THE ASTROPHYSICAL JOURNAL, 605:902–910, 2004 April 20

CORONAL SHOCKS AND SOLAR ENERGETIC PROTON EVENTS

E. W. CLIVER AND S. W. KAHLER
Space Vehicles Directorate, Air Force Research Laboratory, Hanscom AFB, MA 01731; edward.cliver@hanscom.af.mil, stephen.kahler@hanscom.af.mil

AND

D. V. REAMES
NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771; reames@milkyway.gsfc.nasa.gov
Received 2003 May 2; accepted 2004 January 8

ABSTRACT

From 1996 July through 2001 June, less than half (43/98) of all favorably located (from solar western hemisphere sources) metric type II radio bursts were associated with solar energetic proton (SEP) events observed at Earth. When western hemisphere metric type IIs were accompanied by decametric-hectometric (DH; 1–14 MHz) type II emission (observed by *Wind*/WAVES) during this period, their association with ~20 MeV SEP events (with peak fluxes $\geq 10^{-3}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}) was 90% (26/29), versus only 25% (17/69) for metric IIs without a DH counterpart. Overall, 82% (63%) of all SEP events with visible disk origins were associated with metric (DH) type II bursts, with the percentage associations increasing with SEP event size to 88% (96%) for ~20 MeV SEP events with peak intensities of $\geq 10^{-1}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}. Our results are consistent with the following possibilities (which are not mutually exclusive): (1) large ~20 MeV SEP events result from strong shocks that are capable of persisting well beyond ~3 $R_\odot$ (the nominal 14 MHz plasma level); (2) shock acceleration is most efficient above ~3 $R_\odot$; and (3) shocks that survive beyond ~3 $R_\odot$ are more likely to have broad longitudinal extents, enabling less well connected shocks to intercept open field lines connecting to Earth.

Subject headings: shock waves — Sun: corona — Sun: particle emission — Sun: radio radiation

1. INTRODUCTION

It is generally accepted that metric type II (slow-drift) solar radio bursts are manifestations of coronal shock waves caused by disturbances moving outward through the solar atmosphere with speeds of several hundred kilometers per second (Nelson & Melrose 1985). These disturbances accelerate electrons that excite plasma waves that convert into escaping radio waves at a frequency proportional to the square root of the local electron density. Metric type II bursts have typical starting frequencies of ~100 MHz (plasma frequency corresponding to ~1.5 $R_\odot$) and drift toward the lowest frequencies commonly observable from Earth (~20 MHz; ~2.5 $R_\odot$), with a drift rate of ~0.1–1 MHz s^{-1}. Coronal shock waves are thought to be the principal acceleration mechanism for the largest ("gradual") solar energetic proton (SEP) events observed at 1 AU; a class of smaller ("impulsive") SEP events are attributed to resonant wave-particle acceleration in solar flares (see reviews by Reames 1999; Cliver 2000; Kahler 2001a).

While coronal shocks are held to be a necessary condition for large SEP events, metric type II bursts are not a sufficient condition for a SEP event to occur. Kahler (1982) found that only about half (31/58) of favorably connected (W10–W85) metric IIs observed from 1973 June through 1980 June were associated with ~20 MeV SEP events. He found that the metric type IIs most likely to be followed by SEPs near Earth were those that had longer type II burst durations, larger associated Hα flares, and accompanying metric type IV (broadband) emission. The second and third of these criteria, in particular, are indicators of coronal mass ejections (CMEs). Flare area can be expected to scale with flare duration, and long-duration soft X-ray flares have been linked to CMEs (Sheeley et al. 1975, 1983; Kahler 1977). Cliver et al. (1986) suggested that storm continuum type IV emission results from reconnection in post-CME arcades. Following the hypothesis of Maxwell & Dryer (1982) that metric type II bursts could be manifestations of either localized (flare) blast waves or CME-driven shocks, Kahler (1982) suggested that the blast wave shocks were weak proton accelerators.

The origin of metric type II bursts has been a controversial subject, with one camp arguing that all such events are CME-driven (Cliver, Webb, & Howard 1999) and the other (e.g., Cane & White 1989; Reiner & Kaiser 1999b) favoring a flare-generated blast wave picture. While it has been long known that type IIs are strongly (essentially 100%) associated with flares (e.g., Nelson & Melrose 1985), the most recent evidence indicates that (1) metric type IIs are also highly associated with CMEs (Cliver & Hudson 2002; taking into account the fact that CMEs are most visible for eruptions near the solar limb [Webb & Howard 1994]) but that (2) the shock drivers are not necessarily the CME leading edge and, at least in some cases (Klein et al. 1999; see also Klassen & Pohjolainen 2002), are flare ejecta (Nitta & Akiyama 1999) associated with CMEs. In either case, the general association of metric type IIs with CMEs indicates that the presence or absence of a CME is not the key discriminator between SEP-associated and non–SEP-associated metric type II bursts.

Can such a discriminator be identified? In this study, we investigate the possibility that the presence or absence of a decametric-hectometric (DH) type II burst observed in the 1–14 MHz range by the (radio and plasma) WAVES experiment (Bougeret et al. 1995) on the *Wind* spacecraft may distinguish between SEP-associated and non–SEP-associated metric type II bursts. Cane & Stone (1984) showed that 32 of 37 interplanetary (<1 MHz) type IIs observed by the low-frequency radio experiment on *ISEE 3* were associated with

SEP events. More recently, Gopalswamy et al. (2002) found that 40 of 42 SEP events exceeding the Space Environment Center $J(>10\ \mathrm{MeV}) = 10$ protons cm $^{-2}$ s^{-1} sr^{-1} threshold were associated with DH type IIs from 1996 to 2001. An example of a type II burst observed in the metric and DH wavelength ranges is given in Figure 1. The DH emission in this figure nominally originates between $\sim 3\ R_\odot$ (14 MHz) and $\sim 10\ R_\odot$ (1 MHz), depending on which density model (e.g., Saito 1970; Robinson 1985; Leblanc, Dulk, & Bougeret 1998) is assumed. Neither Cane & Stone (1984) nor Gopalswamy et al. (2002) investigated SEP associations by beginning with a sample of metric type II bursts. Here we examine the DH type II and SEP associations of all metric type II bursts observed from 1996 July through 2001 June, taking into account the well-known western hemisphere propagation effect for SEPs (McCracken & Rao 1970). In a reverse study, we determine the degree of association of all $\sim$20 MeV SEP events during this period (with peak intensities of $\geq 10^{-3}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}) with metric and DH type IIs.

As is the case for the origin of metric type IIs, the relationship of metric IIs to DH IIs has been a matter of debate (see the exchange between Cliver 1999 and Gopalswamy et al. 1999). Various investigators (e.g., Reiner & Kaiser 1999b; Reiner et al. 2001; Vršnak & Lulić 2000a, 2000b; Vršnak, Magdalenić, & Aurass 2001) have argued for the existence of two distinct types of coronal shocks, one primarily observed only in the metric range (identified by the above authors with flare blast waves) and the other characteristically observed in the DH range (generally interpreted in terms of CME-driven shocks [Gopalswamy et al. 2000, 2001b; Lara et al. 2003]). The alternative view of a unified metric and DH type II shock that we take as our working hypothesis has appeal because of its simplicity. The close association of both metric and DH type IIs with fast CMEs suggests that such a CME is the "special condition" (Cliver et al. 1999) required for coronal shock formation. Moreover, ascribing different physical origins to similar phenomena such as metric and DH type II bursts that are observed in different instruments (frequency ranges) seems suspect, especially when in certain cases such as Figure 1, the DH IIs appear to be continuations of metric IIs.

