ON THE ORIGIN OF SOLAR METRIC TYPE II BURSTS [*]

EDWARD W. CLIVER[1], DAVID F. WEBB[2] and RUSSELL A. HOWARD[3]
[1] *Air Force Research Laboratory, Space Vehicles Directorate, Hanscom Air Force Base, MA 01731-3010, U.S.A. (cliver@plh.af.mil)*
[2] *Institute for Scientific Research, Boston College, Chestnut Hill, MA 02167-3862, U.S.A. (webb@plh.af.mil)*
[3] *E.O. Hulburt Center for Space Research, U.S. Naval Research Laboratory, Washington, DC 20375, U.S.A. (howard@maple.nrl.navy.mil)*

(Received 13 August 1998; accepted 19 February 1999)

Abstract. The vast majority of solar flares are not associated with metric Type II radio bursts. For example, for the period February 1980–July 1982, corresponding to the first two and one-half years of the Solar Maximum Mission, 95% of the $\sim$2500 flares with peak $>$ 25 keV count rates $>$ 100 c s^{-1} lacked associated Type II emission. Even the $\sim$360 largest flares, i.e., those having $>$ 25 keV peak count rates $>$ 1000 c s^{-1}, had a Type II association rate of only 24%. The lack of a close correlation between flare size and Type II occurrence implies the need for a 'special condition' that distinguishes flares that are accompanied by metric Type II radio bursts from those of comparable size that are not. The leading candidates for this special condition are: (1) an unusually low Alfvén speed in the flaring region; and (2) fast material motion. We present evidence based on SMM and GOES X-ray data and *Solwind* coronagraph data that argues against the first of these hypotheses and supports the second. Type II bursts linked to flares within 30° of the solar limb are well associated (64%; 49/76) with fast ($>$ 400 km s^{-1}) coronal mass ejections (CMEs); for Type II flares within 15° of the limb, the association rate is 79% (30/38). An examination of the characteristics of 'non-CME' flares associated with Type IIs does not support the flare-initiated blast wave picture that has been proposed for these events and suggests instead that CMEs may have escaped detection. While the degree of Type II–CME association increases with flare size, there are notable cases of small Type II flares whose outstanding attribute is a fast CME. Thus we argue that metric Type II bursts (as well as the Moreton waves and kilometric Type II bursts that may accompany them) have their root cause in fast coronal mass ejections.

1. Introduction

One of the long-standing controversies of solar and solar-terrestrial physics involves the origin of the shock waves in the solar corona that manifest themselves as Type II radio bursts. In spectrograph records, Type II bursts appear as bands of emission in the metric range that drift to lower frequencies at rates $\sim$0.1–1 MHz s^{-1} with characteristic durations $\sim$10 min (e.g., Kundu, 1965). The Type II emission is attributed to shock-accelerated electrons that excite plasma waves that convert into escaping radio waves. At various times during the past

---

[*] The U.S. Government's right to retain a non-exclusive, royalty-free licence in and to any copyright is acknowledged.

Solar Physics **187:** 89–114, 1999.

fifty years, Type II-associated shock waves have been attributed either to solar flares or to coronal mass ejections (CMEs), or to some combination of the two phenomena. At present, the picture that all Type II bursts are flare-initiated blast waves appears to be gaining ascendancy (e.g., Cane, 1997; Gopalswamy *et al.*, 1998). The question of the source of coronal (metric Type II) shocks is tied to the question of the origin of the interplanetary (kilometric Type II) shocks that signal the onset of sporadic geomagnetic storms. It is now generally accepted that interplanetary shocks are CME-driven (Sheeley *et al.*, 1985; Cane, Sheeley, and Howard 1987; Gosling, 1993) and thus may have an origin separate from coronal shocks.

In this study of the origins of metric Type II bursts, we review the evolution of thinking that has led to our current understanding. We take this approach because it highlights an old lesson, now apparently forgotten, that constitutes a difficulty we have with the current view that CMEs are extraneous to coronal shocks. Our case, which we develop below, may be summarized as follows: (1) While there is a clear tendency for the rate of Type II association to increase with flare size (as measured by Hα area, hard or soft X-ray peak intensity, etc.), only a small fraction of flares at every size range, except the very largest, is associated with Type II bursts. Many Type IIs arise in relatively small flares (e.g., Dodge, 1975). Thus some rare or special condition is required for Type II formation (Roberts, 1959). (2) Special conditions which have been suggested to date include: (a) the presence of high velocity ejecta (Giovanelli and Roberts, 1958); (b) a CME (density enhancement) which is overtaken by a blast wave (Wagner and MacQueen, 1983); (c) special ambient conditions in the flaring region, such as low Alfvén speed (Uchida, 1974a, b; Kahler *et al.*, 1984b); and (d) a short-lived flare spray (Gopalswamy *et al.*, 1998). The first of these is essentially the view we favor and two of the other three (b and d) also require or suggest the presence of a CME. Suggestion (c) is based primarily on the poor correlation between flare size and Type II occurrence; we will present evidence against the low Alfvén speed hypothesis below. (3) A reasonably good association ($\sim$ 65–80%) does exist between metric Type II bursts and fast ($>$ 400 km s^{-1}) CMEs. In fact, Type IIs are rarely associated with slower CMEs, despite the fact that the median speed of all CMEs is $\sim$ 300 km s^{-1} (Howard *et al.*, 1985; Hundhausen, Burkepile, and St. Cyr, 1994). It is difficult to see why this should be the case if CMEs were immaterial to Type II formation. Thus we believe that a fast CME is the special condition required for coronal – as well as for interplanetary – shock formation. Our conclusion also has implications for the coronal waves (Thompson *et al.*, 1998a) recently discovered by the Extreme ultraviolet Imaging Telescope (EIT; Delaboudinière *et al.*, 1995) on the joint ESA/NASA Solar and Heliospheric Observatory (SOHO). Such waves are thought to be the coronal counterpart of chromospheric Moreton waves that in turn have been linked to metric Type II bursts (Moreton, 1964; Uchida, 1968, 1973, 1974b; Smith and Harvey, 1971; Harvey, Martin, and Riddle, 1974).

Our historical review is given in Section 2. In Section 3, we compare Type II bursts and hard X-ray bursts over the interval from February 1980 to July 1982, corresponding to the first two and one-half years of the Solar Maximum Mission, in order to demonstrate the lack of a tight correlation between flare size and Type II occurrence and to highlight the need for a special circumstance for Type II formation. We then examine the relationship between Type II bursts and CMEs for the 1979–1985 period covered by the *Solwind* coronagraph (Sheeley *et al.*, 1980) to show that a fast CME is likely the essential ingredient for a slow-drift burst to occur. Our results are summarized and discussed in Section 4.

2. Historical Development: 1947–Present

Solar radio bursts which drift slowly through the metric range from high to low frequencies at rates $\sim$ 0.5 MHz s^{-1} were discovered by Payne-Scott, Yabsley, and Bolton (1947) over fifty years ago. The similarity between the characteristic exciter speed ($\sim$ 500 km s^{-1}) of Type II bursts (as they came to be called) through the corona and the speeds of eruptive prominence material (hundreds of km s^{-1}) and the disturbances responsible for terrestrial aurorae (1600 km s^{-1}) was noted in the discovery paper. Thus for half a century the link between solar eruptions, metric Type II bursts, and geomagnetic storms has been more-or-less tacitly accepted by solar-terrestrial physicists (cf., Wild and McReady, 1950). The idea that Type IIs are related to solar flares can also be traced to these early studies. For example, Wild, Roberts, and Murray (1954) noted that time-height plots of Type III (fast-drift) and Type II bursts could be traced back to a common origin in the low corona. They suggested that both aspects (Type III and Type II) of the compound burst might have originated in an ‘explosion’ which might also cause the flare. The close timing between flare onset or maximum and Type II onset would be demonstrated statistically in several subsequent studies (e.g., Maxwell and Thompson, 1962; Švestka and Fritzová-Švestková, 1974; Dodge, 1975).

Early support for a material driver for Type II bursts was provided by Dodson, Hedeman, and Chamberlain (1953) who, on the basis of comparative studies of flares and 200 MHz bursts, suggested that metric ‘outbursts’ (of unknown spectral type) were more likely to be linked to high-velocity ejections than to solar flares. Subsequently, Giovanelli and Roberts (1958, 1959) on the basis of an investigation of flares associated with Type II bursts, concluded that ‘the ejections seen in Hα could well be the exciting agency responsible for Type II bursts’ and suggested that ‘Type II bursts accompany only supersonic ejections’. Swarup, Stone, and Maxwell (1960), however, found a low degree of association between eruptive limb phenomena and Type II bursts and surmised that it resulted from an unfavorable viewing geometry for the radio waves. They also pointed out that most eruptive phenomena had velocities well below the $\sim$1000 km s^{-1} inferred for Type II bursts.

Uchida (1960) attributed Type II bursts to hydromagnetic shocks (cf., Wild, Roberts, and Murray, 1954; Westfold, 1957) and cited the work of Giovanelli and Roberts to suggest that the initial disturbance responsible for such shocks might be the ‘flare surge’ phenomenon. Uchida calculated the duration of the Type II emission to be ∼5 min, in general agreement with observations. Note that this idea of a short-lived shock propelled by a surge – a type of solar eruption in which material returns to the Sun after its initial outward motion – is an important conceptual departure from earlier ideas that the Type II disturbance was linked to ‘auroral particles’ that propagated all the way to the Earth.

Parker’s (1961) paper entitled ‘Sudden expansion of the corona following a large solar flare and the attendant magnetic field and cosmic-ray effects’ is another work from this period which had long-lasting implications. Here we see a cornerstone of the viewpoint later described and discounted by Gosling (1993) as the ‘solar flare myth’. Parker argued that the sudden heating of the corona after a solar flare would create a hydrodynamic blast wave which would serve as the accelerating mechanism for the plasma clouds subsequently made manifest at Earth through geomagnetic storms and Forbush decreases. Although Parker did not explicitly mention Type II bursts, his paper represents an important turning point in the view of the relationship between flares, mass ejecta, and slow-drift bursts. The flare was of primary importance – it produced the shock and the mass ejection was a secondary effect, albeit one with important geophysical consequences.

