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A Search for Geomagnetic Storm Evidence of the Reversal of the Solar Dipole Magnetic Field and Interplanetary B_z

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The axis of the solar dipole magnetic field is aligned to within 30° of the solar rotational axis for up to 2 years during solar minima. Coronal mass ejections (CMEs) during those periods arise from the equatorial streamer belts and should share the magnetic orientation of the dipole field. If those field orientations are maintained in interplanetary space, CMEs producing geomagnetic storms should be characterized by southward B_z during minima when the fields point outward in the northern solar hemisphere and by northward B_z at alternate minima when the solar dipole is reversed. Since southward B_z is an important factor in producing geomagnetic storms, we should expect that storms during minima characterized by southward B_z are significantly larger than those during the alternate minima. Storm data from 10 solar minima are used to test this hypothesis. The test yields a null result.

1. Introduction

B_z, the component of the interplanetary magnetic field-directed normal to the ecliptic plane, is known to be a key parameter for geomagnetic storms. The largest storms appear to be due to the presence of strong southward pointing B_z fields [e.g., *Tsurutani et al.*, 1990, 1992]. Guided by the *Gold* [1959] cartoon of a bottle or tongue for the interplanetary magnetic field resulting from a solar eruption (Figure 1), some workers have sought to relate the basic magnetic structure of the erupting solar region to the structure of the resulting interplanetary field, especially the B_z component. *Pudovkin and Chertkov* [1976] found that flares with large-scale ($\sim 10^5$ km) southward fields were associated with intense geomagnetic storms, but flares with northward fields were rarely associated. The subject is controversial [*Kahler*, 1992], with some studies [e.g., *Tang et al.*, 1985, 1986, 1989] finding little success in using the directions of flare fields to predict either the direction of B_z or the occurrence of geomagnetic storms.

Recently, *Hoeksema and Zhao* [1992] (hereinafter H&Z) have examined the magnetic field orientations of the presumed solar sources of five strong southward B_z events detected at 1 AU. Rather than using the photospheric fields as earlier investigators have done, they examined the coronal fields over the parent event sites. H&Z used a potential field model [*Hoeksema et al.*, 1982] to calculate the coronal field orientations over the solar sources at heights of 1.03, 1.20, and 2.49 R_S. In the one case of a prominence eruption, no southward field component was found at any of these heights. However, for three of the four events associated with flares a southward field component was calculated at 1.03 R_S. Neither candidate flare of April 10, 1981 [*Sheeley et al.*, 1985], was associated with a calculated southward field component at any height.

Encouraged by this agreement in field directions for three of their five cases, *Zhao and Hoeksema* [1992] selected periods of strong B_z at 1 AU and then examined the solar coronal fields of associated flare regions. In four additional cases they found southward (northward) coronal field components at heights of 1.03 R_S over the associated flares which matched the southward (northward) orientation of B_z at 1 AU. They suggested that the magnetic orientation in driver gas generated by flare-associated CMEs may be predictable.

While further studies may validate the H&Z technique for predicting B_z fields in shock driver gases, several aspects of their approach are open to question. The first is their assumption that the coronal fields directly over the flare site expand in the CME to become the fields observed at 1 AU. The angular width of a typical CME measured in the corona is ~45° [*Kahler*, 1987], greatly exceeding that of active regions or flares [*Kahler et al.*, 1989; *Harrison et al.*, 1990]. In addition, the locations of flares associated with CMEs range from the edges to the centers of the CME spans [*Kahler et al.*, 1989; *Harrison*, 1991]. Thus a priori, one would expect the coronal fields appropriate for a prediction of interplanetary B_z to be much larger in scale than those of active regions and to lie outside active regions. A related question about the H&Z technique is why the prediction of B_z at the Earth should be independent of the relative location of the flare on the disk. We might expect that the H&Z prediction is good only for CMEs ejected directly toward the Earth, with fields poorly predicted when the associated CMEs originate well away from central meridian.