The existence of separate flare blast wave and CME-driven shocks would have interesting implications for SEP acceleration. As of yet, there have been relatively few reports (e.g., Kocharov & Torsti 2002) of changes in SEP time profiles or spectra indicating more than one "SEP-effective" shock at work.

Our analysis is presented in § 2, and the results are summarized and discussed in § 3.

2. ANALYSIS

2.1. *Event Associations*

2.1.1. *Metric Type IIs and* Hα *Flares*

We began with the list of metric type II bursts reported in Solar-Geophysical Data (SGD). We considered reports from all stations (with one exception: Blenheim, which has a high-frequency cutoff of $\geq$110 MHz) and of all durations, but excluded metric type II events qualified as UE (uncertain emission). With these exceptions, 447 separate metric type II bursts were reported between 1996 July 1 and 2001 June 30, with more than 75% (348/447) of the events reported by more than one station (or with a single station reporting fundamental/harmonic or two separate time portions; for this analysis, we also used Blenheim and UE events to corroborate single reports). Because the timings of metric type II bursts as reported by different stations do not always agree and because

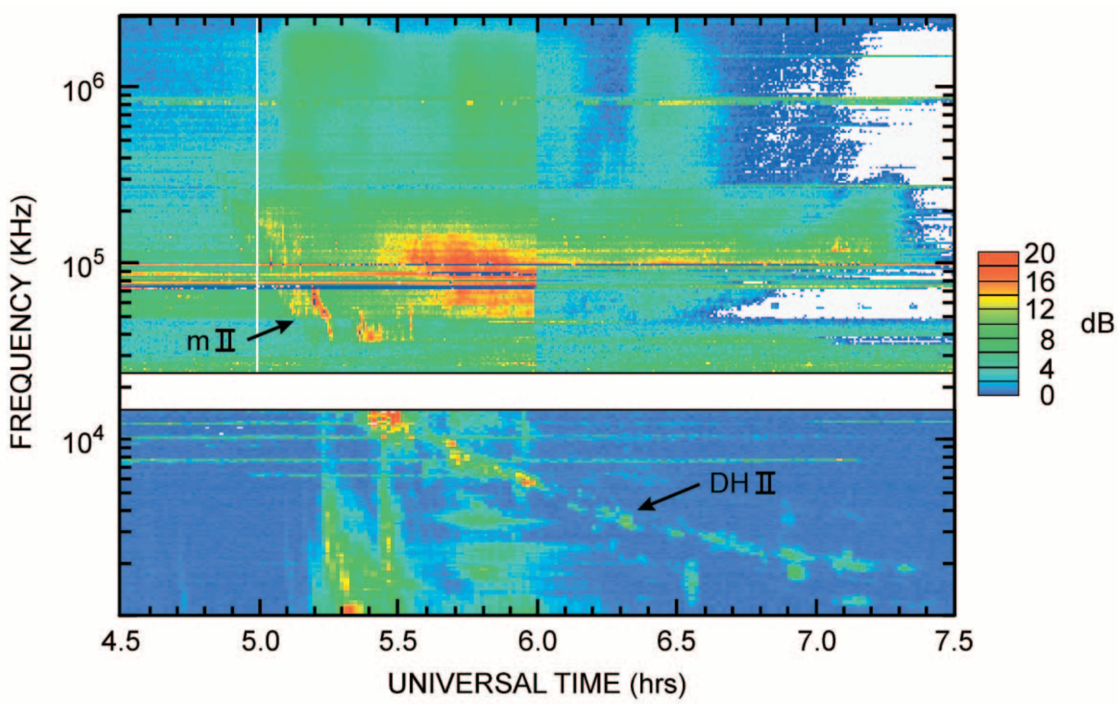

Fig. 1.—Solar type II radio burst on 2001 December 26 observed at Hiraiso ($\geq$25 MHz) and by *Wind*/WAVES ($\leq$14 MHz) showing metric (m) and DH components.

more than one type II may be reported by a given station during a single event, we grouped reports for which the start times between sequential events were $\leq$15 minutes apart.

We then attempted to associate the identified metric type IIs with Hα flares, using flare data from SGD. We considered a type II burst to be associated with a flare if it began anytime after the reported onset of the flare but no more than 15 minutes (see Dodge 1975) after the Hα flare maximum. We did not attempt to associate metric IIs with flares behind the limb on the basis of soft X-ray emission or coronagraph data and eliminated from further consideration seven events with nearly simultaneous (and equivalent) flares in the eastern and western solar hemispheres. We were able to associate 57% (253/447) of the metric type II bursts with Hα disk flares. Our 57% association rate compares with 79% (459/580) obtained by Dodge (1975) and 62% (416/673) by Wright (1980). One might presume that we should be able to associate a much higher percentage of type IIs with flares than 57%, even after making allowance for the estimated $\sim$13% $\pm$ 4% of metric IIs originating from beyond the limb (Kahler et al. 1985; cf. Vršnak et al. 2001). Such a presumption, however, assumes that flare reporting is complete and independent of solar longitude. During the 5 years of the study, the worldwide flare patrol provided 91% coverage. In addition, flare visibility drops off toward the solar limb, particularly for subflares (Smith & Smith 1963, p. 49). We determined that 37% (93/253) of the type II source flares in our sample were subflares (on the basis of group reports in SGD), in good agreement with the values of 40% and 37% obtained by Dodge (1975) and Wright (1980), respectively. The effect of the underreporting of Hα flares near the limb on the longitudinal distribution of type II burst flares—seen in Figure 2 for the 253 flare-associated events in our sample—was pointed out by Wright (1980), who concluded that the actual distribution of type II–associated flares across the disk was relatively flat (see Cane & Reames 1988). If we assume that flare reporting is perfect for events within 15° of longitude from disk center (after correcting the number of type II flares in this bin for the 91% flare coverage rate), then we calculate that 89% ($6 \times 66 = 396/447$) of type II bursts originated in frontside events, implying that 11% were due to backside activity.

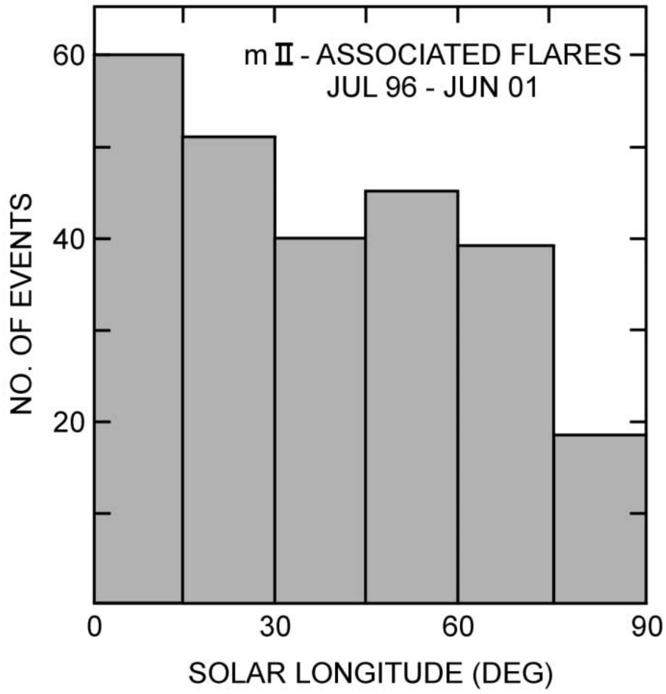

FIG. 2.—Solar longitude distribution of Hα flares associated with metric type II radio bursts, 1996 July–2001 June. East and west longitude bins are combined.

