
Wiik, J. E., Schmieder, B., Kucera, T., Poland, A., Brekke, P. and Simnett, G.: 1997, *Solar Phys.* **175**, 411.
Wood, B. E., Karovska, M., Chen, J., Brueckner, G. E., Cook, J. W. and Howard, R. A.: 1999, *Astrophys. J.* **512**, 484.
Yajima, S.: 1971, *Tokyo Astron. Bull.* No. 207.