Another question about this scheme concerns the concept of source heights for flare-associated CMEs. Even if we accept the flare site as the appropriate place to measure the field direction, it is clear from H&Z that the coronal field direction varies considerably with height above the flare. Since we expect all the field lines over the flare region to be carried out to 1 AU by the CME, these various field orientations should also be observed at the Earth. However, H&Z chose 1.03 and 1.20 R_S as candidate "release heights", regions in which the coronal field directions should match the interplanetary field directions. Implicit in this scheme is the assumption that only the fields from the release height make a substantial contribution to the interplanetary B_z. This may require that lower and higher coronal field lines not erupt, contrary to our understanding of CMEs. Furthermore, observations show that the interior features of CMEs, such as prominences, move more slowly than the leading edges and hence cannot be driving CMEs [*Kahler*, 1988]. To

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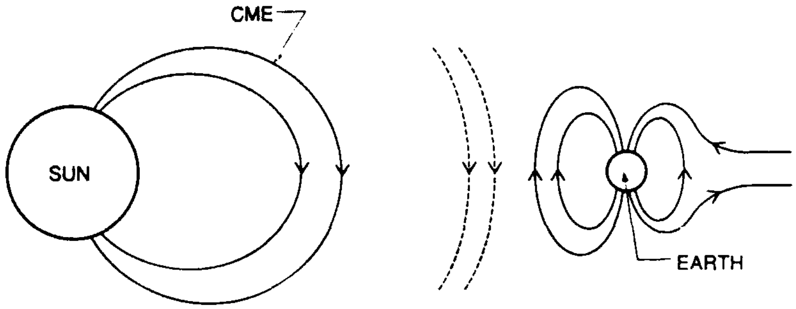

Fig. 1. Schematic showing how the southward pointing magnetic field of a CME reaches the Earth, where the southward B_z fields (dashed lines) can reconnect with the northward pointed dipole field lines of the Earth during a geomagnetic storm. In alternate solar minima the fields of CMEs should be northward pointing, resulting in little reconnection and weaker geomagnetic storms.

summarize, there are several serious conceptual difficulties with the H&Z scheme for predicting the direction of the B_z driver gas at 1 AU.

The uncertainties in predicting either B_z or geomagnetic storms are compounded by difficulties in testing those predictions. *Tsurutani et al.* [1988] pointed out that storms often consist of two or more steps, each of which corresponds to significant changes in the interplanetary field. B_z fields often fluctuate substantially over 12 to 24 hour periods, so the success of predictions of net B_z directions [*McComas et al.*, 1989] can be very dependent on the time intervals over which one averages the B_z fields. Changing the geomagnetic storm threshold will also change the statistics of any study relating storm occurrence to interplanetary fields [e.g., *Gosling et al.*, 1991].

The question of whether one can relate coronal magnetic field directions to interplanetary B_z directions or to associated geomagnetic storms is obviously difficult to answer. We will attempt to address this question with a synoptic and statistical approach which avoids the detailed problems discussed above. It is based on the facts that the solar magnetic dipole axis is nearly aligned with the rotational axis at times of solar activity minima and that the polarities are reversed at alternate minima. At one minimum, CMEs sharing the orientation of the dipole field should result in net southward B_z fields and large geomagnetic storms; at the next minimum the CMEs should result in northward B_z fields and small geomagnetic storms. If this is the case, a statistical comparison of storm sizes at alternate minima should yield a distinct difference between the two groups. A null result implies that some crucial element in the chain of assumptions linking coronal magnetic fields to interplanetary B_z fields and geomagnetic storms is incorrect. Before examining the geomagnetic data, we discuss the basic assumptions linking CMEs at solar minimum to geomagnetic storms.