2.1.2. *DH Type IIs and* Hα *Flares*

For a list of DH type IIs, we used the compilation by M. Kaiser posted on the *Wind*/WAVES World Wide Web site,[1] considering only those events with starting frequencies of $\geq$1 MHz. Although the *Wind*/WAVES list is described as preliminary, it has been used by other authors (e.g., Gopalswamy et al. 2003) and is homogeneous in the sense that it was compiled by a single person. During the period of interest, 177 DH type IIs were reported. (Kaiser's list also includes a total of eight DH events described as type IVs [including possible or questionable IVs], interacting CME signatures, or unclassified events [which were not linked to a DH II]; we did not consider these events in our analysis.) We treated all DH type IIs with start times within an hour of each other to be single events. There were five such cases of closely spaced events, so our final list contained 172 independent events. Our flare association procedure here was the same as that for metric type IIs, although we modified our algorithm to consider DH IIs to be associated with Hα flares if they occurred within 1 hr after Hα maximum to make allowance for the greater range of heights ($\sim$3–10 $R_\odot$) over which DH emission can form. Most delays were less than 30 minutes.

When multiple flares fell within the 1 hr window, we selected those with more important Hα classifications or more intense associated soft X-ray flares. We were able to associate 54% (93/172) of DH type IIs during this period with Hα disk flares (Fig. 3). The median starting frequency of the flare-associated DH type IIs (14 MHz) was higher than that of the non–flare-associated events (8 MHz), but the durations of the two groups were comparable (median of 50 minutes vs. 45 minutes). Although we have combined the east and west

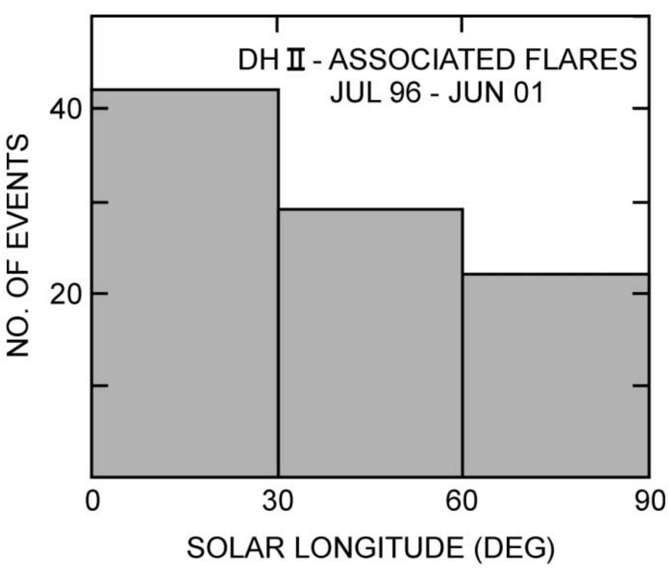

FIG. 3.—Solar longitude distribution of Hα flares associated with DH type II radio bursts, 1996 July–2001 June. East and west longitude bins are combined.

[1] See http://www-lep.gsfc.nasa.gov/waves/waves.html.

longitude bins in Figure 3, we note a possible east-west bias in the distribution, with 58% (54/93) of the events arising in the west. As was the case for the metric type IIs, no attempt was made to associate DH IIs with backside solar events. Only 15% (14/93) of the DH type IIs were associated with subflares, reflecting the energetic nature of these events (Gopalswamy et al. 2001b). If we assume a flat longitudinal distribution for DH II solar sources, then we calculate, after correcting for Hα flare patrol coverage, that 80% ($3 \times 46 = 138/172$) of DH type IIs originated in frontside eruptions.

2.1.3. *SEP Events and* Hα *Flares*

To compile a SEP event list, we used 19–22 MeV data from the Energetic Particles: Acceleration, Composition, and Transport (EPACT) investigation on the *Wind* spacecraft (von Rosenvinge et al. 1995). This channel has a background of $\sim(2\text{–}3) \times 10^{-4}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}; the fraction of time that this threshold is exceeded varies significantly over the solar cycle, from ~1% during the second half of 1996 to ~50% during the first half of 2001. We required a peak ~20 MeV intensity $\geq 10^{-3}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} and also considered the SEP intensity time profile and velocity dispersion between ~2 and ~20 MeV protons to eliminate delayed components of events associated with local shocks or modulations of high background levels from previous SEP activity. With these criteria, we were able to identify 134 increases of ~20 MeV protons during the 5 yr interval under consideration.

Approximately 30% of the 134 events occurred during periods of elevated ($>10^{-3}$) SEP flux due to a decaying portion of an earlier event, but in our determinations of peak fluxes for each event, we did not subtract disturbed (or quiet) pre-event backgrounds. Such background corrections, which at most would reduce peak fluxes by factors of 2 or 3, are not significant in comparison with the nearly 5 orders of magnitude range encompassed by the peak ~20 MeV fluxes in our sample.

To associate the SEP events with Hα flares, we used the standard tools such as Hα flare size and soft X-ray intensity/duration, as well as CME association (Kahler et al. 1984) and intense *Wind*/WAVES type III radio emission extending to the orbit of Earth (Cane, Erickson, & Prestage 2002). Our flare association criteria for SEP events were not as strict as those that we used for the metric and DH type II events. For example, we used flares observed in *Yohkoh* Soft X-Ray Telescope images but not reported in SGD, as well as flares reported in SGD that started later than associated type II bursts because of reported gaps in the Hα patrol. In addition, we made use of frontside associations reported in the Boulder Preliminary Report of Solar Geophysical Data; occasionally flares reported there did not appear in SGD. For the SEP event associations, we also relaxed the $\leq$15 minute and $\leq$60 minute requirements on delays between flare maxima and onsets of linked metric type II and DH type II bursts, respectively, admitting a few events that fell outside these windows. In all, we found disk-flare associations for 88 of the 134 events (Fig. 4). To investigate the sources of the 46 unassociated events, we fitted the data in Figure 4 to a Gaussian distribution (Smart et al. 1976) centered at W60 (the footpoint of the nominal spiral field line connected to Earth). This analysis indicated that the bulk of the unassociated SEP events (35 of 46) originated behind the limb.

2.2. *Association of SEP Events with Metric and DH Type IIs*

We find that 82% (72/88) of our SEP events are associated with metric type IIs and 63% (55/88) are associated with DH type IIs. For over half the cases (31/55) with DH association, the DH type II started at the highest frequency observable (14 MHz) on the WAVES instrument. Ninety-one percent (80/88) of SEP events are associated with metric and/or DH type II emission. Of the 80 SEP events with metric and/or DH type II emission, the breakdown is as follows: metric type II and DH type II (47); metric II only (25), DH II only (8 events). We checked both the ground-based patrol times for metric reporting stations and *Wind*/WAVES data to ensure that radio observations were available for all of the SEP events.

In Figure 5 it can be seen that smaller SEP events are more likely to be associated with metric type IIs than with DH type IIs and that the association of SEP events with DH type II bursts increases rapidly with SEP event size; 80% (51/64) of SEP events with peak ~20 MeV proton intensities of less than 0.1 protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} had metric II association, versus 88% (21/24) of SEP events with peak intensities

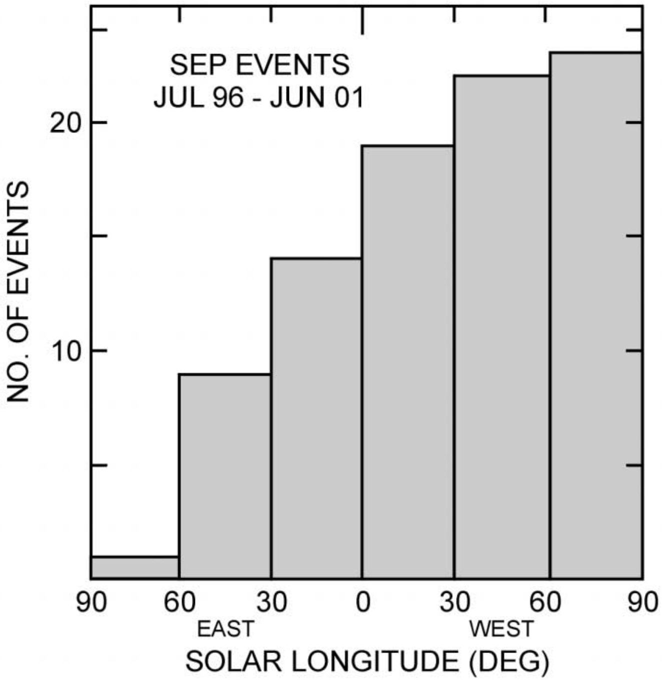

Fig. 4.—Solar longitude distribution of Hα flares associated with ~20 MeV SEP events, 1996 July–2001 June.