Roberts (1959) provided an early review and comprehensive investigation of Type II bursts which pointed out a persistent problem that is the point of departure of the present paper – the lack of close correlation between flare size and Type II occurrence. Such a lack of correlation runs counter to the flare-initiated blast wave hypothesis under which we would expect Type II bursts to be associated mainly with large flares. In a study covering the period from January 1955 to March 1958, Roberts found that while upwards of 80% of all Type II bursts were associated with flares (cf., Swarup, Stone, and Maxwell, 1960), only 3% of flares of importance ≥ 1 were associated with Type II bursts. He noted that the percentage of association increased to ∼30% for class 3 flares and concluded: ‘Evidently some rare condition must be satisfied before a flare is accompanied by a Type II burst. Since many flares are accompanied by visible ejections, we may conclude that the presence of an ejected stream is not a sufficient criterion for the occurrence of a Type II burst. If only those ejections with supersonic speeds are effective (see . . . Giovanelli and Roberts (1958)), the numerical agreement would probably be better’.

This then was the situation ca. 1960. Type IIs were linked to flares because of the high degree of association of the two phenomena and also because of their tight timing relationship – Type II bursts generally begin within 5–10 min of Hα flare onset (e.g., Roberts, 1959; Maxwell and Thompson, 1962) – but it was recognized that some special circumstance beyond a flare was required for Type II formation, and that special condition was generally thought to be fast material motion.

The next key advance in understanding came with Uchida's seminal work (Uchida, 1968, 1973, 1974a, b; cf., Anderson, 1966; Meyer, 1968) linking Type II bursts to the fast optical disturbances emanating outward from flares that were discovered by Moreton and Ramsey (1960) (cf., Moreton, 1960; Athay and Moreton, 1961) and subsequently came to be known as Moreton waves. The 'Solar Flares' book by Smith and Smith (1963) does not draw a connection between Type II bursts and Moreton waves. In his 'Solar Radio Astronomy' monograph, Kundu (1965) cautiously comments, 'It should be remarked that high-resolution Hα cinematography of Athay and Moreton (1961) has revealed the existence of disturbances, believed to be plasma clouds moving out from the flare region with (tangential) velocities of about 1000 to 2500 km s^{-1}, that is, of the order of Type II velocities'. Uchida modeled the Moreton wave (previously thought to represent material motion (Athay and Moreton, 1961)) as the 'sweeping skirt' of a flare-induced hydromagnetic shock wave that expands upward into the corona. The skirt of the wavefront surface sweeps over the chromosphere much faster than the fast-mode speed of the chromosphere. Uchida, Altschuler, and Newkirk (1973) drew attention to the directional properties of Moreton waves, specifically, their tendency to propagate over a limited cone of azimuth away from a flare. They showed for two specific cases that such motions were consistent with the refraction of a weak blast-type MHD fast-mode shock toward pre-existing low-Alfvén speed regions in the corona. (See Bruzek, 1974, however.) Subsequently, Uchida (1973, 1974a, b) successfully extended this positional analysis to Type II bursts (cf., Kai, 1969) and thus proposed a unified explanation of Type II bursts and Moreton waves. Sections from the conclusion of Uchida's (1974b) paper are worth quoting verbatim because they mark the first clear exposition (to our knowledge) of the current two-shock picture, i.e., separate coronal and interplanetary shocks:

"We have assumed . . . that our MHD disturbance is a weak blast-type fast-mode shock caused by an explosion which takes place at the beginning of a flare (cf., Smith and Harvey, 1971). That the shock is a weak blast type may be a reasonable assumption since the velocity of the mass motion involved in the explosive phase is less than a few hundred kilometers per second and apparently quite sub-Alfvénic if we remember the typical Alfvén speed in the corona around active regions is of the order of several to few tens of thousand kilometers per second. The expanding mass flow in the explosion, therefore, lags far behind the quickly propagating weak MHD fast-mode wavefront sometimes after the start of the explosion. The slower mass flow in the explosion can not continue to play the role of the piston gas, and an isolated weak blast is propagated. In our hypothesis we therefore regard the systematic mass ejection processes from a flare such as surges and sprays (Roy, 1974) as the escaping mass flow from the exploding region, whose MHD effect has already gone far isotropically in the form of weak blast which causes Type II bursts and/or Moreton waves at some particular locations."

"These escaping masses, on the other hand, gradually gain higher Alfvén-Mach number mainly due to the decrease in Alfvén velocity in the surrounding medium when they reach the outer corona, and they may begin to produce a second bow-shock type disturbance (Kawabata, 1966), and may, in some cases, blow off the material in the high corona (Hansen *et al.*, 1971). So-called interplanetary shock observed near the Earth (Hundhausen, 1972; Dryer, 1974) may be an extension of this kind followed by a large amount of piston gas.”

Uchida goes on to say, however, that he is inclined to view the (then) recently discovered interplanetary Type II bursts (Fainberg and Stone, 1970; Malitson, Fainberg, and Stone, 1973) as extensions of the Type II-Moreton wave (i.e., blast wave) phenomenon rather than as piston-driven shocks.

Uchida (1973) noted the ‘mysterious preference’ for only certain flares to have associated Moreton waves, ‘even a powerful flare does not necessarily produce Moreton waves, while sometimes a subflare may produce them’ (cf., Smith, 1968; Smith and Harvey, 1971). The appearance or non-appearance of Moreton waves was attributed to the variation of the ambient Alfvén speed. The same reasoning accounted for the low degree of association of Type II bursts with flares. From Uchida (1974a), ‘... the chance of association of Type II bursts with a flare depends on such circumstantial situations as the existence of the low Alfvén velocity region within the reach of the wave. It is, thus, understandable that some large flares are not accompanied by a Type II burst while much smaller flares may be accompanied by one. The probability of the association may increase with the flare importance because a more complex structure of the magnetic field and density is associated for the occurrence of a large flare’.

Uchida’s several papers in the early 1970s that united Type II bursts and Moreton waves with a theoretical and observational underpinning gained acceptance for the blast wave (vs. piston) picture (e.g., Švestka, 1976; Lin and Hudson, 1976; Kosugi, 1976). The mid-1970s, however, represents the high point of the initial epoch in which coronal Type II shocks were thought to be flare-initiated blast waves. As noted in the introduction, this viewpoint is coming into vogue again today; however, for a brief period centered roughly on 1980, the picture of piston-driven Type II shocks had strong support.

Such a view was undoubtedly influenced by *in situ* solar wind observations which revealed plasma clouds with enhanced helium abundances following interplanetary shocks (Hirshberg *et al.*, 1970; Hundhausen, 1972) indicating that shocks at 1 AU were piston-driven. Subsequently, Stewart *et al.* (1974a, b) studied two events on 11 January 1973 in which CMEs observed by the NRL coronagraph on OSO-7 apparently drove Type II bursts that were imaged by the Culgoora radioheliograph. Moreover, statistical evidence presented by Gosling *et al.* (1976) showed that metric Type II bursts were highly associated with fast coronal mass ejections, i.e., having speeds >400 km s^{-1}. Thus it appeared that Giovanelli and Roberts’ conjecture (1958) that the special condition required for Type II emission was a high-speed ejection was correct.

This picture did not go unchallenged for long, however. At a STIP Symposium in 1982, Gergely (1984) reported that the average speed of metric Type II bursts was nearly twice as high as that of coronal transients (CMEs), raising doubts about their causal relationship. In the same year, Maxwell and Dryer (1982) and Kahler (1982b) suggested that there might be two kinds of coronal Type II bursts – those driven by a CME and those that were flare-induced. Kahler based his argument on the observation that a large fraction of Type II bursts associated with well-connected (western-hemisphere) flares was not followed by solar energetic particle events, contrary to expectations.

Cane (1983) suggested a slightly different type of two-shock scenario – independent coronal (flare-blast) and interplanetary (CME-driven) shocks – similar to Uchida's (1974b) conjecture, based on mismatches in time-height profiles of Type II bursts between the metric and kilometric range. A positional study by Gary *et al.* (1984) of an event on 29 June 1980 showed that the metric Type II emission lagged behind the leading edge of the CME, inconsistent with the bow shock picture. A similar result was reported by Gergely *et al.* (1984) for an event on 9 April 1980. A subsequent study by Robinson and Stewart (1985) showed that Type II emission was located radially behind the CME leading edge in 7 of 22 events for which they compared radio and coronagraph data. To reconcile the Gary *et al.* (1984) observation and the high degree of association of Type II bursts and CMEs, Wagner and MacQueen (1983) (cf., Cane, 1984) proposed a hybrid picture in which a blast wave from a flare gave rise to metric Type II emission when it overtook the high density region of a preceding CME.

About this time the statistical association between fast CMEs and Type II bursts also began to break down. Sheeley *et al.* (1984) found that a significant fraction, perhaps as high as one-third, of Type II bursts lacked associated CMEs. Subsequently, Kahler *et al.* (1984b) showed that $\sim$ 40% of Type IIs within 60° of the solar limb lacked CMEs. Moreover, Sheeley *et al.* (1984) and Kahler *et al.* (1985) found that approximately one-third of fast ($>$500 km s^{-1}) CMEs lacked metric Type II bursts. This unraveling of the presumed tight statistical relationship between CMEs and metric Type IIs lent support to Cane's (1983) picture of independent flare-induced coronal shocks and driven interplanetary shocks. Evidence that the interplanetary shocks were, in fact, piston-driven was provided by comparisons of *Solwind* CMEs with shocks at Helios (Sheeley *et al.*, 1985) and kilometric Type II bursts (Cane, Sheeley, and Howard, 1987). Robinson *et al.* (1986) looked for and found differences in the emission characteristics of coronal Type II bursts with and without associated CMEs. For example, Type II bursts associated with CMEs tended to be more complex and had lower starting and ending frequencies than non-CME Type IIs. Somewhat surprisingly, however, Kahler *et al.* (1984b) found that the impulsive phases of Type II flares that lacked CME association could be relatively small (as measured by microwave burst peak flux densities), calling the blast wave picture into question. Following Uchida (1974a, b), Kahler *et al.* (1984b) suggested that 'very special ambient conditions, such as low Alfvén speed, might be required for shock generation' in the events that lacked both CMEs and strong impulsive phases.