2. Assumptions Linking CME Fields to Geomagnetic Storms

The large-scale solar magnetic field can be characterized as a dipole, with the two hemispheres of opposite magnetic polarity separated by a warped neutral sheet [e.g., *Hoeksema et al.*, 1982; *Mihalov et al.*, 1990; *Hoeksema*, 1991]. Source surface calculations using a potential field model [*Hoeksema*, 1991] show that near solar minimum the neutral sheet extends less than 20° from the solar equator, as seen in Figure 2. With the rise in solar activity the sheet extends to increasingly higher latitudes until the polar fields reverse at solar maximum [e.g., *Hoeksema*, 1989]. As the next minimum is approached, the neutral sheet again lies at low solar latitudes, but now the polarity of the dipole is reversed from that of the previous minimum.

Around the period of minimum a belt of coronal streamers surrounds the Sun near its equator [*Mihalov et al.*, 1990]. A comparison between the locations of the white-light streamer belt and the neutral sheet of the potential-field calculation [*Hoeksema et al.*, 1982] has shown good agreement [*Wilcox and Hundhausen*, 1983], indicating that the streamer belt bisects the two hemispheres of the solar dipole.

The apparent latitudes of CMEs also follow the projected latitudes of the streamer belt and neutral sheet through the solar cycle [*Hundhausen*, 1993]. The average width of the SMM CMEs is about 45°, with little variation throughout the solar cycle [*St. Cyr and Burkepile*, 1990]. If we therefore suppose that CMEs are eruptions of large-scale closed coronal fields generally centered under the streamer belt, then the polarity of the CME magnetic fields should match that of the larger solar dipole field. *Kahler* [1991] has presented evidence that when active regions are associated with transequatorial loops, the loops are formed from the leading polarities of the regions, which also match the polarities of the dipole field. While we have no measurements of magnetic fields in CMEs, it is very plausible to assume that the transequatorial direction of the CME field matches that of the dipole field. This direction is least ambiguous around solar minimum when the neutral sheet lies closest to both the equator and the ecliptic. If the CME fields are southward pointing around one minimum, as shown in Figure 1, they should be northward pointing around the preceding and following minima.

If the large-scale structure of a fast CME is maintained out to 1 AU, as suggested in Figure 1, then we can expect to observe in the shock driver gas a significant B_z component matching that of the solar dipole field. *Mullan* [1991] has estimated time scales for survival against magnetic reconnection for solar structures ejected into the solar wind. He found that structures with widths >5° at 2 R_S may still be identifiable in the solar wind at 1 AU. *Detman et al.* [1991] simulated the ejection of a spherical plasmoid with an angular size of 36° into the solar wind and found that the

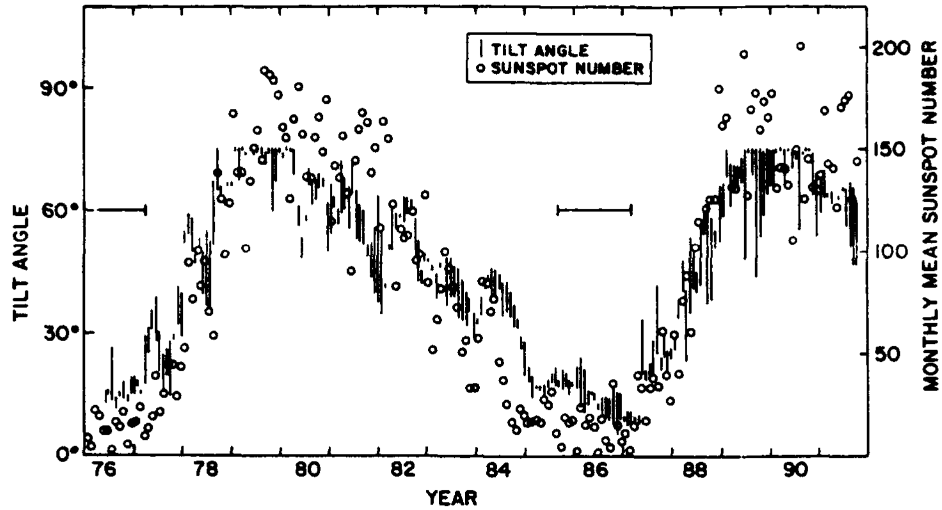

Fig. 2. Solar dipole tilt angles and monthly mean sunspot numbers from 1976 to 1991. For each solar rotation, vertical lines connect the values of the southern and northern latitudes of the heliospheric neutral sheet, calculated by J. T. Hoeksema (private communication, 1992). The tilt angles were limited to ±75°. During the 18-month periods of this study, indicated by the horizontal lines, the tilt angles were ≤20°.