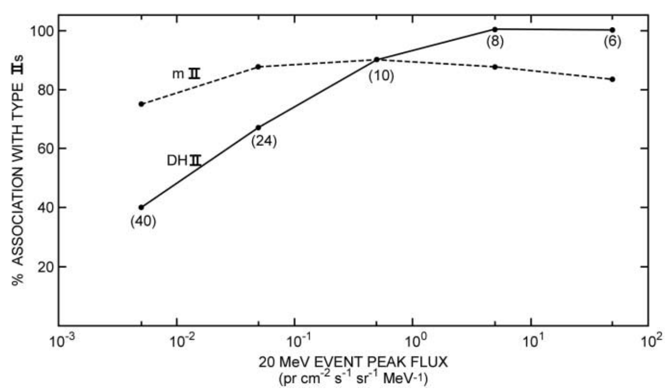

Fig. 5.—Percentage association of ~20 MeV SEP events with metric type II (*dashed line*) and DH type II (*solid line*) bursts as a function of SEP event peak intensity. The numbers of SEP events in each decadal bin are given in parentheses.

greater than or equal to this threshold. Corresponding figures for DH type II associations with SEP events are 50% (32/64; <0.1 protons) and 96% (23/24; ≥ 0.1 protons), while the breakdown for SEP events with associated metric and/or DH type II emission is 88% (56/64) and 100% (24/24). For the large SEP events (≥ 0.1 protons), only the 2001 April 12 event lacked a DH type II burst; it did have an associated ~ 20 minute metric type II that drifted beyond the lowest frequency (25 MHz) observed by the ground-based patrol.

Figure 6 contains histograms of SEP peak ~ 20 MeV fluxes for western hemisphere SEP events: without associated type II bursts (*top*); with only metric type IIs (*middle*); and with accompanying metric and DH IIs (*bottom*). The median peak intensities of events in the first two categories are ~ 15–20 times smaller than the peak fluxes of SEP events preceded by metric and DH type IIs.

2.3. *Factors Affecting Metric Type II–SEP Association*

2.3.1. *Flare Longitude*

It has long been known (McCracken 1962; Anderson & Lin 1966) that SEP events are preferentially observed in association with western hemisphere flares (Fig. 4). The "SEP visibility function" for both metric (*dashed line*) and DH type IIs (*solid line*) in our sample is shown in Figure 7. To construct these curves, we began with our samples of flare-associated metric IIs (253) and DH IIs (93) and determined their SEP associations as a function of flare longitude. We eliminated 75 metric type II events for which an enhanced SEP background ($>10^{-3}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}) may have precluded the observation of a fresh SEP injection; another seven metric type IIs occurred during SEP data gaps. For the DH type IIs, we dropped 22 high ($>10^{-3}$) background events. In the figure it can be seen that the SEP visibility for both metric IIs and DH IIs increases as one goes from the east limb to the west limb, with the percentage association for DH type IIs being approximately twice that for metric IIs at all longitudes. The curves in Figure 8 are similar to those in Figure 7, except here we have separated metric type IIs with (*solid line*) and without (*dashed line*) DH counterparts, dropping the "DH-only" type IIs. (For completeness, DH type II events from the western hemisphere that lacked a metric type II counterpart were followed by SEPs at 1 AU 73% [8/11] of the time [discarding enhanced background events], vs. 25% [2/8] for such events

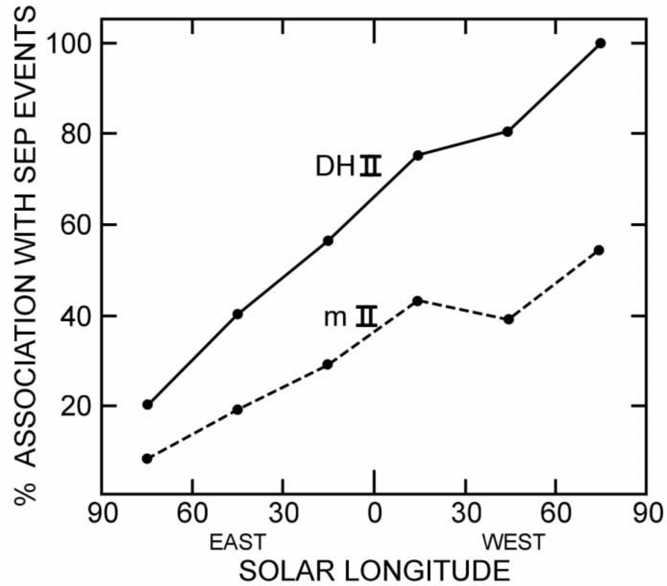

FIG. 7.—Percentages of metric (*dashed line*) and DH type II (*solid line*) bursts associated with ~ 20 MeV SEP events as a function of flare longitude.

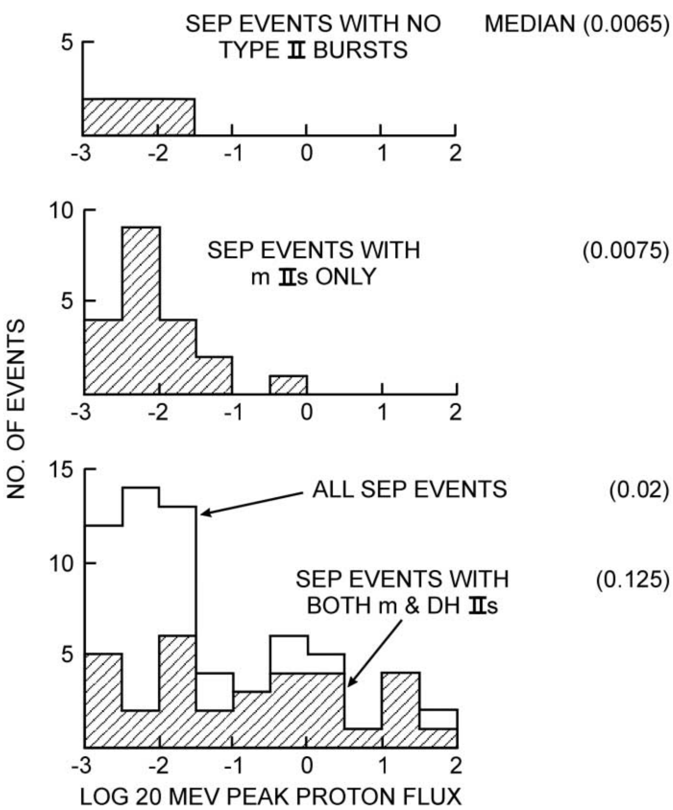

FIG. 6.—Histograms of SEP peak ~ 20 MeV fluxes for western hemisphere SEP events: without associated type II bursts (*top*), with only metric type IIs (*middle*), and with accompanying metric and DH IIs (*bottom*). The histogram for all western hemisphere SEP events (including those with only DH type II associations) is also shown at the bottom.