In sum, the situation ca. 1985 regarding Type IIs, flares, and CMEs was complicated and uncertain. While it was generally accepted that all interplanetary shocks were CME-driven, there was little consensus on coronal shocks. Each of the following scenarios remained in play: (1) all metric Type II shocks were CME-driven (rapidly falling from favor); (2) all coronal shocks were flare-initiated blast waves; (3) Type II shocks resulted when flare-initiated blast waves overtook CMEs; and (4) Type II shocks were some mixture of blast and driven waves. To judge which, if any, of these viewpoints was most widely accepted, we refer to contemporary reviews by Steinolfson (1985), Bougeret (1985), and Nelson and Melrose (1985). Steinolfson discussed the Wagner and MacQueen (1983) model but suggested an alternative picture based on the work of Holman and Pesses (1983) and Steinolfson (1984) that explained the discrepancy between the positions of the transient leading edge and Type II emission in terms of a driven shock and the shock-drift theory of electron acceleration. Bougeret (1985) summed up the puzzling effect of the new observational results, ‘The white-light coronagraph and IPS [interplanetary scintillation] observations of CMEs provide a direct monitoring of mass ejecta, but the relation to both their solar source and MHD or shock waves is still unclear . . . All we can say is that several analyses (Sheeley *et al.*, 1984, 1985; Gary *et al.*, 1984; Robinson, Stewart, and Cane, 1984; Kahler *et al.*, 1984a, b, 1985) are suggesting both blast and piston-driven Type II generation in the corona and interplanetary medium’. In Chapter 13 of *Solar Radiophysics*, the summation of the results of the Australian school of solar radio astronomers, Nelson and Melrose (1985) addressed the ‘blast wave or driven shock wave’ question directly, and concluded: ‘It is quite likely that [metric] Type II bursts are produced at different times by both piston-driven shocks and by blast waves’. Thus ended a phase of intensive study on the origins of metric Type II bursts. The complexity and uncertainty which attended this question during the early and mid-1980s has since evolved toward a simpler picture, a dichotomy between flare-initiated Type II bursts (coronal shocks) and piston-driven interplanetary shocks.

The revived notion that all Type II bursts were flare-induced blast waves was first expressed by Cane and Reames (1988). In support of their suggestion, they cited Roberts (1959) on the high association of flares and Type II bursts and the tight timing relationship between these phenomena. More recently, Gopalswamy and Kundu (1992, 1995a, b) in a series of papers culminating in Gopalswamy *et al.* (1998) have argued that all Type II shocks are caused by flares. They cite several lines of evidence that we will discuss in Section 4. We believe that their conclusion is, at best, premature because it ignores the poor correlation between flare size and Type II occurrence that forced earlier investigators to accept the need for a special condition for Type II formation. Appreciation for this early finding seems to have been lost. Relatively few papers in recent decades (e.g., Uchida, 1974a; Dodge, 1975; Kahler, 1984b) addressed the problem, even in passing. Today the implication of this result – that something rare or unusual is needed for Type II occurrence – appears to have been largely forgotten. In the following section we

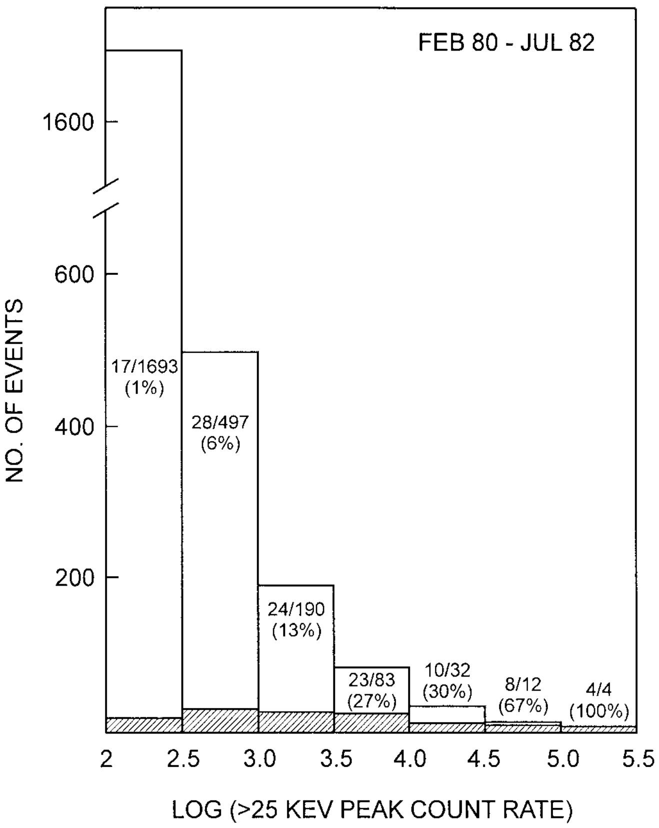

Figure 1. Histogram of HXRBS peak counting rates for flares observed between February 1980 and July 1982. The numbers and percentages of events in each bin that were associated with metric Type II bursts are indicated.

will demonstrate the weak correlation between Type II occurrence and flare size (in hard X-rays) and present statistical evidence that fast CMEs are the necessary circumstance required for Type II emission.

3. Analysis

3.1. TYPE II BURSTS AND HARD X-RAY FLARES

To show the lack of correspondence between flare size and the occurrence of a Type II burst, we used flare >25 keV peak flux data (Dennis *et al.*, 1991) obtained by the Hard X-Ray Burst Spectrometer (HXRBS; Orwig, Frost, and Dennis, 1980) for the first two and one-half years (February 1980–July 1982) of the Solar Maximum Mission. We compared flare associated hard X-ray bursts with metric Type II bursts observed by the three standard stations at the time (Culgoora, Weissenau, and Ft. Davis (Harvard)). We only considered hard X-ray bursts when at least one of these three stations was on patrol. To further ensure the validity of Type II reports, we eliminated events classified as 'weak', 'possible' Type IIs reported by Culgoora, Type IIs only observed in the decimetric band, or events having durations <3 min. Our Type II – hard X-ray burst association procedure was similar to that of Pearson *et al.* (1989). We only considered those hard X-ray events for which the peak of the event was observed and determined if it was by comparison with microwave data reported in *Solar-Geophysical Data*. The peak hard X-ray count rate is taken to be a measure of the impulsive phase energy release during a flare because >20 keV electrons are thought to contain a significant fraction of the flare energy budget (e.g., Lin and Hudson, 1976). We constructed the histogram of peak >25 keV counting rates (>100 c s^{-1}) in Figure 1 where we have indicated the fraction of events associated with Type II bursts by cross-hatching. It can be seen that while the percentage association of Type II bursts increases with the peak size of the hard X-ray burst (from 2% to 17% to 41% to 100% for successive decade sizes in Figure 1), the great majority (95%; 2397/2511) of the hard X-ray bursts lacked Type II association. Even large (>1000 c s^{-1}) hard X-ray bursts were accompanied by Type IIs only 21% (69/321) of the time. If we include all >1000 c s^{-1} X-ray bursts for which the peak may have been missed (such events tend to be larger and thus have a higher degree of association with Type II bursts) and count all 'marginal' Type IIs, i.e., short, weak, possible, and decimetric events, or Type II bursts reported by any observatory, as legitimate Type IIs, then the percentage association of Type II bursts with these large hard X-ray flares increases to 24% (87/358).

The 114 Type II bursts from Figure 1 account for 36% (114/318) of all Type II bursts meeting our selection criteria that were observed during the two and a half year interval we considered. For an additional 30 Type II bursts, HXRBS was observing the Sun and recorded either no event or an event with a peak counting rate ≤ 100 c s^{-1}. Thus the overall HXRBS duty cycle for Type II flares during this interval was $\sim$ 45% (144/318), somewhat lower than the $\sim$ 50% HXRBS time coverage available for the entire 1980–1989 SMM lifetime.

There is some debate in the literature as to whether Type II bursts are a big (e.g., Wild and Smerd, 1972) or a small (Dodge, 1975) flare phenomenon. Dodge (1975) reported that 40% of Type II bursts originated in optical subflares while another 40% are associated with class 1 flares. Thus, Type II bursts are linked to small optical flares*. At the same time, Type II-associated flares tend to have strong impulsive phase emissions; $\sim$ 60% of the Type II bursts in Figure 1 are associated with hard X-ray flares with peak count rates >1000 c s^{-1}. In sum, Type II flares tend to be spatially small but intense events (cf., Cane and Reames, 1988). As

---

[*] Flares associated with metric Type II bursts tend to be somewhat larger as a group than flares in general. As reported by Dodge (1975), 97% of all flares are $\leq$ class 1 vs 80% for Type II-associated flares. Also Pearson *et al.* (1989) showed that the size distribution of hard X-ray bursts associated with Type II bursts is flatter than that of all X-ray bursts.

can be seen in Figure 1, Type II burst associations exist across the range of peak $>$25 keV intensities we considered, forcing the question: what distinguishes the hard X-ray flares of a given peak intensity that are associated with Type II bursts from the majority of flares of equal intensity (for all except the highest bins) that are not? For example, only 6% (28/497) of the events in the second smallest bin in the histogram in Figure 1 were associated with Type II bursts. These 28 Type II bursts represent 25% of the 114 events in all bins. All but three of the 28 Type II bursts were associated with reported Hα flares, so the relatively low peak hard X-ray count rates cannot be due to occultation effects. There seems no escaping the fact that some special condition or circumstance as first posited by Roberts (1959) (cf., Dodson, Hedeman, and Chamberlain, 1953) is required for the formation of a Type II burst.

3.2. SPECIAL CONDITION FOR TYPE II FORMATION: LOW ALFVÉN SPEED IN THE FLARING REGION

One such special condition which has been invoked for the presence of a metric Type II burst is a low Alfvén speed in the flaring region (Uchida *et al.*, 1974a, b; Kahler *et al.*, 1984b). While (to our knowledge) no systematic study has ever been undertaken of density and field strengths of regions which do, and do not, produce Type II bursts, there are observations of repeated flares from an active region – some with and some without associated Type II bursts – that make the variable Alfvén speed hypothesis problematic as the special condition required for Type II emission. Figure 2 contains the SMS-GOES soft X-ray plot for 10–13 August 1981 during which time Hale Plage Region 17777 dominated solar activity. We have indicated the occurrence of Type II bursts during this period. For each flare with GOES soft X-ray class $\geq$ M3, the flare longitude and $\sim$ 9 GHz peak flux density are given. The $\sim$ 9 GHz peak flux density is a measure of the size of the flare impulsive phase and is used in lieu of the peak hard X-ray flux because of their close correlation (Kundu, 1961; Arnoldy *et al.*, 1968) and because microwave coverage of the Sun is essentially continuous throughout the UT day. Within region 17777 during 10–13 August, large flares originated in two distinct locations separated by $\sim$ 10° in longitude. In Figure 2, flares from these two locations are labeled ‘A’ and ‘B’, respectively. For the A sequence, we note that the flare on the 10th, that lacked a Type II burst, was comparable in size to the flare near 02:00 UT on the 11th that was accompanied by Type II emission. The third flare in the sequence at $\sim$ 15:00 UT on the 11th was significantly smaller than either of the earlier flares (in terms of microwave but not soft X-ray emission) and no Type II burst was observed. The first two flares in the B sequence had Type II emission. The second of these flares, $\sim$ 06:30 UT on the 12th, was an intense (X2) soft X-ray event with a peak $\sim$ 9 GHz flux density of $\sim$ 1000 s.f.u. However, the earlier Type II-associated flare, at $\sim$ 08:00 UT on the 11th, was comparable to the last three M-class flares in the B sequence, none of which were accompanied by Type II bursts. Clearly some

