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Geomagnetic Activity Associated With Earth Passage of Interplanetary Shock Disturbances and Coronal Mass Ejections

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Coronal mass ejection events (CMEs) are important occasional sources of plasma and magnetic field in the solar wind at 1 AU, accounting for approximately 10% of all solar wind measurements in the ecliptic plane during the last solar activity maximum. Previous work indicates that virtually all transient shock wave disturbances in the solar wind are driven by fast CMEs. Using a recently appreciated capability for distinguishing CMEs in solar wind data in the form of counterstreaming solar wind electron events, this paper explores the overall effectiveness of shock wave disturbances and CMEs in general in stimulating geomagnetic activity. The study is confined to the interval from mid-August 1978 through mid-October 1982, spanning the last solar activity maximum, when ISEE 3 was in orbit about the L1 Lagrange point 220 R_e upstream from Earth. We find that all but one of the 37 largest geomagnetic storms in that era were associated with Earth passage of CMEs and/or shock disturbances, with the large majority of these storms (27 out of 37) being associated with interplanetary events where Earth encountered both a shock and the CME driving the shock (shock/CME events). Although CMEs and/or shock disturbances were increasingly the cause of geomagnetic activity as the level of geomagnetic activity increased, many smaller geomagnetic disturbances were unrelated to these events. Further, approximately half of all CMEs and half of all shock disturbances encountered by Earth did not produce any substantial geomagnetic activity as measured by the planetary geomagnetic index Kp. The geomagnetic effectiveness of Earth directed CMEs and shock wave disturbances was directly related to the flow speed, the magnetic field magnitude, and the strength of the southward (GSM) field component associated with the events. The initial speed of a CME close to the Sun appears to be the most crucial factor in determining if an earthward directed event will be effective in exciting a large geomagnetic disturbance.

INTRODUCTION

Coronal mass ejection events (CMEs) are spectacular manifestations of solar activity in which 10^{+15}–10^{+16} gms of solar material are suddenly propelled outward into interplanetary space (see *Hundhausen* [1988] and *Kahler* [1987, 1988] for recent reviews). CMEs are commonly associated with other forms of solar activity such as eruptive prominences and solar flares [e.g., *Gosling et al.*, 1974; *Munro et al.*, 1979] and have outward speeds at distances of several solar radii above the solar surface ranging from less than 50 km s^{-1} to greater than 1200 km s^{-1} [e.g., *Gosling et al.*, 1976; *Howard et al.*, 1985].

The leading edges of the faster CMEs have outward speeds considerably greater than that associated with the normal solar wind expansion. When the speed difference between a CME and the ambient solar wind ahead exceeds the local fast mode speed, a shock should form ahead of the CME. In fact, a nearly one-to-one correlation exists between large, fast CMEs detected by satellite coronagraphs and transient shock wave disturbances in the solar wind observed at roughly the same solar longitudes [*Sheeley et al.*, 1985]. Transient interplanetary shocks thus serve as useful fiducials for searching for plasma and/or field anomalies by which one might uniquely identify CMEs in the solar wind. Over the years a number of plasma and field signatures have been identified which qualify as unusual compared to the normal solar wind but which are commonly observed a number of hours after shock passage (see, for example, reviews by *Schwenn* [1986] and *Gosling* [1990]). Of these anomalous signatures, perhaps the most common is a counterstreaming (along the interplanetary magnetic field (IMF)) flux of solar wind halo (suprathermal) electrons at energies above about 80 eV. Previous work indicates that counterstreaming solar wind halo electron events (also called bidirectional electron heat flux events) are also often observed without shock associations, and presumably identify CME events in the solar wind regardless of their speed relative to the ambient wind ahead [*Gosling et al.*, 1987]. The counterstreaming signature is an indication that CMEs in the solar wind at 1 AU typically are closed magnetic field structures (either rooted at both ends in the Sun or partially or entirely disconnected from it as either flux ropes or plasmoids). Such field topologies are consistent with the observation that CMEs generally originate in closed magnetic field regions in the solar atmosphere not previously participating directly in the solar wind expansion [e.g., *Hundhausen*, 1988].