basic magnetic topology was preserved out to 1 AU. Reconnection in their modeling, however, was due only to numerical diffusion. Large-scale transient structures, assumed to be CMEs, have been inferred to be present at 1 AU from the detection of magnetic clouds and counterstreaming solar wind halo electron events [*Gosling et al.*, 1992]. In their examination of magnetic clouds *Kahler and Reames* [1991] used solar energetic particles to show that clouds cannot be plasmoids. This means that the B_z fields should not reverse within CMEs from reconnection. The theoretical and observational evidence are therefore consistent with the preservation of large-scale transient structures to 1 AU.

Geomagnetic activity is highly dependent on the interplanetary B_z field [e.g., *Gonzalez et al.*, 1989]. *Russell and McPherron* [1973] explained the semiannual variation of geomagnetic activity in terms of a net southward magnetic field component at the Earth when viewed in the solar-magnetospheric coordinate system near the equinoxes. Enhanced activity occurs when the spiral field in the ecliptic points toward the Sun in the spring or away from the Sun in the fall. *Crooker et al.* [1992] recently extended this explanation to account for the strong semiannual variation of large geomagnetic storms. Since the Earth also lies at high heliographic latitude near the equinoxes, during one solar cycle the field will preferentially point toward the Sun in March and away from the Sun in September, a condition favorable for a net southward B_z and enhanced geomagnetic activity. During alternate cycles the solar dipole field is reversed, the interplanetary field directions are preferentially reversed during the equinoxes, and geomagnetic activity is significantly diminished [*Russell*, 1974, 1975]. Since these variations in the in-ecliptic fields result in significant variations of the consequent geomagnetic activity, we should expect even larger geomagnetic variations from the changes in B_z field directions of CMEs at solar minimum. We have no reason to expect that the speeds and pressures of disturbed solar wind, the other parameters of importance in driving geomagnetic storms, will differ significantly from one solar minimum period to the next.

In this study we use storm sudden commencements (SSCs) to detect the presence of CMEs at the Earth. SSCs are well associated with interplanetary shocks [*Smith*, 1983], and interplanetary shocks within 1 AU are known to be well associated with fast CMEs [*Sheeley et al.*, 1985; *Cane et al.*, 1987]. Geomagnetic storms with SSCs are poorly associated with recurrent high-speed streams [*Feynman and Gu*, 1986], so the occurrence of an SSC can serve as a proxy for a CME, although several factors may compromise the usefulness of this proxy. The first is that the CME driving the interplanetary shock will not necessarily intersect the Earth. Cane [1988] estimated the longitudinal widths of flare-associated interplanetary shocks to be ~100°, in contrast to inferred widths of ≤60° for the CMEs themselves. This suggests that the associated CME, with its B_z field matching the solar dipole, will not always follow an SSC at the Earth. Another concern is that a strong B_z field may arise from draping about a CME [*Gosling and McComas*, 1987]. These draped fields are an important source of southward B_z in major geomagnetic storms [*Tsurutani et al.*, 1988]. In this study we assume that the B_z fields following SSCs but not lying within CMEs should average either to 0 or to a value with a sign matching the solar dipole field. These fields will produce a source of noise in our comparison between geomagnetic storms of even and odd-numbered minima.