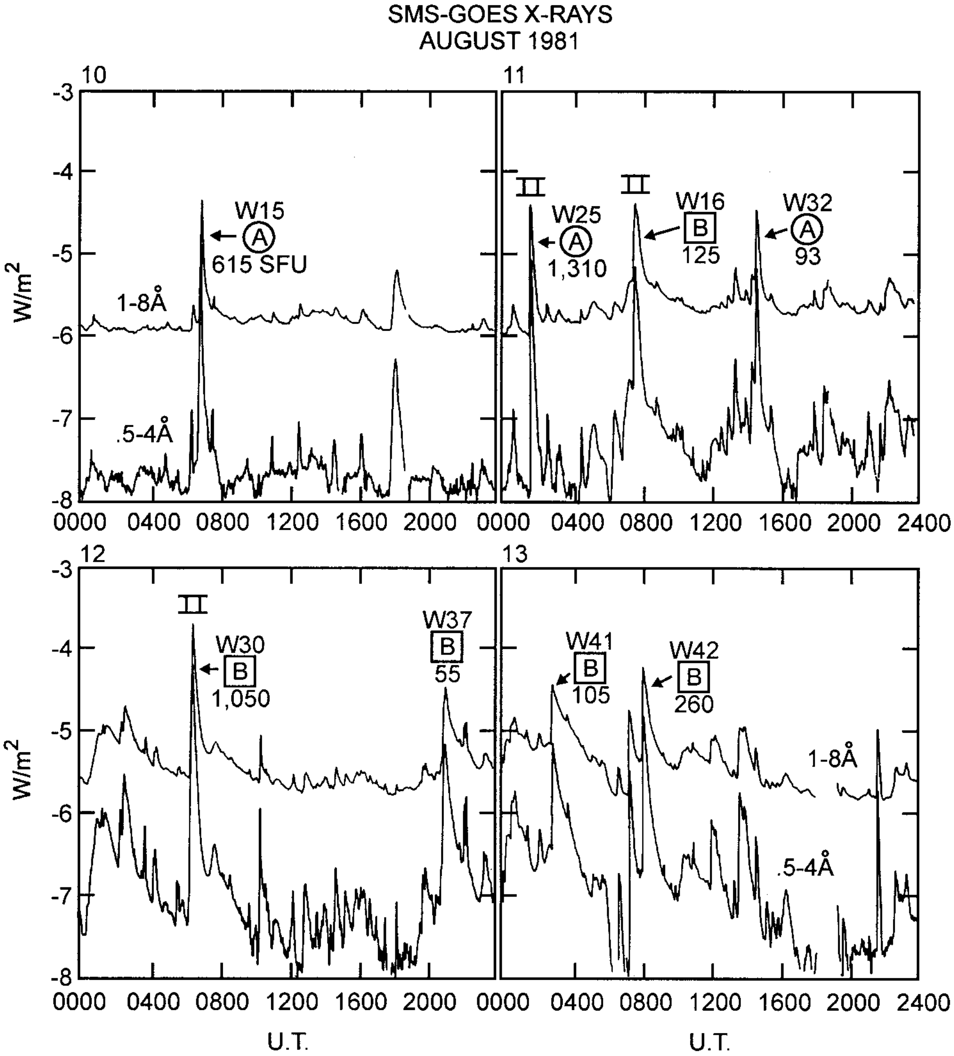

Figure 2. GOES soft X-ray plots for 10–13 August 1981. The flare longitude and ~ 9 GHz peak flux are given for all flares with 1–8 Å class ≥ M3. The 'A' and 'B' descriptors denote flares from two separate locations within Hale Plage Region 17777.

special circumstance, more or less independent of flare size, is required for Type II formation. If that special condition is a low Alfvén speed in the region within reach of a flare-generated wave, then it appears from Figure 2 that the ambient Alfvén speed can change fairly rapidly (~ 1 day) from favorable to unfavorable conditions or vice versa.

Another example illustrating this assumed effect is given in Figure 3 which contains soft X-ray plots for 8–11 September 1981. In Figure 3, we have labeled all M-class flares from Hale Plage Region 17830 that was active during this interval.

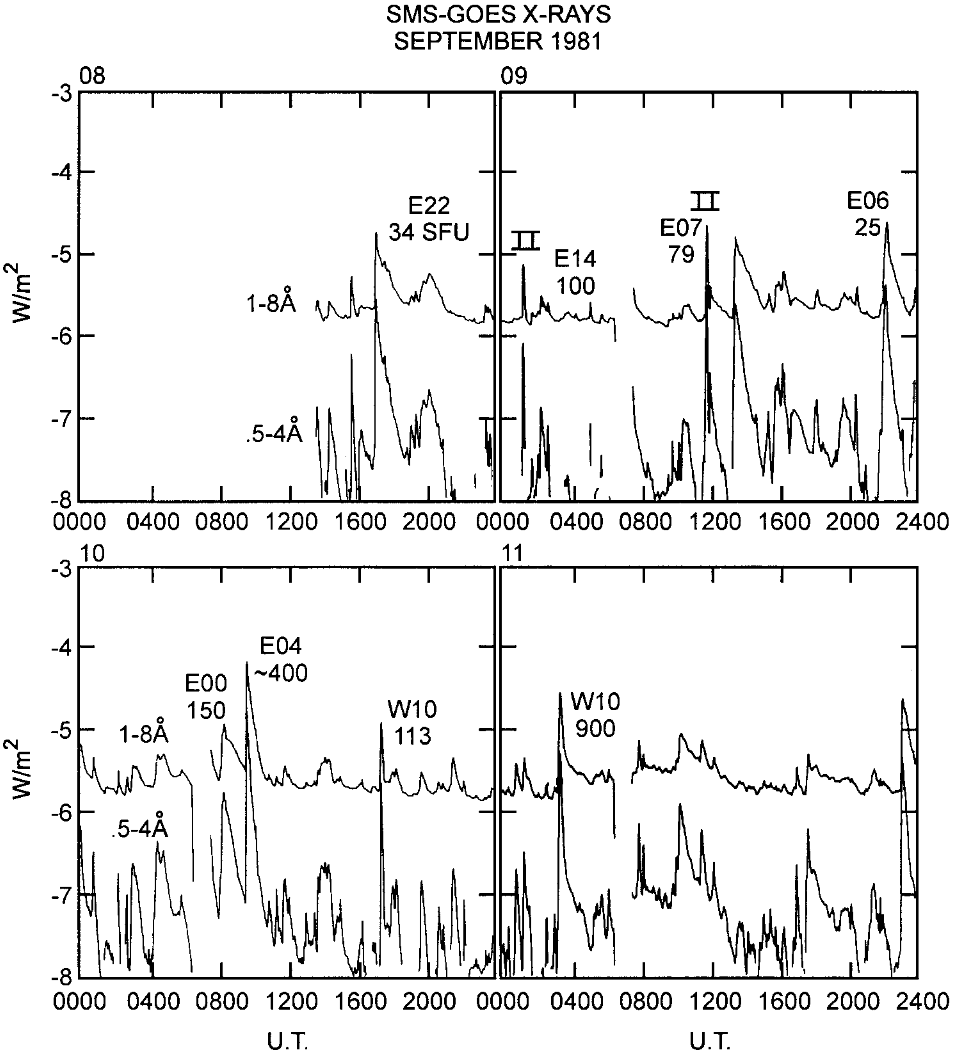

Figure 3. GOES soft X-ray plot for 8–11 September 1981. The flare longitude and ~9 GHz peak flux are given for all M-class flares from Hale Plage Region 17830.

As in the above case (Figure 2), we can see that the Type II-associated flares are indistinguishable from those without Type II bursts. The activity from region 10830 implies that the ambient Alfvén speed in a region can change significantly on a time scale of several hours. Such behavior is difficult to reconcile with the notion – based on Figure 1 – that the low Alfvén speed required for shock formation is a rare condition. While the possibility that special ambient Alfvén-speed conditions enabled certain flares in Figures 2 and 3 to generate Type II emission cannot be ruled out, there is no evidence for it either, other than the existence of the Type II bursts themselves. We suspect rather that active regions with a proclivity toward shock

TABLE I

Previous studies of the limbward fraction of Type II flares associated with CMEs

Coronagraph	Longitude bin	Fraction with CMEs	Years	Reference
Skylab	46–90	21 of 23; 91%	1973–1974	Munro *et al.* (1979) (Includes Type IVs)
Skylab	61–90	4 of 5; 80%	1973–1974	Kahler *et al.* (1984b)
Solwind	61–90	34 of 55; 62%	1979–1982	Kahler *et al.* (1984b)
	76–90	20 of 23; 87%	1979–1982	
SMM	76–90	8 of 10; 80%	1980	Sawyer (1985)
SMM	61–90	12 of 18; 67%	1980	Webb (1986)

generation (Dodge, 1975) are those more likely to produce CMEs. The occurrence of CMEs indicates a cataclysmic rearrangement of large-scale magnetic fields and density structures that contrasts with the rather static and localized picture of flares and active regions that was in place (see Cliver, 1995) when Uchida introduced the variable Alfvén speed hypothesis as the special condition required for Type II formation. In the next section, we present statistical evidence for the Type II/CME link.