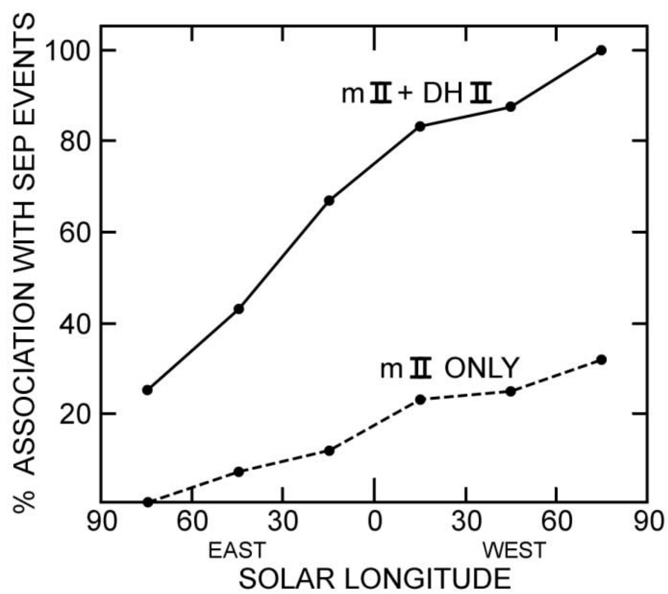

FIG. 8.—Percentages of metric type II only (*dashed line*) and metric II + DH II (*solid line*) bursts associated with ~ 20 MeV SEP events as a function of flare longitude.

TABLE 1

Contingency Matrix Showing the Effect of DH Association on ~20 MeV SEP Association for Favorably Located (Western Hemisphere, WH) Metric Type II Bursts

WH Metric II	20 MeV SEP Event? Yes	No	Total
With DH II	26	3	29
Without DH II	17	52	69
Total	43	55	98

from the eastern hemisphere.) The marked difference between the two curves is examined in the next subsection.

2.3.2. *DH Association*

The 2×2 contingency matrix in Table 1 includes only the metric type IIs from western hemisphere sources in Figure 8. Comparing the first and second columns of the matrix confirms Kahler's (1982) finding that approximately half of favorably located type II bursts ($55/98 = 56\%$) are not accompanied by SEP events at Earth. Comparing the first and second rows of the matrix indicates that only 30% (29/98) of western hemisphere metric type II bursts have DH counterparts. For the full disk, the association rate is 25% (63/253; based on all metric IIs, without consideration for SEP circumstances). Conversely, 69% (64/93) of DH type IIs have associated metric type IIs (73% [68/93] if UE type IIs are considered).

The key result of our study is the marked difference in the degree of SEP association between metric IIs with and without an accompanying DH type II burst. Only 25% (17/69) of western hemisphere metric type II bursts without a DH II counterpart are followed by SEPs at Earth, versus 90% (26/29) of favorably located metric IIs with associated DH type II emission. Corresponding figures for eastern hemisphere metric IIs are 8% (4/50) and 52% (12/23).[2]

2.4. *Uncertainties*

The results of our study (or any association study) are critically dependent on the identification of SEP events and our flare associations. Identifying fresh injections of SEPs on enhanced backgrounds, often with questionable time-intensity profiles, involves a subjective judgment based on experience. The flare association process is also subjective, and multiple passes are used to ensure uniform technique over the data set (see Cane et al. 2002).

To gauge the reproducibility of our results, we compared our list of SEP events and associated flares with that compiled by Cane et al. (2002), which covered almost the same period and was based on an examination of ~20 MeV SEP data from the Goddard Space Flight Center experiment (McGuire, von Rosenvinge, & McDonald 1986) on the *Interplanetary Monitoring Platform 8* (*IMP 8*) spacecraft. Because the time intervals, energies considered, and event selection criteria were not identical, differences exist between the two lists. For the period of overlap, there are 83 common disk-flare–associated SEP events. Beyond these 83 SEP events, Cane et al. identified seven small (≤ 0.02 protons) frontside events not on our list, and we identified eight small (≤ 0.03 protons) disk events not on their list. Some of the discrepancies in the two lists result because one of us identified a disk-flare candidate for a given event while the other favored a behind-the-limb origin. Other differences are due to incomplete coverage by either spacecraft, justifiable disagreements about the reality of certain events (as fresh SEP injections), and our SEP event size threshold of $\geq 10^{-3}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} (vs. none used by Cane et al.). Seventy-one percent (5/7) of the Cane et al. "only" events had metric type II association (1 of 7 with a possibly associated DH type II), versus 88% (7/8; 1 of 8 with a possible DH II) of those included only on our list. This comparison shows that we would have obtained similar results from an independently compiled list.

3. DISCUSSION

3.1. *Summary*

In this comparison of type II radio bursts (both metric [~25–250 MHz] and decametric-hectometric [DH; 1–14 MHz]) and solar energetic proton (SEP) events from July 1996–2001 June, we have found the following:

1. During this period, the following numbers of events were observed: 447 metric type IIs, 172 DH type IIs, and 134 SEP events with peak ~20 MeV fluxes of $\geq 10^{-1}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}. We were able to associate 57% (253/447) of the metric type IIs, 54% (93/172) of the DH type IIs, and 66% (88/134) of the SEP events with frontside flares. Assuming a flat distribution of type II occurrence across the solar disk implies that ~10% of metric IIs and ~20% of DH IIs originate in backside solar activity. Assuming a Gaussian distribution centered at 60° west solar longitude for SEP sources implies that ~25% of ~20 MeV proton events originate on the invisible solar hemisphere.
2. Twenty-five percent (63/253) of flare-associated metric type IIs have associated DH II counterparts; conversely, 69% (64/93) of flare-associated DH IIs have associated metric type II emission.
3. Eighty-two percent (72/88) of all SEP events with visible disk origins were associated with metric type II bursts, with the percentage association increasing with SEP event size to 88% (21/24) for ~20 MeV SEP events with peak fluxes $\geq 10^{-1}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} (corresponding the top 3 decades of ~20 MeV SEP intensity; Fig. 5).
4. Sixty-three percent (55/88) of all SEP events with visible disk origins were associated with DH type II bursts, with the percentage increasing to 96% (23/24) for events with ~20 MeV peak fluxes of $\geq 10^{-1}$ (Fig. 5).
5. SEP "visibility functions" for metric type IIs and DH type IIs are given in Figure 7. For any solar longitude, DH type IIs are about twice as likely as metric type IIs to be followed by SEPs near Earth.
6. Less than half (44%; 43/98) of all favorably located (from solar western hemisphere sources) metric type II radio bursts were associated with SEP events at Earth (confirming Kahler 1982; Table 1).
7. Only 25% (17/69) of western hemisphere metric type IIs without a DH II counterpart were followed by SEPs at Earth, versus 90% (26/29) of favorably located metric IIs

[2] Note that because we used less strict criteria for associating SEPs with flares (and type II bursts) than we did for associating type II bursts with flares, apparent accounting discrepancies occur. For example, the analysis in this section implies that 21 (17 + 4) SEP events had metric II–only association, vs. the 25 given in § 2.2. These differences, which arose because we wanted a simple and objective procedure for making flare associations for the 447 metric type IIs and 172 DH type IIs, do not change our basic results.

with associated DH type II emission (Table 1, Fig. 8). Corresponding figures for eastern hemisphere metric type IIs are 8% (4/50) and 52% (12/23).