3. DATA ANALYSIS

We used monthly mean sunspot numbers [*McKinnon*, 1987] as a proxy for dipole tilt angles. Those numbers track very well the dipole tilt angles calculated by J. T. Hoeksema (private communication, 1992), as shown in Figure 2. Since the number of SSCs is relatively low at solar minimum [*Mayaud*, 1975; *Feynman and Gu*, 1986], we took 18 months as an appropriate interval to obtain adequate statistics of SSCs while remaining within small tilt angles. It is necessary to select an interval which is a multiple of 6 months to avoid a bias from the tendency for geomagnetic storms to occur near equinoxes [*Crooker et al.*, 1992]. For each of 10 solar

TABLE 1. Sums of *aa* Following SSCs at Solar Minima

Minimum Period	24-Hour *aa* Sum			36-Hour *aa* Sum		
	0–40	41–80	>81	0–60	61–120	>121
B_z North	42	43	18	47	40	16
B_z South	43	42	23	46	39	23

minima we selected the 18-month period with the smallest running total of monthly mean sunspot numbers. The first minimum period was December 1877 to May 1879, and the last was October 1975 to March 1977. The monthly mean sunspot number exceeded 20 on only 7 of the 180 months of the study. The horizontal lines in Figure 2 show the 18-month periods for the last two minima. The average tilt angle was <20° for each entire period, although no calculations exist prior to May 1976.

In our analysis we consider only geomagnetic storms following SSCs. *Mayaud* [1973] published a list of SSCs compiled from 1868 through 1967, a period including nine minima. To extend the analysis to the 1975-77 minimum we used the lists of SSCs published by *van Sabben* [1976, 1977, 1978]. All SSCs from the 10 solar minimum periods were used in the analysis. Several indices are available to characterize geomagnetic disturbances [*Feynman and Gu*, 1986], but only the *aa* index has been calculated for all 10 periods of solar minima [*Mayaud*, 1973]. These indices are calculated only for 12 hour periods. For each SSC the sums of the *aa* values for the 24-hour and 36-hour periods following the SSC were calculated. For SSCs occurring on or before 0600 UT, the first *aa* value was the first of the day; for SSCs after 0600 UT but on or before 1800 UT, the first *aa* value was the second of the day; and for SSCs after 1800 UT, the first *aa* value was the first of the following day. In seven cases, pairs of SSCs were so close together that the same set of *aa* values was used for each pair. In each case we used only one of these pairs; thus seven SSCs were eliminated from the analysis. This left a total of 103 SSCs for the minima with B_z northward and 108 for those with B_z southward.

The distributions of the *aa* sums for the five minima when B_z is expected to be southward pointing and for the five with B_z expected northward are shown in Table 1. Contrary to the expectations of the hypothesis of section 1, we find no statistically significant difference between the two distributions of *aa* sums. Comparing the two distributions with the χ^2 test, we find that the probabilities that the distributions are different are only 37% for the 24-hour sums and 70% for the 36-hour sums. The only obvious difference between the two distributions is a slightly higher number of storms in the largest *aa* values. The median sums for the northward and southward B_z distributions for 24-hour periods are 44 and 48, respectively, and for the 36-hour periods the median sums are both 67. These values also show the similarity between the two B_z distributions.

The search for an effect of the expected change in direction of B_z between alternate solar minima is complicated by the presence of a 22-year cycle in geomagnetic activity. During minima when B_z is south, the interplanetary field also points predominantly away from the Sun in September and toward the Sun in March, a situation favorable for enhanced geomagnetic activity due to the Russell-McPherron effect. When B_z is north, the situation is reversed and less favorable for geomagnetic activity. *Russell* [1974] used the geomagnetic activity index, *Ci*, to show that those cycles that we characterized by B_z south generally, but not always, have enhanced activity, consistent with the Russell-McPherron effect. When we divide the *aa* sums of our study into two 3-month periods centered on the solstices and two 3-month periods centered on the equinoxes, we find that the slightly enhanced values of B_z south shown in Table 1 are due entirely to enhancements during the periods around the equinoxes. The χ^2 probabilities that B_z north and B_z south distributions are different for the solstice months are only 8% for the 24-hour sums and 4% for the 36-hour sums. We therefore suggest that the slightly higher number of large storms during the periods of B_z south shown in Table 1 result only from the Russell-McPherron effect.