As illustrated in Figure 1, high flow speeds and strong magnetic fields (often with strong southward components) are features common to most interplanetary disturbances driven by fast CMEs. There thus is good reason to believe that fast CMEs are the crucial links between solar activity and large, nonrecurrent geomagnetic storms. Indeed, prior to the direct detection of CMEs by satellite-borne coronagraphs and their identification in solar wind data, the existence of CME-like events had been inferred from ground-based studies of geomagnetic storms (see, for

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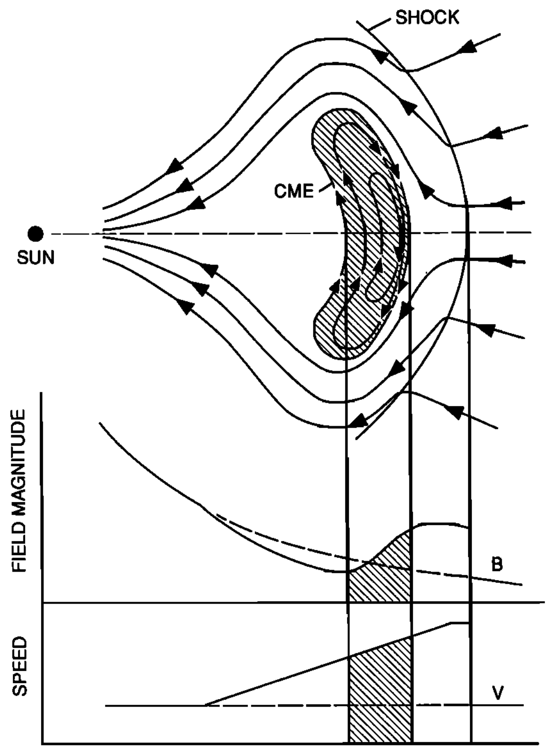

Fig. 1. A sketch of a meridional cut through a hypothetical interplanetary shock wave disturbance driven by a very fast coronal mass ejection (CME) (above) and the corresponding radial variation of solar wind speed and field strength along the centerline of the disturbance (below). A reverse shock is possible near the rear of the disturbance, but has not been sketched. Observations suggest that shock disturbances typically are considerably broader in extent than the CMEs that drive them, somewhat as drawn. Thus the Earth does not always directly encounter the CMEs responsible for observed shock disturbances. Compression resulting from the relative motion between a fast CME and its surroundings produces strong magnetic fields in a broad region extending sunward from the shock to well within the leading portion of the CME itself. The ambient magnetic field drapes about the CME because CMEs generally originate in closed field regions in the corona not previously participating in the solar wind expansion. The strong fields and high flow speeds commonly associated with interplanetary disturbances driven by fast CMEs are what make such disturbances effective in stimulating geomagnetic activity.

example, *Chapman* [1964]), as well as from in situ observations of transient shock wave disturbances in the solar wind [e.g., *Hundhausen*, 1972].

We have previously documented the very strong association between large geomagnetic storms and transient interplanetary shock disturbances and CMEs (as distinguished by the counterstreaming electron signature) during the years spanning the last solar maximum (1978 - 1982) [*Gosling et al.*, 1990]. All but one of the largest geomagnetic storms in that era were caused by Earth passage of either a shock disturbance or a CME or both. Our purpose here is to present the results of a study exploring the overall geomagnetic effectiveness of all shock disturbances and all CMEs (as distinguished by the counterstreaming electron signature) in the 1978 - 1982 interval. The paper is complementary to a large body of work extending back to the days before direct measurements of the solar wind and in situ detection of CMEs were possible. Recent related work includes that documenting geomagnetic effects associated with Earth passage of magnetic clouds [*Wilson* 1987, 1990; *Zhang and Burlaga*, 1988], which form a small subset of all counterstreaming electron events [*Gosling*, 1990]. Additional related work includes that documenting geomagnetic activity associated with shock disturbances followed by helium abundance enhancements [*Borrini et al.*, 1982], as well as that correlating interplanetary parameters with geomagnetic activity for specific large storms [e.g., *Akasofu et al.*, 1985; *Gonzalez and Tsurutani*, 1987; *Tsurutani et al.*, 1988].