Our study follows in a long line of investigations linking SEP events to coronal shocks (Wild, Smerd, & Weiss 1963; Lin 1970; Švestka & Fritzová-Švestková 1974; Cliver, Kahler, & McIntosh 1983; Cane, McGuire, & von Rosenvinge 1986). Our finding that 82% of ~20 MeV proton events are associated with metric type II bursts from 1996 July through 2001 June is consistent with results obtained in earlier studies, e.g., Lin (1970) (77% [20/26] for ~15 MeV protons from 1964 to 1967) and Cliver et al. (1989) (78% [51/65 events] for ~10 MeV protons from 1980 to 1985). Each of these studies considered proton events down to the limit of detectability. Our metric and DH type II associations for large SEP events are consistent with those recently reported by Gopalswamy (2003) for the SEP Coordinated Data Analysis Workshop.

Ninety-one percent (80/88) of all SEP events with visible disk origins were associated with metric and/or DH type II bursts, with the percentage increasing to 100% (24/24) for events with ~20 MeV peak fluxes of $\geq 10^{-1}$ protons. What is the origin of the eight relatively small SEP events (see Fig. 6) that lacked reported type IIs in both wavelength ranges? For at least one of these cases (2000 May 1; Reames 2000; Kahler, Reames, & Sheeley 2001), SEPs can be traced to acceleration in the flare on the basis of the particle event composition (i.e., ^{3}He/^{4}He ~ 0.05, Fe/O > 1). We note that one of the 25 events with metric II "only" association (2001 April 14) was a classic "impulsive event," exhibiting strong ($\sim 10^2$–10^3 fold) enhancements of $Z \geq 34$ elements (Tylka et al. 2002), as well as a modest proton increase.

3.2. *Interpretation*

Our principal new result is that favorably located metric type II bursts that have a DH counterpart are much more likely to be followed by SEPs in space than metric IIs that lack such low-frequency emission. How do we interpret this result? There are several possibilities, which are not mutually exclusive.

First, the strongest/fastest shocks that are likely to survive into the DH range are also those that are most likely to be efficient proton accelerators (at all heights in the corona) since CME speed is correlated with peak ~20 MeV SEP intensity (Kahler 2001b). Consistent with this picture, western hemisphere metric type IIs with DH counterparts and SEP association tend to have higher peak intensities and longer durations (lower ending frequencies) than those without DH/SEP association, although there is considerable overlap between the two groups in both of these characteristics. Classen & Aurass (2002) note that the *Wind*/WAVES instrument may be ~10–100 times less sensitive than the ground-based type II patrol, rendering weak shocks undetectable as they progress from metric to DH altitudes. Finally, CMEs associated with DH type IIs are faster and broader (i.e., more energetic) than those associated with only metric IIs (Gopalswamy et al. 2001b; Lara et al. 2003). As reported by Lara et al. (2003), the average CME speed for DH-associated events is 964 km s^{-1}, versus 545 km s^{-1} for CMEs associated with metric IIs (without DH IIs), while the angular width distribution of (nonhalo) CMEs associated with DH type IIs peaks at ~100°, versus ~70° for CMEs with metric IIs.

An alternative (or contributing) explanation for the high association between DH type IIs and SEP events is suggested by the work of Mann et al. (1999), Gopalswamy et al. (2001a), Gopalswamy & Kaiser (2002), and Vršnak et al. (2002), who determined that the Alfvén speed in the corona typically has a peak value of ~3 $R_\odot$, corresponding to the ~14 MHz plasma level in the DH range. Above (and below) this height, shock acceleration will become more efficient as the Alfvén speed decreases. Support for the viewpoint that shock acceleration of SEPs is most efficient above ~3 $R_\odot$ comes from persistent evidence for delayed injection onsets of high-energy protons and mildly relativistic electrons (Cliver et al. 1982; Kahler 1994; Klassen et al. 2002; Haggerty & Roelof 2002). In a study of 32 ground-level events (GLEs; >500 MeV protons), Cliver et al. (1982) found typical SEP onset delays of ~15–20 minutes from Hα start time (and 5–10 minutes from the first significant microwave peak), implying an injection height of ~2.5 $R_\odot$ for a ~1000 km s^{-1} CME-driven shock (assuming CME liftoff at Hα onset and scatter-free propagation for the earliest arriving particles). For three GLEs in 1989, Kahler (1994) used a simple propagation model and coronagraph observations to infer an injection onset (peak) height of ~2–4 $R_\odot$ (5–15 $R_\odot$) for GeV protons. Injection onset in these events was no earlier than the maxima of the associated microwave bursts. From an examination of a sample of ~80 38–315 keV beamlike electron events, Haggerty & Roelof (2002) obtained a median injection onset delay of ~10 minutes from the flare impulsive phase. Haggerty & Roelof (2002) and Simnett, Roelof, & Haggerty (2002) interpreted these delays in terms of particle acceleration at a CME-driven shock at characteristic heights of 2–3 $R_\odot$. Finally, recent analyses of the GLE events on 1997 November 6 (Falcone et al. 2003) and 2001 April 15 (Bieber et al. 2004) have indicated injection onset heights for GeV protons of ~3–4 $R_\odot$ (see also Tylka et al. 2003).

A third possible explanation for the link between DH type IIs and SEP events indicated by Table 1 might be that those shocks that survive to greater coronal heights will also span a broader range of longitudes and thus be more likely to reach the magnetic field line connected to Earth. This effect is best illustrated by considering eastern hemisphere solar activity: eastern hemisphere metric IIs without accompanying DH type II bursts are much less likely to have SEP association (8%; 4/50) than is the case for such events with associated DH type II emission (52%; 12/23). Following the work of Reinhard & Wibberenz (1974), shock acceleration has been an attractive candidate for a "fast-propagation mechanism" (Lin & Hudson 1976; Mason, Gloeckler, & Hovestadt 1984). Anecdotal and statistical evidence based on imaged solar emissions for this point of view has been provided for type II bursts (Cliver 1982, for the GLE on 1971 September 1), Hα Moreton waves (Cliver et al. 1995), and EIT waves (Torsti et al. 1999; Krucker et al. 1999).

As noted in the introduction, our working hypothesis of a single CME-driven shock from the metric through the DH (and kilometric) range (Cliver 1999; Cliver et al. 1999)—on which the above discussion is predicated—conflicts with the view of other researchers (e.g., Reiner & Kaiser 1999b), who favor a two-shock scenario, with metric type II bursts attributed primarily to flares and DH and lower frequency bursts attributed to CME drivers. While our reasons for favoring a single shock are based as much on aesthetics (Occam's razor) as on an assessment of the available evidence, we are encouraged by a recent paper by Reiner et al. (2003) in which a detailed comparison of coronagraph data (*SOHO*/LASCO [C2 and C3; covering from 2 to 32 $R_\odot$] and Mark IV from Mauna Loa Solar Observatory [1.08–2.85 $R_\odot$]) with radio data

(Culgoora and *Wind*/WAVES) led those authors to interpret a metric-DH type II burst on 2001 January 20 as a CME-driven shock from 160 to ~1 MHz (~1.3 to ~25 $R_\odot$).

3.3. *Flare and Shock Contributions to Large SEP Events*

Cane et al. (2002) have drawn attention to long-lasting type III bursts (termed type III-*l*s) in *Wind*/WAVES spectra that are highly associated with ~20 MeV proton events at Earth (confirmed by MacDowall et al. 2003 for large SEP events) to argue for a flare-particle component in all SEP events. Cane et al. interpreted these events in terms of reconnection regions below fast CMEs. Because type III-*l*s are characteristically associated with metric type II bursts, they have generally been explained in terms of electrons accelerated at (or as a result of) coronal shocks (Cane et al. 1981; MacDowall, Stone, & Kundu 1987; Kahler, Cliver, & Cane 1989; Bougeret et al. 1998; Dulk et al. 2000; Klassen et al. 2002) and were referred to as either "shock-accelerated" or "shock-associated" (SA) events, although other authors (Kundu, MacDowall, & Stone 1990; Klein & Trottet 1994; Reiner & Kaiser 1999a; Reiner et al. 2000) favor a (presumably) reconnection-based acceleration mechanism for at least some (or some parts) of these events.