4. DISCUSSION

The behavior of the interplanetary B_z field is of great importance for predicting the size of a geomagnetic storm. There have been suggestions that it may be possible to predict the interplanetary B_z field based on a knowledge of the calculated coronal field of the CME. If such predictions are feasible, we should certainly find a clear signature in our comparison of geomagnetic storm sizes at alternate solar minima, when the large-scale coronal field is in its simplest state. The implication of the null result is that we cannot expect to predict B_z from knowledge of the more complex coronal fields found during periods of high solar activity.

The failure to find a significant difference between the sizes of geomagnetic storms of alternate solar minima suggests that one or more of the assumptions discussed in section 2 is in error. One possibility is that the B_z fields of CMEs do systematically reverse with the solar cycle, as expected, but somehow fail to produce a difference in levels of geomagnetic activity. However, averages of interplanetary B_z measurements are essentially 0 both within [*Mariani and Neubauer*, 1990] and beyond [*Thomas and Smith*, 1980] 1 AU and therefore provide no evidence of a solar cycle dependence on the direction of B_z. Since CMEs contribute only ~1% of the solar wind mass flux at solar minimum (D. Webb, private communication, 1992), they may not make a significant contribution to long-term averages. On the other hand, we should generally expect that as previously closed magnetic field lines are convected away from the Sun by the solar wind, the dipole component would be detectable in the solar wind as a net bias in the average B_z fields.

It should be remembered that in the absence of direct measurements we must infer the directions of magnetic fields in CMEs. Perhaps the stronger, smaller-scale fields of active regions may grow to dominate the CME fields in the interplanetary medium, as implied by H&Z. If these fields are randomly oriented with respect to the solar dipole fields, the interplanetary fields would then bear little resemblance to the dipole fields. At the present time our poor knowledge of coronal fields allows only speculation about the true nature of the fields in CMEs.

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REFERENCES

Cane, H. V., The large-scale structure of flare-associated interplanetary shocks, *J. Geophys. Res.*, *93*, 1, 1988.

Cane, H. V., N. R. Sheeley, Jr., and R. A. Howard, Energetic interplanetary shocks, radio emission, and coronal mass ejections, *J. Geophys. Res.*, *92*, 9869, 1987.

Crooker, N. U., E. W. Cliver, and B. T. Tsurutani, The semiannual variation of great geomagnetic storms and the postshock Russell-McPherron effect preceding coronal mass ejecta, *Geophys. Res. Let.*, *19*, 429, 1992.

Detman, T. R., M. Dryer, T. Yeh, S. M. Han, S. T. Wu, and D. J. McComas, A time-dependent, three-dimensional mhd numerical study of interplanetary magnetic draping around plasmoids in the solar wind, *J. Geophys. Res.*, *96*, 9531, 1991.

Feynman, J., and X. Y. Gu, Prediction of geomagnetic activity on time scales of one to ten years, *Rev. Geophys.*, *24*, 650, 1986.

Gold, T., Plasma and magnetic fields in the solar system, *J. Geophys. Res.*, *64*, 1665, 1959.

Gonzalez, W. D., B. T. Tsurutani, A. L. C. Gonzalez, E. J. Smith, F. Tang, and S. -I. Akasofu, Solar wind-magnetosphere coupling during intense magnetic storms (1978-1979), *J. Geophys. Res.*, *94*, 8835, 1989.

Gosling, J. T., and D. J. McComas, Field line draping about fast coronal mass ejecta: A source of strong out-of-the-ecliptic interplanetary magnetic fields, *Geophys. Res. Lett.*, *14*, 355, 1987.