3.3. SPECIAL CONDITION FOR TYPE II FORMATION: FAST CORONAL MASS EJECTION

Table I summarizes the results of previous studies on the association between metric Type II bursts and coronal mass ejections (cf., Sawyer, 1985; Webb and Howard, 1994). The salient features from all of these studies are the increasing degree of association of Type II flares with CMEs as one approaches the solar limb and the high degree of association (∼60–90%) for flares near the limb. The Thomson scattered white light from CMEs that is imaged by coronagraphs is most visible in the plane of the sky (Hundhausen, 1993), making eruptions at the solar limb easier to detect than those with sources closer to solar central meridian. The most comprehensive of the studies referenced in Table I was that of Kahler *et al.* (1984b); their investigation was based on NRL *Solwind* coronagraph data for the solar maximum period from March 1979 through August 1982. These authors required that at least one processed subtracted image of the corona be available within a 4-hr window following the onset of the Type II burst for an event to be included in their analysis. They listed 10 non-CME Type II bursts that were associated with near-limb (within 30°) flares with moderately strong (≥M1 soft X-ray class and peak 3 cm impulsive burst ≥100 solar flux units) as particularly good counter examples to the CME-piston hypothesis for Type II bursts. Similar to the finding of Sheeley *et al.* (1984),

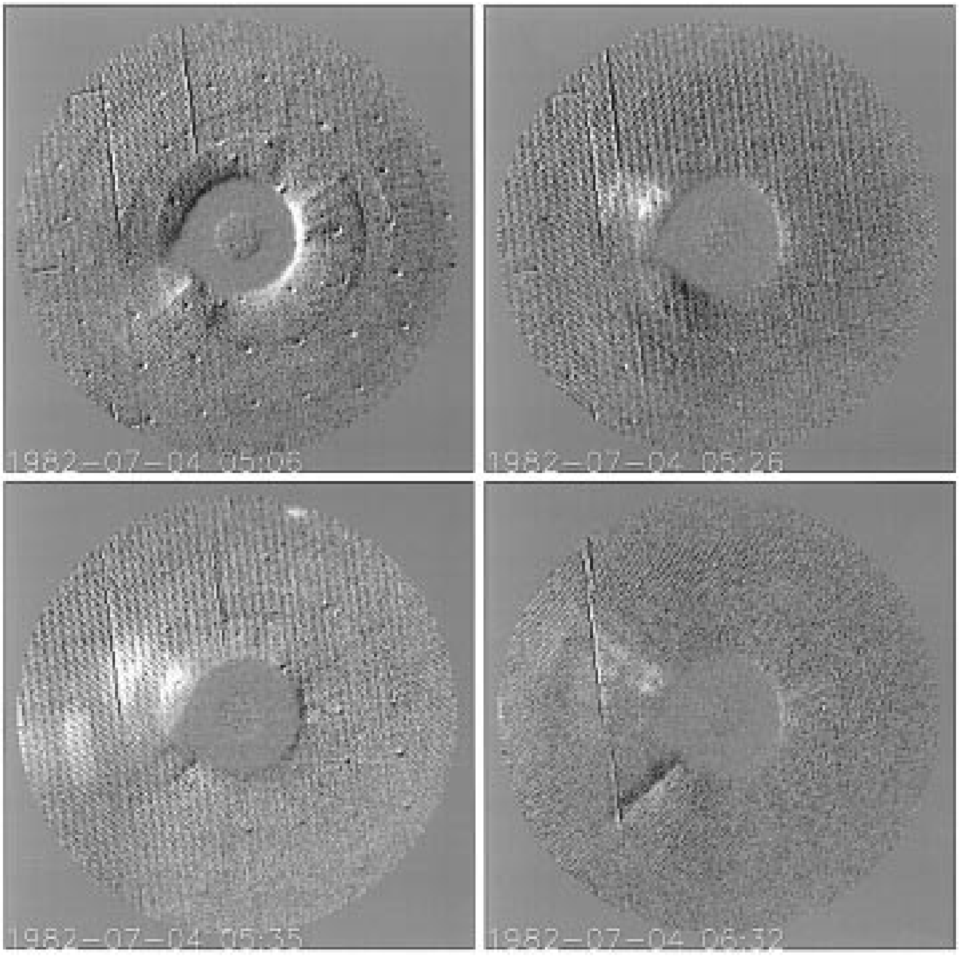

Figure 4. Solwind images for a CME on 4 July 1982. A base image taken at 04:56 UT is subtracted from each frame. In the 05:06 UT image, the base image is slightly misregistered. The bright area on the far left in the 05:35 UT image is caused by a shutter problem; it is not part of the CME.

these 10 non-CME Type II events were associated with impulsive soft X-ray flares. For these 10 events, we examined all of the available *Solwind* coronagraph images (as subtractions), not only the preliminary run of processed images (one per orbit) available to Kahler *et al.* (1984b). We found that two of these 10 events (4 July 1982 and 8 August 1982) had definitely associated CMEs. The subtracted images for one of these events (4 July 1982), shown in Figure 4, reveal a fast CME with speed $\sim$ 1450 km s^{-1}. The leading edge of such a CME will pass out of the 10 R_0 field of view of the coronagraph in $\sim$ 1.25 hr. For two other of the 10 events the first available image was taken $>$3 hr after Type II onset. For one event, the Type II had an alternate source flare close to central meridian and in another case, the associated flare was located directly under the *Solwind* pylon, making observations difficult.

For an event on 7 June 1980, the Type II classification is questionable (Hilary Cane, 1997, private communication), and for the 28 March 1981 event, the Type II burst was qualified as a 'possible event', leaving only two (of 10) unambiguous cases.

As a result of this preliminary exercise, we decided to re-examine the relationship between metric Type II bursts and CMEs using all available coronagraph images (subtracted) for times of interest. We considered the entire *Solwind* interval of operation, from March 1979 to September 1985 and compiled a list of all Type II bursts reported in *Solar-Geophysical Data* as well as in separate unpublished reports for the Nancay and Weissenau Observatories. We considered all Type IIs (of any length and intensity), including decimetric Type IIs, reported by any station. We only excluded the possible Type IIs reported by Culgoora. From our Type II list, we selected the subset of all events associated with Hα flares located $>60°$ in longitude from solar central meridian. In all, 147 such events were reported during this period, corresponding to the peak and decay of solar cycle 21. For 90 of these 147 events, at least one *Solwind* image existed within a 2 hr and 15 min window beginning 15 min after the onset of the metric Type II burst. The 15-min delay was required because a CME with an assumed height of 1.5 R_0 (from Sun center) at the time of Type II onset and a leading edge speed of 600 km s^{-1} will reach a height of $\sim$ 2.3 R_0 in 15 min, still below the 2.5 R_0 edge of the occulting disk of the coronagraph. The outer limit of 2.5 hr after Type II onset was chosen because in that time interval, the leading edge of a 1000 km s^{-1} CME originating at the solar limb will reach $\sim$ 13 R_0, beyond the field of view of the coronagraph. The rates of CME association for the 90 Type II bursts with coronagraph coverage are given in Table II, for Type II associated flares within 30° and 15° of the limb. For the 76 definitive cases in the 30° column, 64% (49/76) of the Type II bursts were accompanied by fast CMEs, comparable to the results of previous investigators. For 14 of the 90 events (16%), a CME was possibly associated with a Type II burst but we could not say for certain because of timing or positional discrepancies or observational difficulties. We examined the associations made independently by Kahler *et al.* (1984b) (Steve Kahler, 1997, private communication) for the 14 events in our possible or questionable category and found that those authors considered six of the eight events in this category that were common to both studies to have definite CME associations. Thus we believe that the overall association rate we obtain of 64% is valid. For Type II bursts associated with flares within 15° of the limb, the CME association rate increases to 79% (30/38).

Based on our reanalysis of the 10 counter-examples to the CME-piston hypothesis listed by Kahler *et al.* (1984b), we expected that our Type II/CME association rate would increase over the 60–70% from the previous studies of Sheeley *et al.* (1984) and Kahler *et al.*, but our results are in good agreement with theirs. For example, Kahler *et al.* (1984b) found that 62% (34/55) of Type II bursts associated with flares within 30° of the limb had Type II association; for events within 15° of the limb the percentage association was 87% (20/23) (Table I). These percentages compare with our values of 64% and 79%, respectively.

TABLE II

Limbward fraction of Type II flares associated with CMEs for the 1979–1985 *Solwind* data set

Longitude Bin	Number of Cases			% associated
	CME	No CME	Indeterminate	
61–90	49	27	14	49/76 = 64%
76–90	30	38	5	30/38 = 79%

Does this mean that the ∼20–35% of Type IIs that lack CME association are flare-generated blast waves? To examine this possibility, we compiled histograms of the peak GOES 1–8 Å soft X-ray flux and the peak 9 GHz (∼3 cm) fluxes of the microwave bursts associated with the 49 CME-associated Type IIs and the 27 events that definitely lacked *Solwind* CMEs in our study. As can be seen from Figures 5(a) and 5(b), the soft X-ray/9 GHz bursts associated with the non-CME Type IIs are smaller (by a factor of ∼2.5/∼4 in the medians) than the Type IIs with CME association. Although some of the non-CME flares are big events, the median peak soft X-ray/microwave flux for the group as a whole (M1/∼60 s.f.u.) indicates a fairly garden-variety event, not indicative of the substantial energy release one might expect to be required for a blast wave Type II (cf., Kahler *et al.*, 1984b). Thus we suspect that CMEs went unobserved in the ‘non-CME’ Type II events in Table II.

There is an additional reason to believe that CMEs may have gone unobserved in these cases. Type IIs that lack CMEs tend to be associated with impulsive flares (Sheeley *et al.*, 1984; Kahler *et al.*, 1984b). In our sample, the median duration of 1–8 Å bursts above the C2 level (cf., Kahler, Sheeley, and Liggett, 1989) was 0.6 hr for the non-CME-associated flares vs 1.7 hr for the Type II flares with CMEs. As Kahler *et al.* (1989) have shown, CME angular span varies with soft X-ray duration. CMEs associated with impulsive flares tend to be narrow, making them more difficult to observe. From the least-squares best-fit line through the data in Figure 2 of Kahler *et al.* (1989), soft X-ray durations (above the C2 level) of 0.6 hr and 1.7 hr imply angular CME widths of $\sim 10^\circ$ and $\sim 40^\circ$, respectively, with a good deal of scatter.