A shock interpretation for type III-*l*s is actually consistent with the finding by Cane et al. (2002) that broad frontside CMEs with low speeds (<600 km s^{-1}) tend to lack type III-*l*s (see also Kahler, McAllister, & Cane 2000). The relatively low CME speeds in these events imply the absence of coronal shocks but do not, in the standard "CSHKP" picture (see Hudson & Cliver 2001 for a gallery of cartoons of proposed flare/CME magnetic field configurations), preclude magnetic reconnection and, therefore, type III-*l*s. Moreover, as a group, fast CMEs deficient in type II emission characteristically lack type III-*l* bursts as well. MacDowall et al. (2003) considered a "control group" (non–SEP-associated) of 19 fast (>700 km s^{-1}) CMEs; inspection shows that only four of these 19 CMEs had associated metric type II bursts and only two had accompanying DH type IIs. MacDowall et al. determined that none of the 19 events had type III-*l* emission meeting their criteria. This is consistent with our attribution of type III-*l*s to shock acceleration rather than to reconnection, which presumably should occur following each of the fast CMEs.

Regardless of the interpretation of the type III-*l* (or SA) events, particle acceleration via reconnection following a CME (e.g., Švestka, Martin, & Kopp 1980; Cliver et al. 1986; Litvinenko & Somov 1995) warrants further comment. Švestka et al. (1980) proposed that such acceleration could be the source of long-lived SEP (large gradual) events. The schematic in Figure 9 adapted from Švestka et al. (1980) shows that particles accelerated in this manner, particularly those accelerated late relative to the start of the flare as required by the Cane et al. (2002) definition of type III-*l* emission, can serve as seed particles for a shock upon escaping the confines of the CME. In our opinion (see Reames 2002), this is the most likely way in which flare particles can make a significant contribution to large SEP events.

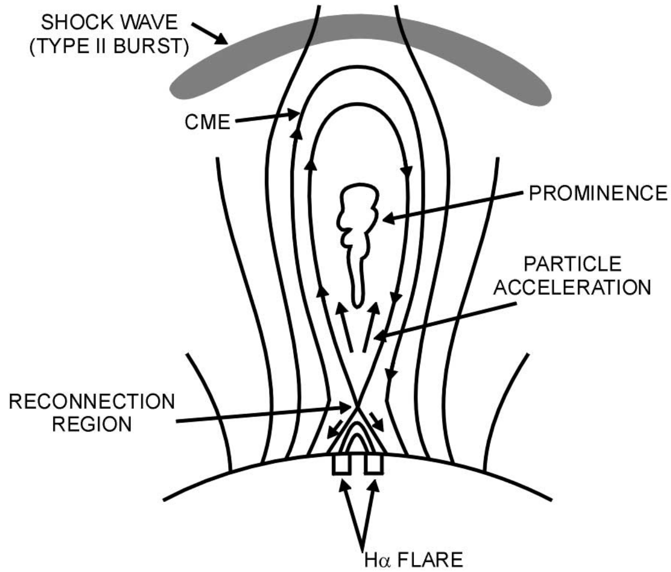

Fig. 9.—Schematic adapted from Švestka et al. (1980) showing how particles accelerated via reconnection in the wake of a CME might serve as seed particles for a CME-driven shock.

3.4. *Conclusion*

The statistics presented in this study support the widely held view that the SEPs observed near Earth are accelerated at coronal shock waves. But not all coronal shocks are "SEP-effective"; only about half of favorably located metric type II bursts are linked to SEPs. The shocks that are strong enough to produce type II emission in the decametric-hectometric range (>3 $R_\odot$) are the ones most likely to be followed by proton events at 1 AU.

We thank Allan Tylka for helpful discussions and Ed Erwin for assistance with the Hα flare patrol data.

REFERENCES

Anderson, K. A., & Lin, R. P. 1966, Phys. Rev. Lett., 16, 1121
Bieber, J. W., Evenson, P., Dröge, W., Pyle, R., Ruffolo, D., Rujiwarodom, M., Tooprakai, P., & Khumlumlert, T. 2004, ApJ, 601, L103
Bougeret, J.-L., et al. 1995, Space Sci. Rev., 71, 231
———. 1998, Geophys. Res. Lett., 25, 2513
Cane, H. V., Erickson, W. C., & Prestage, N. P. 2002, J. Geophys. Res., 107(A10), SSH 14-1
Cane, H. V., McGuire, R. E., & von Rosenvinge, T. T. 1986, ApJ, 301, 448
Cane, H. V., & Reames, D. V. 1988, ApJ, 325, 901
Cane, H. V., & Stone, R. G. 1984, ApJ, 282, 339
Cane, H. V., Stone, R. G., Fainberg, J., Steinberg, J. L., & Hoang, S. 1981, Geophys. Res. Lett., 8, 1285
Cane, H. V., & White, S. M. 1989, Sol. Phys., 120, 137
Classen, H. T., & Aurass, H. 2002, A&A, 384, 1098
Cliver, E. W. 1982, Sol. Phys., 75, 341
———. 1999, J. Geophys. Res., 104, 4629
———. 2000, in AIP Conf. Proc. 528, Acceleration and Transport of Energetic Particles Observed in the Heliosphere, ed. R. A. Mewaldt, J. R. Jokipii, M. A. Lee, E. Möbius, & T. H. Zurbuchen (Melville: AIP), 21
Cliver, E. W., Dennis, B. R., Kiplinger, A. L., Kane, S. R., Neidig, D. F., Sheeley, N. R., Jr., & Koomen, M. J. 1986, ApJ, 305, 920
Cliver, E. W., Forrest, D. J., Cane, H. V., Reames, D. V., McGuire, R. E., von Rosenvinge, T. T., Kane, S. R., & MacDowall, R. J. 1989, ApJ, 343, 953
Cliver, E. W., & Hudson, H. S. 2002, J. Atmos. Sol.-Terr. Phys., 64, 231
Cliver, E. W., Kahler, S. W., & McIntosh, P. S. 1983, ApJ, 264, 699
Cliver, E. W., Kahler, S. W., Neidig, D. F., Cane, H. V., Richardson, I. G., Kallenrode, M.-B., & Wibberenz, G. 1995, Proc. 24th Int. Cosmic Ray Conf., 4, 257