Gosling, J. T., D. J. McComas, J. L. Phillips, and S. J. Bame, Geomagnetic activity associated with earth passage of interplanetary shock disturbances and coronal mass ejections, *J. Geophys. Res.*, *96*, 7831, 1991.

Gosling, J. T. , D. J. McComas, J. L. Phillips, and S. J. Bame, Counterstreaming solar wind halo electron events: Solar cycle variations, *J. Geophys. Res.*, *97*, 6531, 1992.

Harrison, R. A., Coronal transients and their relation to solar flares, *Adv. Space Res.*, *11*, (1)25, 1991.

Harrison, R. A., E. Hildner, A. J. Hundhausen, D. G. Sime, and G. M. Simnett, The launch of solar coronal mass ejections: Results from the coronal mass ejection onset program, *J. Geophys. Res.*, *95*, 917, 1990.

Hoeksema, J. T., Extending the sun's magnetic field through the three-dimensional heliosphere, *Adv. Space Res.*, *9* (4), 141, 1989.

Hoeksema, J. T., Large-scale solar and heliospheric magnetic fields, *Adv. Space Res.*, *11* (1), 15, 1991.

Hoeksema, J. T., and X. Zhao, Prediction of magnetic orientation in driver gas associated $-B_z$ events, *J. Geophys. Res.*, *97*, 3151, 1992.

Hoeksema, J. T., J. M. Wilcox, and P. H. Scherrer, Structure of the heliospheric current sheet in the early portion of sunspot cycle 21, *J. Geophys. Res.*, *87*, 10, 331, 1982.

Hundhausen, A. J., The sizes and locations of coronal mass ejections: SMM observations from 1980 and 1984–1989, *J. Geophys. Res.*, in press, 1993.

Kahler, S., Coronal mass ejections, *Rev. Geophys.*, *25*, 663, 1987.

Kahler, S., Observations of coronal mass ejections near the sun, in *Proceedings of the Sixth International Solar Wind Conference*, vol. 1, edited by V. J. Pizzo, T. E. Holzer and D. G. Sime, p. 215, National Center for Atmospheric Research, Boulder, Colo., 1988.

Kahler, S., Coronal mass ejections and streamers associated with the new cycle active regions at solar minimum, *Astrophys. J.*, *378*, 398, 1991.

Kahler, S. W., Solar flares and coronal mass ejections, *Annu. Rev. Astron. Astrophys.*, *30*, 113, 1992.

Kahler, S. W., and D. V. Reames, Probing the magnetic topologies of magnetic clouds by means of solar energetic particles, *J. Geophys. Res.*, *96*, 9419, 1991.

Kahler, S. W., N. R. Sheeley, Jr., and M. Liggett, Coronal mass ejections and associated x-ray flare durations, *Astrophys. J.*, *344*, 1026, 1989.

Mariani, F., and F. M. Neubauer, The interplanetary magnetic field, in *Physics of the Inner Heliosphere, 1. Large-Scale Phenomena*, edited by R. Schwenn and E. Marsch, p. 183, Springer-Verlag, New York, 1990.

Mayaud, P. N., A hundred year series of geomagnetic data 1868-1967, *IAGA Bull.*, *33*, 1973.

Mayaud, P. N., Analysis of storm sudden commencements for the years 1868-1967, *J. Geophys. Res.*, *80*, 111, 1975.

McComas, D. J., J. T. Gosling, S. J. Bame, E. J. Smith, and H. V. Cane, A test of magnetic field draping induced B_z perturbations ahead of fast coronal mass ejecta, *J. Geophys. Res.*, *94*, 1465, 1989.

McKinnon, J. A., Sunspot numbers: 1610-1985, *UAG Rep.*, *95*, 1987.

Mihalov, J. D., A. Barnes, A. J. Hundhausen, and E. J. Smith, Solar wind and coronal structure near sunspot minimum: Pioneer and SMM observations from 1985-1987, *J. Geophys. Res.*, *95*, 8231, 1990.