Figure 6(a) contains a histogram of the leading edge speed of the CMEs for the 43 of 49 Type IIs in Table II with CME association for which the speed could be determined. A normalized histogram of speeds of all *Solwind* CMEs observed from 1979–1981 (Howard *et al.*, 1985) is shown for comparison in Figure 6(b). As reported by Gosling *et al.* (1976), Sheeley *et al.* (1984), and others, it can be seen that the CMEs associated with Type II bursts are characteristically fast events with speeds $>$400 km s^{-1}, well above the ∼300 km s^{-1} median speed of all CMEs

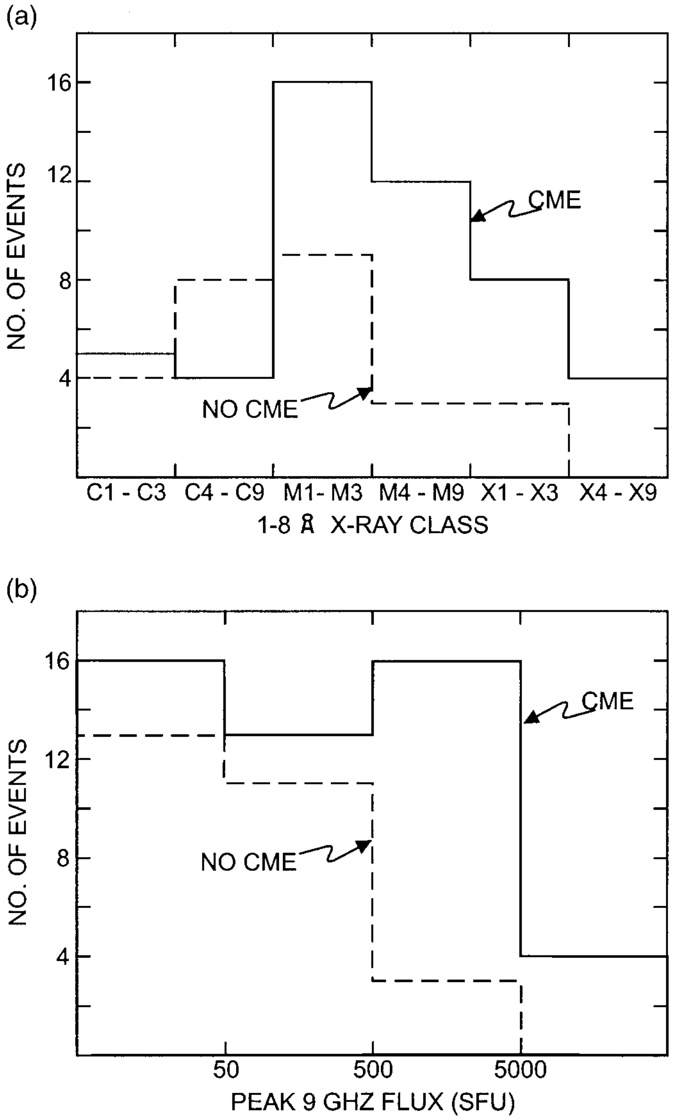

Figure 5. Histograms of (a) 1–8 Å intensity classes and (b) peak 9 GHz flux densities of Type II limb flares with and without associated CMEs.

(Howard *et al.*, 1985; Hundhausen *et al.*, 1994). We regard this selective association between Type II bursts and fast CMEs as strong evidence for our thesis that most and possibly all metric Type IIs are driven by CMEs, particularly since it is generally accepted that fast CMEs drive kilometric Type II shocks in the interplanetary medium.

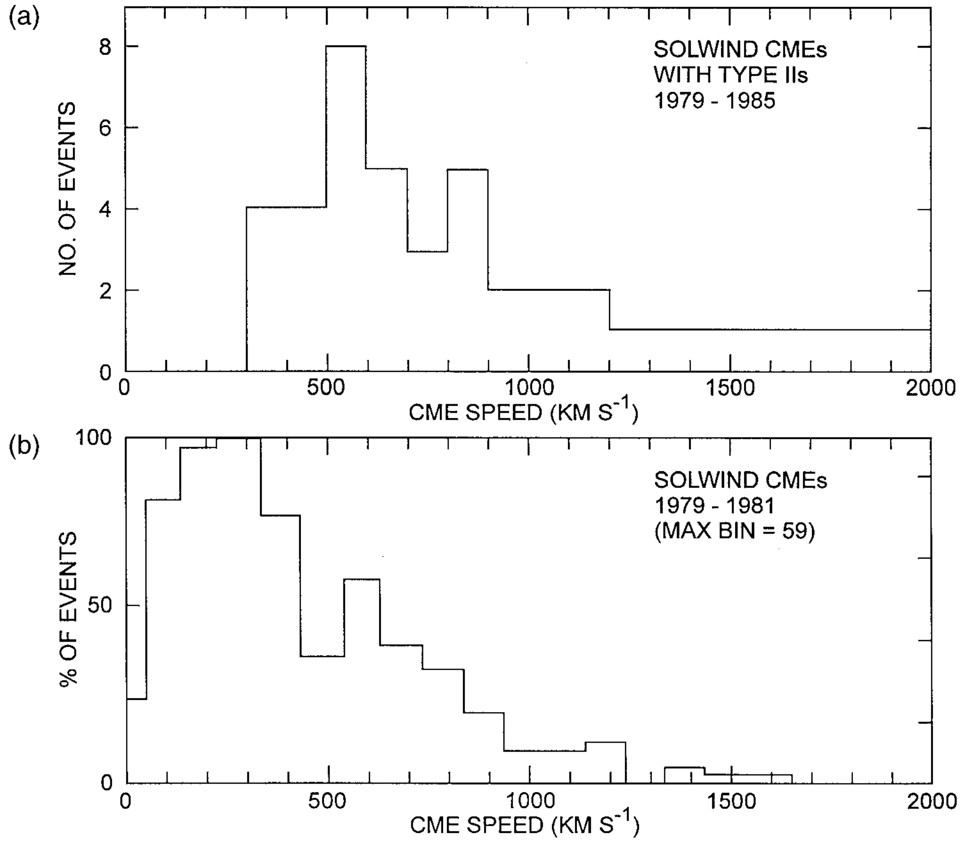

Figure 6. (a) Histogram of speeds of *Solwind* CMEs associated with metric Type II bursts, 1979–1985. (b) Normalized histogram of speeds of all *Solwind* CMEs observed from 1979–1981 (from Howard *et al.*, 1985).

4. Conclusion

4.1. REVIEW OF THE EVIDENCE FOR THE FLARE VS CME ORIGIN OF CORONAL SHOCK WAVES

Over the years an impressive array of arguments has arisen to support both the flare- and CME-based pictures for metric Type IIs (e.g., Cane, 1984). We begin with the observations that support the flare-initiated blast wave picture:

(1) There exists a close timing between flares and Type II bursts, with Type II emission typically commencing within several minutes of microwave burst (hard X-ray) maximum (Kundu, 1965; Švestka and Fritzová-Švestková, 1974; Vršnak *et al.*, 1995). While this argument seems compelling on the surface, Figure 7, a modification of a figure from Hundhausen (1999), shows that the rapid acceleration of fast CMEs can also occur near Type II onset (and the flare impulsive phase). An

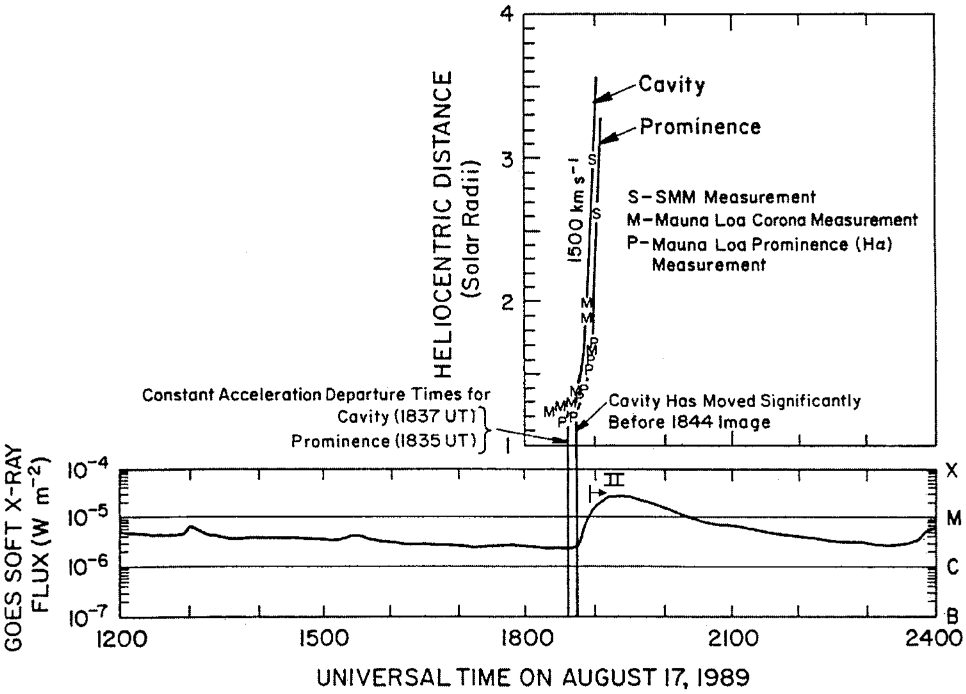

Figure 7. CME time-height plot and soft X-ray profile for the Type II-associated limb flare on 17 August 1989 (from Hundhausen, 1999). The onset time of the Type II is indicated.

additional example from Hundhausen (1999) of close timing between the launch of a fast CME and Type II onset is discussed by Cliver (1999).

(2) As shown again in the present study, a non-negligible fraction (∼20–35%) of Type II bursts associated with limb flares lack associated CMEs. As argued above, we believe that CMEs may have gone unobserved in these events based on: (1) the high (∼80%) percentage of Type II bursts accompanied by fast CMEs for flares under the most favorable circumstance, within 15° of the solar limb; (2) the relatively weak impulsive phases of non-CME Type II flares (Figure 5), inconsistent with the blast-wave picture; and (3) the short durations of the non-CME Type II flares, indicating narrower, and therefore more difficult to observe, CMEs. In addition, the CME observing rate for the Large Angle Spectroscopic Coronagraph (LASCO) (Brueckner *et al.*, 1995) on SOHO for the current solar minimum is a factor of two or more higher than the rate obtained from coronagraph observations for the previous solar minimum (Howard *et al.*, 1997). This higher rate presumably results from the improved sensitivity, more regular observing cadence, and extended field of view of LASCO in comparison with earlier instruments (although intrinsic differences between solar minima cannot be ruled out) and suggests that some narrow and perhaps fainter CMEs of the type which we would expect to be associated with the flares in the non-CME category of Table II, may have been

missed by *Solwind*. Thus we are inclined to believe that the true association rate of Type IIs with fast CMEs is higher than 65% or 80% and may well be 100%. LASCO observations during the coming solar maximum should be adequate to confirm or rule out this working hypothesis. A comparison of Type II bursts and CMEs during the first two years of LASCO operation is underway. Preliminary results are consistent with the high degree of association we found for near limb events with Solwind.

(3) As shown by Gary *et al.* (1984) and others (e.g., Gopalswamy and Kundu, 1992), the spatial relationship between CMEs and Type IIs is not always consistent with a piston-driven shock. Often, the radio emission appears to lie within the CME, behind the leading edge. We do not regard this as a fatal objection. As Cane (1984) noted, the observed Type II positions may be affected by ducting in the corona and ionospheric refraction. Moreover, projection effects come into play (see Bougeret, 1985). For non-imaged observations, lack of precise information about the density profile makes comparisons problematic. Finally, Holman and Pesses (1983) and Steinolfson (1984) have shown theoretically that emission might be more readily produced at the flanks of the CME.