OBSERVATIONS

ISEE 3 was launched into orbit about the L1 Lagrange point approximately 220 R_e sunward of Earth in mid-August 1978. From then until the spacecraft was diverted into the distant geomagnetic tail in mid-October 1982 the Los Alamos plasma experiment [*Bame et al.*, 1978] and the Jet Propulsion Laboratory magnetic field experiment [*Frandsen et al.*, 1978] onboard returned almost continuous solar wind measurements well upstream from the Earth's bow shock. Counterstreaming solar wind electron events have been identified in the plasma data by scanning color-coded plots of solar wind electron angular distributions similar to those previously displayed (see, for example, *Gosling et al.* [1987]). Care was taken during the scanning process to eliminate counterstreaming events caused by magnetic connection to the Earth's bow shock [e.g., *Stansberry et al.*, 1988]. A total of 191 interplanetary counterstreaming events, which we henceforth equate with CMEs, were identified for the approximately 50-month interval prior to ISEE 3's passage into the geomagnetic tail. Although the events were distributed unevenly in time and had variable durations, the average occurrence rate was 3.9 events per month and the average event duration was 18 hours. Thus counterstreaming electron events constituted about 10% of all the solar wind measurements in the ecliptic plane at 1 AU during this interval of high solar activity. The above values are all somewhat larger than were obtained from our earlier study of just the 1978 and 1979 data [*Gosling et al.*, 1987].

In a similar fashion, plots of the high time resolution ISEE 3 plasma moments and magnetic field data were scanned in order to identify interplanetary shocks. A total of 171 forward shocks were identified in this survey. Most of these shocks passed ISEE 3 at times when the data record is complete. However, a small fraction of the shock events occurred during gaps in the data transmission; in such cases, shock passage has been inferred from examination of the plasma and field parameters on either side of the data gaps. Although it is possible that some shock events have been missed in our survey, we believe it is unlikely that we have misidentified many shock events. Whenever a shock passed ISEE 3 during a gap in the data transmission, we have assumed that it passed the spacecraft at a point midway within the gap. As with the counterstreaming electron events, the shock events were distributed unevenly in time. The average shock occurrence rate for the 50-month interval was 3.4 events per month.

In our earlier study of the 1978, 1979 interval we found that 49% of all the counterstreaming electron events were preceded within 36 hours by passage of a shock, with the average delay from shock passage to onset of counterstreaming being about 13 hours [*Gosling et al.*, 1987]. Only a minor fraction of the events had delays greater than 24 hours. In the present study, covering the much longer interval through mid-October 1982, we find that only 32% of the counterstreaming electron events were preceded by a shock within 24 hours. On the other hand, as in the previous study, we find that 36% of all the shocks observed were followed by counterstreaming electron events within 24 hours. These statistics can be interpreted to mean that: (1) many CMEs do not have sufficiently high speeds relative to the ambient solar wind ahead to produce shock disturbances at 1 AU; and (2) the typical shock disturbance at 1 AU is considerably broader than the CME that drives it (see Figure 1).