Mullan, D. J., Survival of discrete structures in the solar wind, *Astron. Astrophys.*, *248*, 256, 1991.

Pudovkin, M. I., and A. D. Chertkov, Magnetic field of the solar wind, *Solar Phys.*, *50*, 213, 1976.

Russell, C. T., On the heliographic latitude dependence of the interplanetary magnetic field as deduced from the 22-year cycle of geomagnetic activity, *Geophys. Res. Lett.*, *1*, 11, 1974.

Russell, C. T., On the possibility of deducing interplanetary and solar parameters from geomagnetic records, *Solar Phys.*, *42*, 259, 1975.

Russell, C. T., and R. L. McPherron, Semi-annual variation of geomagnetic activity, *J. Geophys. Res.*, *78*, 92, 1973.

Sheeley, N. R., Jr., R. A. Howard, M. J. Koomen, D. J. Michels, R. Schwenn, K. H. Muhlhauser, and H. Rosenbauer, Coronal mass ejections and interplanetary shocks, *J. Geophys. Res.*, *90*, 163, 1985.

Smith, E. J., Observations of interplanetary shocks: recent progress, *Space Science Reviews*, *34*, 101, 1983.

St. Cyr, O. C., and J. T. Burkepile, A catalog of mass ejections observed by the solar maximum mission coronagraph, *NCAR Tech. Note NCAR/TN-352+STR*, Natl. Cent. Atmos. Res., Boulder, Colo., 1990.

Tang, F., S. -I. Akasofu, E. Smith, and B. Tsurutani, Magnetic fields on the sun and the north-south component of transient variations of the interplanetary magnetic field at 1 AU, *J. Geophys. Res.*, *90*, 2703, 1985.

Tang, F., S. -I. Akasofu, E. Smith, and B. Tsurutani, Reply, *J. Geophys. Res.*, *91*, 13, 769, 1986.

Tang, F., B. T. Tsurutani, W. D. Gonzalez, S. I. Akasofu, and E. J. Smith, Solar sources of interplanetary southward B_z events responsible for major magnetic storms (1978-1979), *J. Geophys. Res.*, *94*, 3535, 1989.

Thomas, B. T., and E. J. Smith, The Parker spiral configuration of the interplanetary magnetic field between 1 and 8.5 AU, *J. Geophys. Res.*, *85*, 6861, 1980.

Tsurutani, B. T., W. D. Gonzalez, F. Tang, S. I. Akasofu, and E. J. Smith, Origin of interplanetary southward magnetic fields responsible for major magnetic storms near solar minimum (1978-1979), *J. Geophys. Res.*, *93*, 8519, 1988.

Tsurutani, B. T., B. E. Goldstein, E. J. Smith, W. D. Gozalez, F. Tang, S. I. Akasofu, and R. R. Anderson, The interplanetary and solar causes of geomagnetic activity, *Planet. Space Sci.*, *38*, 109, 1990.

Tsurutani, B. T., W. D. Gonzalez, F. Tang, and Y. T. Lee, Great magnetic storms, *Geophys. Res. Lett.*, *19*, 73, 1992.

van Sabben, D. Geomagnetic Data 1975 indices rapid variations special intervals, *IAGA Bull.*, *32f*, 1976.

van Sabben, D. Geomagnetic Data 1976 indices rapid variations special intervals, *IAGA Bull.*, *32g*, 1977.

van Sabben, D. Geomagnetic Data 1977 indices rapid variations special intervals, *IAGA Bull.*, *32h*, 1978.

Wilcox, J. M., and A. J. Hundhausen, Comparison of heliospheric current sheet structure obtained from potential magnetic field computations and from observed polarization coronal brightness, *J. Geophys. Res.*, *88*, 8095, 1983.

Zhao, X., and J. T. Hoeksema, Identification of driver gas-associated B_z events and prediction of their orientation, in *Proceedings of the First Soltip Symposium*, vol. 2, 300, 1992.

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