Cliver, E. W., Kahler, S. W., Shea, M. A., & Smart, D. F. 1982, ApJ, 260, 362
Cliver, E. W., Webb, D. F., & Howard, R. A. 1999, Sol. Phys., 187, 89
Dodge, J. C. 1975, Sol. Phys., 42, 445
Dulk, G. A., Leblanc, Y., Bastian, T. S., & Bougeret, J.-L. 2000, J. Geophys. Res., 105, 27343
Falcone, A., et al. 2003, ApJ, 588, 557
Gopalswamy, N. 2003, Geophys. Res. Lett., 30(12), SEP 1-1
Gopalswamy, N., & Kaiser, M. L. 2002, Adv. Space Res., 29, 307
Gopalswamy, N., Lara, A., Kaiser, M. L., & Bougeret, M. L. 2001a, J. Geophys. Res., 106, 25261
Gopalswamy, N., Yashiro, S., Kaiser, M. L., Howard, R. A., & Bougeret, J.-L. 2001b, J. Geophys. Res., 106, 29219
Gopalswamy, N., Yashiro, S., Lara, A., Kaiser, M. L., Thompson, B. J., Gallagher, P. T., & Howard, R. A. 2003, Geophys. Res. Lett., 30(12), SEP 3-1
Gopalswamy, N., Yashiro, S., Michalek, G., Kaiser, M. L., Howard, R. A., Reames, D. V., Leske, R., & von Rosenvinge, T. 1999, J. Geophys. Res., 104, 4748
Gopalswamy, N., et al. 2000, Geophys. Res. Lett., 27, 1427
———. 2002, ApJ, 572, L103
Haggerty, D. K., & Roelof, E. C. 2002, ApJ, 579, 841
Hudson, H. S., & Cliver, E. W. 2001, J. Geophys. Res., 106, 25199
Kahler, S. W. 1977, ApJ, 214, 891
———. 1982, ApJ, 261, 710
———. 1994, ApJ, 428, 837
———. 2001a, in Space Weather, ed. P. Song, H. J. Singer, & G. L. Siscoe (Geophys. Monogr. 125; Washington, DC; AGU), 109
———. 2001b, J. Geophys. Res., 106, 20947
Kahler, S. W., Cliver, E. W., & Cane, H. V. 1989, Sol. Phys., 120, 393
Kahler, S. W., Cliver, E. W., Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J., & Michels, D. J. 1985, J. Geophys. Res., 90, 177
Kahler, S. W., McAllister, A. H., & Cane, H. V. 2000, ApJ, 533, 1063
Kahler, S. W., Reames, D. V., & Sheeley, N. R., Jr. 2001, ApJ, 562, 558
Kahler, S. W., Sheeley, N. R., Jr., Howard, R. A., Michels, D. J., Koomen, M. J., McGuire, R. E., von Rosenvinge, T. T., & Reames, D. V. 1984, J. Geophys. Res., 89, 9683
Klassen, A., Bothmer, V., Mann, G., Reiner, M. J., Krucker, S., Vourlidas, A., & Kunow, H. 2002, A&A, 385, 1078
Klassen, A., & Pohjolainen, S. 2002, in Solar Variability: From Core to Outer Frontiers, ed. A Wilson (ESA SP-506; Noordwijk: ESA), 307
Klein, K.-L., Khan, J. I., Vilmer, N., Delouis, J.-M., & Aurass, H. 1999, A&A, 346, L53
Klein, K.-L., & Trottet, G. 1994, in AIP Conf. Proc. 294, High-Energy Solar Phenomena: A New Era of Spacecraft Measurements, ed. J. M. Ryan & W. T. Vestrand (Woodbury: AIP), 187
Kocharov, L., & Torsti, J. 2002, Sol. Phys., 207, 149
Krucker, S., Larson, D. E., Lin, R. P., & Thompson, B. J. 1999, ApJ, 519, 864
Kundu, M. R., MacDowall, R. J., & Stone, R. G. 1990, Ap&SS, 165, 101
Lara, A., Gopalswamy, N., Nunes, S., Muñoz, G., & Yashiro, S. 2003, Geophys. Res. Lett., 30(12), SEP 4-1
Leblanc, Y., Dulk, G. A., & Bougeret, J.-L. 1998, Sol. Phys., 183, 165
Lin, R. P. 1970, Sol. Phys., 12, 266
Lin, R. P., & Hudson, H. S. 1976, Sol. Phys., 50, 153
Litvinenko, Yu. E., & Somov, B. V. 1995, Sol. Phys., 158, 317
MacDowall, R. J., Lara, A., Manoharan, P. K., Nitta, N. V., Rosas, A. M., & Bougeret, J.-L. 2003, Geophys. Res. Lett., 30(12), SEP 6-1
MacDowall, R. J., Stone, R. G., & Kundu, M. R. 1987, Sol. Phys., 111, 397
Mann, G., Aurass, H., Klassen, A., Estel, C., & Thompson, B. J. 1999, in Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona, ed. J.-C. Vial & B. Kaldeich-Schurmann (ESA SP-446; Noordwijk: ESA), 477
Mason, G. M., Gloeckler, G., & Hovestadt, D. 1984, ApJ, 280, 902
Maxwell, A., & Dryer, M. 1982, Space Sci. Rev., 32, 11
McCracken, K. G. 1962, J. Geophys. Res., 67, 447
McCracken, K. G., & Rao, U. R. 1970, Space Sci. Rev., 11, 155
McGuire, R. E., von Rosenvinge, T. T., & McDonald, F. B. 1986, ApJ, 301, 938
Nelson, G. J., & Melrose, D. B. 1985, in Solar Radiophysics, ed. D. J. McLean & N. R. Labrum (New York: Cambridge Univ. Press), 333
Nitta, N., & Akiyama, S. 1999, ApJ, 525, L57
Reames, D. V. 1999, Space Sci. Rev., 90, 413
———. 2000, ApJ, 540, L111
———. 2002, ApJ, 571, L63
Reiner, M. J., & Kaiser, M. L. 1999a, Geophys. Res. Lett., 26, 397
———. 1999b, J. Geophys. Res., 104, 16979
Reiner, M. J., Kaiser, M. L., Gopalswamy, N., Aurass, H., Mann, G., Vourlidas, A., & Maksimovic, M. 2001, J. Geophys. Res., 106, 25279
Reiner, M. J., Karlický, M., Jiricka, K., Aurass, H., Mann, G., & Kaiser, M. L. 2000, ApJ, 530, 1049
Reiner, M. J., Vourlidas, A., St. Cyr, O. C., Burkepile, J. T., Howard, R. A., Kaiser, M. L., Prestage, N. P., & Bougeret, J.-L. 2003, ApJ, 590, 533
Reinhard, R., & Wibberenz, G. 1974, Sol. Phys., 36, 473
Robinson, R. D. 1985, Sol. Phys., 95, 343
Saito, K. 1970, Ann. Tokyo Astron. Obs., 12, 53
Sheeley, N. R., Jr., Howard, R. A., Koomen, M. J., & Michels, D. J. 1983, ApJ, 272, 349
Sheeley, N. R., Jr., et al. 1975, Sol. Phys., 45, 377
Simnett, G. M., Roelof, E. C., & Haggerty, D. K. 2002, ApJ, 579, 854
Smart, D. F., Shea, M. A., Dodson, H. W., & Hedeman, E. R. 1976, Space Res., 16, 797
Smith, H. J., & Smith, E. v. P. 1963, Solar Flares (New York: Macmillan)
Švestka, Z., & Fritzová-Švestková, L. 1974, Sol. Phys., 36, 417
Švestka, Z., Martin, S. F., & Kopp, R. A. 1980, in IAU Symp. 91, Solar and Interplanetary Dynamics, ed. M. Dryer & E. Tandberg-Hanssen (Boston: Reidel), 217
Torsti, J., Kocharov, L. G., Teittinen, M., & Thompson, B. J. 1999, ApJ, 510, 460
Tylka, A. J., Boberg, P. R., Cohen, C. M. S., Dietrich, W. F., Macclennan, C. G., Mason, G. M., Ng, C. K., & Reames, D. V. 2002, ApJ, 581, L119
Tylka, A. J., et al. 2003, Proc. 28th Int. Cosmic Ray Conf. (Tsukuba), 6, 3305
von Rosenvinge, T. T., et al. 1995, Space Sci. Rev., 71, 155
Vršnak, B., & Lulić, S. 2000a, Sol. Phys., 196, 157
———. 2000b, Sol. Phys., 196, 181
Vršnak, B., Magdalenić, J., & Aurass, H. 2001, Sol. Phys., 202, 319
Vršnak, B., Magdalenić, J., Aurass, H., & Mann, G. 2002, A&A, 396, 673
Webb, D. F., & Howard, R. A. 1994, J. Geophys. Res., 99, 4201
Wild, J. P., Smerd, S. F., & Weiss, A. A. 1963, ARA&A, 1, 291
Wright, C. S. 1980, Proc. Astron. Soc. Australia, 4, 59