(4) Robinson *et al.* (1986) reported differences in the properties of Type IIs with and without CMEs. However, their analysis was based on the Sheeley *et al.* (1984) identification of two classes of events that did not take the increased observability of CMEs near the limb into account. Thus, the median longitude for the CME-associated Type II flares is 54° vs 42° for the non-associated events, and the purity of the two classes and hence the validity of the result is called into question. Also, some of the differences found, e.g., the greater complexity of the CME-associated Type IIs, may simply reflect the larger overall size of these events and may therefore represent a difference of degree rather than of kind.

(5) Most recently, Gopalswamy *et al.* (1998) compared observations of coronal Type II bursts from ground-based instruments with observations of interplanetary (IP) Type II bursts observed by the WAVES experiment on the *Wind* spacecraft. During the interval from November 1994 through April 1996, they found that none of the 34 coronal Type IIs they observed were subsequently detected at kilometric frequencies by WAVES and that none of 3 transient IP shocks observed by the Magnetic Field Instrument on *Wind* were preceded by coronal Type II bursts. From these results, they concluded that ‘coronal and interplanetary shocks are two different populations and are of independent origin’ and attributed coronal shocks to flares. The results of the Gopalswamy *et al.* study were addressed in detail in Cliver (1999) where it was pointed out that: (1) more extensive observations made by the low frequency radio experiment on ISEE-3 from 1978–1983 show that IP Type IIs are characteristically (70% of the time) accompanied by metric Type IIs; and (2) two of the metric Type II bursts reported by Gopalswamy *et al.* were followed by interplanetary shocks that were strong enough to accelerate ∼10 MeV protons but which, for unknown reasons, did not have associated kilometric Type II emission. Thus Cliver (1999) concluded that the attribution of metric and interpla-

netary Type II bursts to separate sources – flares for coronal shocks and fast CMEs for IP shocks – was premature at best. Cliver (1999) also critiqued the suggestion of Gopalswamy *et al.* (1998) that coronal shocks were driven by short-lived flare sprays.

The principal arguments in favor of a CME origin for slow-drift metric bursts are the following:

(1) Type IIs are highly associated with fast ($>$400 km s^{-1}) CMEs (Table II, Figure 6). This high degree of association of two relatively rare phenomena suggests a causal relationship. Moreover, the fact that a high percentage of Type II bursts originate in relatively small flares (Figure 1) argues against a big flare syndrome (Kahler, 1982a) explanation of the association. If CMEs were extraneous to Type II formation, we would expect Type IIs to be better associated with the more common slow CMEs than with those having speeds $>$400 km s^{-1}. In fact, as shown in Figure 6 and other studies, there are only a handful of cases (e.g., Gopalswamy and Kundu, 1995b) of Type IIs that were associated with slow CMEs.

(2) For a large sample of events, Robinson (1985) showed that Type II speeds were consistent with the observed range of speeds of CMEs associated with Type II bursts. It should be pointed out, however, that comparisons of CME speeds and Type II speeds for individual events have produced discordant results (Gergely, 1984; Gopalswamy and Kundu, 1992).

(3) Approximately two-thirds of fast CMEs are accompanied by metric Type IIs (Kahler *et al.*, 1985). We are aware that this argument can be used the other way (one-third not associated), but again, if CMEs are not essential to the Type II process, then why this high degree of association? Robinson, Stewart, and Cane (1984) showed that interplanetary Type II bursts were characteristically associated with metric Type II bursts that had low starting frequencies. This suggests that those metric Type II bursts that are likely to survive into the interplanetary medium start high in the corona. Occasionally, the CME may be expected to exceed the local Alfvén speed only after it has passed beyond the metric range accessible by ground-based radio telescopes. Gopalswamy and Kundu (1995a) suggested that high starting points and late accelerations may preclude ground-based observations of CMEs in general, but the 4 R_0 starting height (from Sun center) they use refers to slowly developing streamer blow out events and not to the more energetic events that produce Type IIs (cf., Cliver, 1999). For example, the major near-limb CME on 29 September 1989 (77° angular width; 1828 km s^{-1}) that produced the largest increase in GeV particles at Earth since 1956 can be clearly seen emerging from below the effective SMM coronagraph occulting disk that extended to 0.8 R_0 above the limb (Joan Burkepile, 1998, private communication).

4.2. DISCUSSION

As noted in the Introduction, the picture that all coronal shock waves are flare-initiated blast waves appears to be gaining acceptance (e.g., Aurass, 1992; Cane, 1997). In contrast, we have argued that both coronal and interplanetary shocks owe their existence to fast material motion. We believe that a fast CME, not an intense flare or an unusually low Alfvén speed in the vicinity of a flare, is the long-sought special condition required for the generation of a metric Type II radio burst.

The scenario we have in mind is that a fast CME drives a shock which is manifested in the chromosphere as a Moreton wave, in the low corona as a Type II burst and the waves detected by the EIT on SOHO, and in the interplanetary medium as an interplanetary shock if the event is fast/strong enough. Given the different mechanisms for acceleration of electrons at shocks and the role played by the ambient medium (Uchida, 1974a, b) and local structures both in the corona (Stewart, 1984) and in the interplanetary medium (e.g., Lengyel-Frey and Stone, 1989) in shock formation, it need not follow that the metric-kilometric shock is a seamless entity (although the analysis of Robinson, Stewart, and Cane (1984) suggests that in some cases it may be).

We note that the coronal waves observed to date by EIT appear to be well-associated with CMEs (Thompson *et al.*, 1998b). The EIT wave that traversed the face of the Sun on 12 May 1997 (Thompson *et al.*, 1998b) is particularly instructive. It was accompanied by a Type II burst, a C1 soft X-ray burst, a 10 solar flux unit burst at 2800 MHz (SGD), and a 1F/N Hα flare. At solar maximum, a dozen flares of this size can occur on a given day; in fact, the soft X-ray background level will generally exceed C1 when a strong active region is on the disk. The remarkable aspect of the 12 May event (i.e., the candidate feature presumably required for Type II formation) was not its associated flare – that would scarcely have been noticed during active periods – but rather an associated halo CME that produced a magnetic storm at Earth (Plunkett *et al.*, 1998). While the Type II burst and widespread EIT wave on 7 April 1997 (Thompson *et al.*, 1998a) were associated with a moderately intense microwave burst (220 s.f.u. at 2800 MHz) and a 2N Hα flare, the soft X-ray event (C6.8) was unexceptional. Like 12 May, this event was distinguished primarily by an associated halo CME (Howard *et al.*, 1998). Previously, small flare (or even non-flare) events with associated CMEs and significant geophysical effects (e.g., Joselyn and McIntosh, 1981; Cliver, Kahler, and McIntosh, 1983) provided underpinning for the paradigm shift from flares to CMEs in solar-terrestrial physics (Kahler, 1992; Gosling, 1993). Back at the Sun, such events support our conclusion that a CME is the essential ingredient, the 'special condition' invoked 40 years ago by Roberts, that distinguishes small flares that have associated metric Type II bursts from the vast majority that do not.

Acknowledgements

We thank Marty Koomen for assistance with the *Solwind* data throughout the course of this study, Jean-Louis Bougeret for helpful comments on the manuscript, and Doug Pearson for providing pre-sorted lists of HXRBS events.

References

Anderson, G. E.: 1966, Thesis, University of Colorado.

Arnoldy, R. L., Kane, S. R., and Winckler, J. R.: 1968, *Astrophys. J.* **151**, 711.

Athay, R. G. and Moreton, G. E.: 1961, *Astrophys. J.* **133**, 935.

Aurass, H.: 1992, *Ann. Geophys.* **10**, 359.

Bougeret, J.-L.: 1985, in B. T. Tsurutani and R. G. Stone (eds.), *Collisionless Shocks in the Heliosphere: Reviews of Current Research*, AGU, Washington, DC, p. 13.

Brueckner, G. E. *et al.*: 1995, *Solar Phys.* **162**, 357.

Bruzek, A.: 1974, in G. Newkirk, Jr. (ed.), ‘Coronal Disturbances’, *IAU Symp.*, **57**, 323.

Cane, H. V.: 1983, in M. Neugebauer (ed.), *Solar Wind Five*, NASA, Greenbelt, MD, p. 703.

Cane, H. V.: 1984, *Astron. Astrophys.* **140**, 205.

Cane, H. V.: 1997, in N. U. Crooker, J. A. Joselyn, and J. Feynman (eds.), *Coronal Mass Ejections*, AGU, Washington, p. 205.

Cane, H. V. and Reames, D. V.: 1988, *Astrophys. J.* **325**, 895.

Cane, H. V., Sheeley, N. R., Jr., and Howard, R. A.: 1987, *J. Geophys. Res.* **92**, 9869.

Cliver, E. W.: 1995, *Solar Phys.* **157**, 285.

Cliver, E. W.: 1999, *J. Geophys. Res.* **104**, 4743.

Cliver, E. W., Kahler, S. W., and Mclntosh, P. S.: 1983, *Astrophys. J.* **264**, 699.

Delaboudinière, J.-P. *et al.*: 1995, *Solar Phys.* **162**, 291.

Dennis, B. R., Orwig, L. E., Kennard, G. S., Labow, G. J., Schwartz, R. A., Shaver, A. K., and Tolbert, A. K.: 1991, *The Complete HXRBS Event Listing, 1980–1989*, NASA TM-4332, Greenbelt, MD.

Dodge, J. C.: 1975, *Solar Phys.* **42**, 445.

Dodson, H. W., Hedeman, E. R., and Chamberlain, J.: 1953, *Astrophys. J.* **117**, 66.

Dryer, M.: 1974, *Space Sci. Rev.* **15**, 403.

Fainberg, J. and Stone, R. G.: 1970, *Solar Phys.* **15**, 222.

Gary, D. E., Dulk, G. A., House, L., Illing, R., Sawyer, C., Wagner, W. J., McLean, D. J., and Hildner, E.: 1984, *Astron. Astrophys.* **134**, 222.

Gergely, T.: 1984, in M. A. Shea, D. F. Smart, and S. M.P. McKenna-Lawlor (eds.), *STIP Symp. on Solar/Interplanetary Intervals*, Bookcrafters, Inc. Chelsea, MI, p. 347.

Gergely, T. E. *et al.*: 1984, *Solar Phys.* **90**, 161.

Giovanelli, R. G. and Roberts, J. A.: 1958, *Australian J. Phys.* **2**, 353.