A variety of indices are available that attempt to quantify the level of geomagnetic activity present at any particular time. Of these, one of the most commonly used, and the one incorporated in the present study, is the planetary 3-hour index, *Kp*. This index of activity is derived from geomagnetic perturbations detected at 12 magnetic observatories, all located at magnetic latitudes between 48 and 63 deg [e.g., *Chapman*, 1964]. Tabulated values of *Kp* range from 0_0 up to 9_0, in 28 steps. Figure 2 provides a plot of the distribution of *Kp* for all of the data within the 50-month interval of the present study. The most probable value of *Kp* was 2_+, while only 8.7% of the *Kp* values in this time interval were greater than or equal to 5_-.

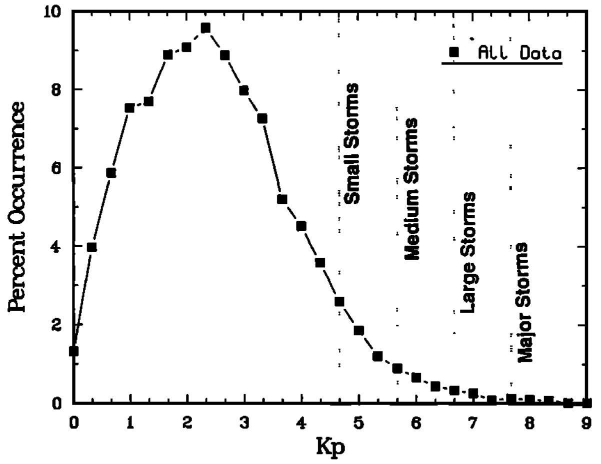

Fig. 2. Plot of the occurrence frequency of the geomagnetic index *Kp* for the entire 50-month interval spanning the last solar maximum, August 15, 1978 - October 17, 1982. Vertical lines and labels indicate lower limits used in defining various storm categories.

As in our previous study [*Gosling et al.*, 1990], we define a major geomagnetic storm to be one where the maximum value of *Kp*, *Kp*-max, is greater than or equal to 8_- and where $Kp \geq 6_-$ for at least three 3-hour intervals during a 24-hour period. Similarly, we define a large storm to be one where $7_- \leq Kp\text{-max} \leq 7_+$ and where $Kp \geq 6_-$ for at least three 3-hour intervals during a 24-hour period. These definitions thus include requirements on both disturbance amplitude and duration. We also define medium geomagnetic storms to be all other disturbances for which $Kp\text{-max} \geq 6_-$, and small geomagnetic storms to be disturbances for which $5_- \leq Kp\text{-max} \leq 5_+$. Note that these latter two definitions make no requirement with regard to disturbance duration. Thus medium and small storms can be, and often are, of shorter duration than large and major storms. A number of events in these latter two categories, particularly in the small storm category, probably more properly qualify as substorms [e.g., *Akasofu*, 1964]. The lower limiting *Kp* values used in the above definitions of storm categories are indicated by vertical lines and labels in Figure 2.

Using the above definitions of geomagnetic disturbance level, we have identified 14 major, 23 large, 84 medium, and 206 small geomagnetic storms during the time interval from mid-August 1978 through mid-October 1982. (In our earlier study [*Gosling et al.*, 1990] we failed to recognize three large geomagnetic storms, those of July 25-26, 1980, November 20-21, 1981, and July 11-13, 1982. Statistics for those storms are included in the present study).

Figure 3 summarizes the associations we have found between geomagnetic storms in our four defined categories and Earth passage of interplanetary shock disturbances and CMEs (as distinguished by the counterstreaming electron signature). All 14 of the major storms were associated with Earth passage of shock disturbances, and in 13 of these storms the Earth also encountered the CME driving the shock (shock/CME events). Of the 23 events in the large storm category, 14 were associated with Earth passage of shock/CME events, four were associated with shock disturbances where the Earth did not encounter the CME driving the shock, four were associated with Earth passage of CMEs not driving shocks, and only one was associated with neither a shock disturbance nor a CME. If we make the reasonable assumption that the shocks lacking direct associations with counterstreaming electron events were driven by CMEs which did not encounter ISEE 3 or Earth,