Giovanelli, R. G. and Roberts, J. A.: 1959, in R. N. Bracewell (ed.), *Paris Symp. on Radio Astronomy*, Stanford University Press, Stanford, CA, p. 201.

Gopalswamy, N. and Kundu, M. R.: 1992, in G. P. Zank and T. K. Gaisser (eds.), *AIP Conf. Proc. 264*, *Particle Acceleration in Cosmic Plasmas*, AIP, New York, p. 257.

Gopalswamy, N. and Kundu, M. R.: 1995a, in T. Watanabe (ed.), *Proc. of the 2nd SOLTIP Symp.*, Ibaraki University, Ibaraki, Japan, p. 177.

Gopalswamy, N. and Kundu, M. R.: 1995b, in A. O. Benz and A. Krüger (eds.), *Coronal Magnetic Energy Releases*, Springer-Verlag, Berlin, p. 223.

Gopalswamy, N. *et al.*: 1998, *J. Geophys. Res.* **103**, 307.

Gosling, J. T.: 1993, *J. Geophys. Res.* **98**, 18937.

Gosling, J. T., Hildner, E., MacQueen, R. M., Munro, R. H., Poland, A. I., and Ross, C. L.: 1976, *Solar Phys.* **48**, 389.

Hansen, R. T., Garcia, C. J., Grognard, R. J.-M., and Sheridan, K. V.: 1971, *Proc. Astron. Soc. Australia* **2**, 57.

Harvey, K. L., Martin, S. F., and Riddle, A. C.: 1974, *Solar Phys.* **36**, 151.

Hirshberg, J., Alksne, A., Colburn, D. S., Bame, S. J. C., and Hundhausen, A. J.: 1970, *J. Geophys. Res.* **75**, 1.

Holman, G. D. and Pesses, M. E.: 1983, *Astrophys. J.* **267**, 837.

Howard, R. A., Sheeley, N. R., Jr., Koomen, M. J., and Michels, D. J.: 1985, *J. Geophys. Res.* **90**, 8173.

Howard, R. A. *et al.*: 1997, in N. Crooker, J. A. Joselyn, and J. Feynman (eds.), *Coronal Mass Ejections*, AGU, Washington, DC, p. 17.

Howard, R.A. *et al.*: 1998, *Geophys. Res. Letters* (submitted).

Hundhausen, A. J.: 1972, *Coronal Expansion and Solar Wind*, Springer-Verlag, New York.

Hundhausen, A. J.: 1993, *J. Geophys. Res.* **98**, 13177.

Hundhausen, A. J.: 1999, in K. T. Strong *et al.* (eds.), *The Many Faces of the Sun*, Springer-Verlag, New York, p. 143.

Hundhausen, A. J., Burkepile, J. T., and St. Cyr, O. C.: 1994. *J. Geophys. Res.* **99**, 6543.

Joselyn, J. A. and McIntosh, P. S.: 1981, *J. Geophys. Res.* **86**, 4555.

Kahler, S. W.: 1982a, *J. Geophys. Res.* **87**, 3439.

Kahler, S. W.: 1982b, *Astrophys. J.* **261**, 710.

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., Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J., Michels, D. J., McGuire, R. E., von Rosenvinge, T. T., and Reames, D. V : 1984a, *J. Geophys. Res.* **89**, 9683.

Kahler, S. W., Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J., and Michels, D. J.: 1984b, *Solar Phys.* **93**, 133.

Kahler, S. W., Cliver, E. W., Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J., and Michels, D. J.: 1985, *J. Geophys. Res.* **90**, 177.

Kai, K.: 1969, *Solar Phys.* **10**, 460.

Kawabata, K.: 1966, *Rep. Ionosph. Space Res. Japan* **20**, 17.

Kosugi, T.: 1976, *Solar Phys.* **48**, 339.

Kundu, M. R.: 1961, *J. Geophys. Res.* **66**, 4308.

Kundu, M. R.: 1965, *Solar Radio Astronomy*, Interscience, New York.

Lengyel-Frey, D. and Stone, R. G.: 1989, *J. Geophys. Res.* **94**, 159.

Lin, R. P. and Hudson, H. S.: 1976, *Solar Phys.* **50**, 153.

Malitson, H. H., Fainberg, J., and Stone, R. G.: 1973, *Astrophys. Letters* **14**, 111.

Maxwell, A. and Dryer, M.: 1982, *Space Sci. Rev.* **32**, 11.

Maxwell, A. and Thompson, A. R.: 1962, *Astrophys. J.* **135**, 138.

Meyer, F.: 1968, in K. O. Kiepenheuer (ed.), ‘Structure and Development of Solar Active Regions’ *IAU Symp.* **35**, 485.

Moreton, G. E.: 1960, *Astron. J.* **65**, 494.

Moreton, G. E.: 1964, *Astron. J.* **69**, 145.

Moreton, G. E. and Ramsey, H. E.: 1960, *Publ. Astron. Soc. Pacific* **72**, 357.

Munro, R. H., Gosling, J. T., Hildner, E., MacQueen, R. M., Poland, A. E., and Ross, C. L.: 1979, *Solar Phys.* **61**, 201.

Nelson, G. J. and Melrose, D. B.: 1985, in D. J. McLean and N. R. Labrum (eds.), *Solar Radiophysics*, Cambridge University Press, New York, p. 333.

Orwig, L. E., Frost, K. J., and Dennis, B. R.: 1980, *Solar Phys.* **65**, 25.

Parker, E. N.: 1961, *Astrophys. J.* **133**, 1014.

Payne-Scott, R., Yabsley, D. E., and Bolton, J. G.: 1947, *Nature* **160**, 256.

Pearson , D. H., Nelson, R., Kojoian, G., and Seal, J.: 1989, *Astrophys. J.* **336**, 1050.

Plunkett, S. P., Thompson, B. J., Howard, R. A., Michels, D. J., St. Cyr, O. C., Tappin, S. J., Schwenn, R., and Lamy, P. L.: 1998, *Geophys. Res. Letters* **25**, 2477.

Roberts, J. A.: 1959, *Australian J. Phys.* **12**, 327.

Robinson, R. D.: 1985, *Solar Phys.* **95**, 343.

Robinson, R. D. and Stewart, R. T.: 1985, *Solar Phys.* **97**, 145.

Robinson, R. D., Stewart, R. T., and Cane, H. V.: 1984, *Solar Phys.* **91**, 159.

Robinson, R. D., Stewart, R. T., Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J., and Michels, D. J.: 1986, *Solar Phys.* **105**, 149.
Roy, J. R.: 1974, Ph.D. Thesis, University of Western Ontario.
Sawyer, C. S.: 1985, *Solar Phys.* **98**, 369.
Sheeley, N. R., Jr., Michels, D. J., Howard, R. A., and Koomen, M. J.: 1980, *Astrophys. J.* **237**, L99.
Sheeley, N. R., Jr., Stewart, R. T., Robinson, R. D., Howard, R. A., Koomen, M. J., and Michels, D. J.: 1984, *Astrophys. J.* **279**, 839.
Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J., Michels, D. J., Schwenn, R., Mühlhäuser, and Rosenbauer, H.: 1985, *J. Geophys. Res.* **90**, 163.
Smith, E. v. P.: 1968, in Y. Öhman (ed.), *Mass Motions in Solar Flares*, Almqvist & Wiksell Förlag AB, Stockholm, p. 137.
Smith, H. J. and Smith, E. v. P.: 1963, *Solar Flares*, Macmillan, New York.
Smith, S. F. and Harvey, K. L.: 1971, in C. J. Macris (ed.), *Physics of the Solar Corona*, D. Reidel Publ. Co., Dordrecht, Holland, p. 156.
Steinolfson, R. S.: 1984, *Solar Phys.* **94**, 193.
Steinolfson, R. S.: 1985, in B. T. Tsurutani and R. G. Stone (eds.), *Collisionless Shocks in the Heliosphere: Reviews of Current Research*, AGU, Washington, p. 1.
Stewart, R. T.: 1984, *Solar Phys.* **94**, 379.
Stewart, R. T., McCabe, M. K., Koomen, M. J., Hansen, R. T., and Dulk, G. A.: 1974a, *Solar Phys.* **36**, 203.
Stewart, R. T., Howard, R. A., Hansen, S. F., Gergely, T., and Kundu, M.: 1974b, *Solar Phys.* **36**, 219.
Švestka, Z.: 1976, *Solar Flares*, D. Reidel Publ. Co., Dordrecht, Holland.
Švestka, Z. and Fritzová-Švestková, L.: 1974, *Solar Phys.* **36**, 417.
Swarup, G., Stone, P. H., and Maxwell, A.: 1960, *Astrophys. J.* **131**, 725.
Thompson, B. J. *et al.*: 1998a, *Astrophys. J. Letters* (in press).
Thompson, B. J., Plunkett, S. P., Gurman, J. B., Newmark, J. S., St. Cyr, O. C., and Michels, D. J.: 1998b, *Geophys. Res. Letters* **25**, 2465.
Uchida, Y.: 1960, *Publ. Astron. Soc. Japan* **12**, 376.
Uchida, Y.: 1968, *Solar Phys.* **4**, 30.
Uchida, Y.: 1973, in R. Ramaty and R. G. Stone (eds.), *NASA Symp. on High Energy Phenomena on the Sun*, NASA, Greenbelt, MD, p. 577.
Uchida, Y.: 1974a, in G. Newkirk (ed.), ‘Coronal Disturbances’, *IAU Symp.* **57**, 383.
Uchida, Y.: 1974b, *Solar Phys.* **39**, 431.
Uchida, Y., Altschuler, M. D., and Newkirk, G. A.: 1973, *Solar Phys.* **28**, 495.
Vršnak, B., Ruždjak, V., Zlobec, P., and Aurass, H.: 1995, *Solar Phys.* **158**, 311.
Wagner, W. J. and MacQueen, R. M.: 1983, *Astron. Astrophys.* **120**, 136.
Webb, D. F.: 1986, in M. R. Kundu *et al.* (eds.), *Solar-Terrestrial Physics*, National Physical Laboratory, New Delhi, p. 283.
Webb, D. F. and Howard, R. A.: 1994, *J. Geophys. Res.* **99**, 4201.
Westfold, K. C.: 1957, *Phil. Mag.* **2**, 1287.
Wild, J. P. and McCready, L. L.: 1950, *Australian J. Sci. Res.* **3**, 387.
Wild, J. P. and Smerd, S. F.: 1972, *Ann. Rev. Astron. Astrophys.* **10**, 159.
Wild, J. P., Roberts, J. A., and Murray, J. D.: 1954, *Nature* **173**, 532.