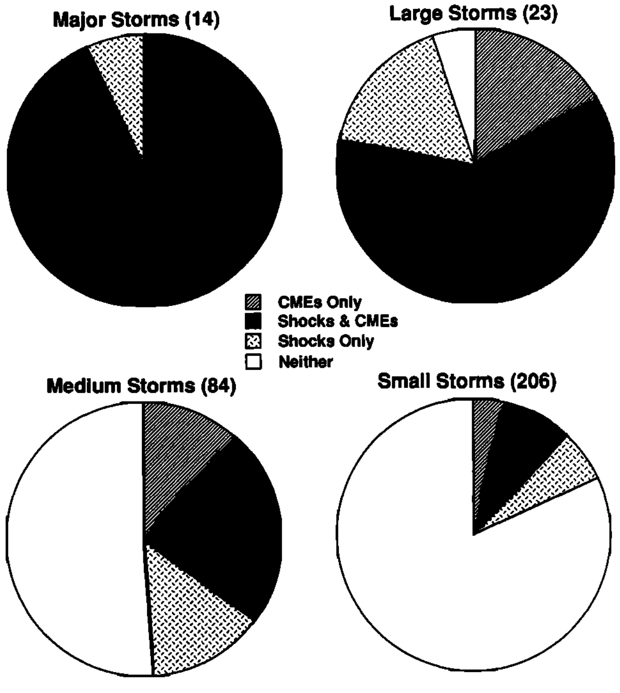

Fig. 3. Pie charts illustrating the association of major, large, medium, and small geomagnetic storms with Earth passage of shock disturbances and coronal mass ejection events (CMEs) during the interval August 15, 1978 - October 17, 1982, spanning the last solar maximum. The numbers in parentheses indicate the number of storms in each category.

then large and major storms during the interval surrounding the last solar maximum were, with one exception, caused by Earth passage of interplanetary disturbances driven by CMEs. Shock/CME events were particularly effective in producing major and large geomagnetic storms, accounting for 27 out of 37 storms in those categories.

On the other hand, Figure 3 also demonstrates that medium and small storms during this era were less strongly associated with CME-driven interplanetary disturbances. Although many CME-related interplanetary disturbances produced medium and small geomagnetic storms, with shock/CME events being more effective than shock disturbances or CME events alone, slightly more than half of all the medium storms had neither a CME nor a shock disturbance association, while about 82% of the small storms lacked such associations. Thus the majority of these lesser geomagnetic disturbances had other origins.

Figure 4 summarizes the overall geomagnetic effectiveness of CMEs and shock disturbances in a slightly different fashion. In constructing the figure we have assumed that an interplanetary event was geomagnetically effective only if it produced Kp-max $\geq 5_{-}$, and was geomagnetically ineffective otherwise. According to this criterion, 44% of all CMEs, and 53% of all shock disturbances encountering the Earth were geomagnetically effective. However, 85% of all events in which the Earth encountered both a shock and the CME driving it were geomagnetically effective. Thus not only were events in this last category responsible for exciting a large fraction of all major and large geomagnetic storms, but they were also usually effective in stimulating some sort of geomagnetic disturbance

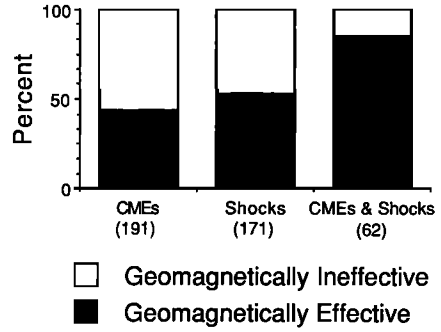

Fig. 4. Bar graph indicating the geomagnetic effectiveness of shock disturbances, CMEs, and shock/CME events in the interval spanning the last solar maximum. The numbers in parentheses indicate the number of interplanetary events in each category. The different types of events are not mutually exclusive.

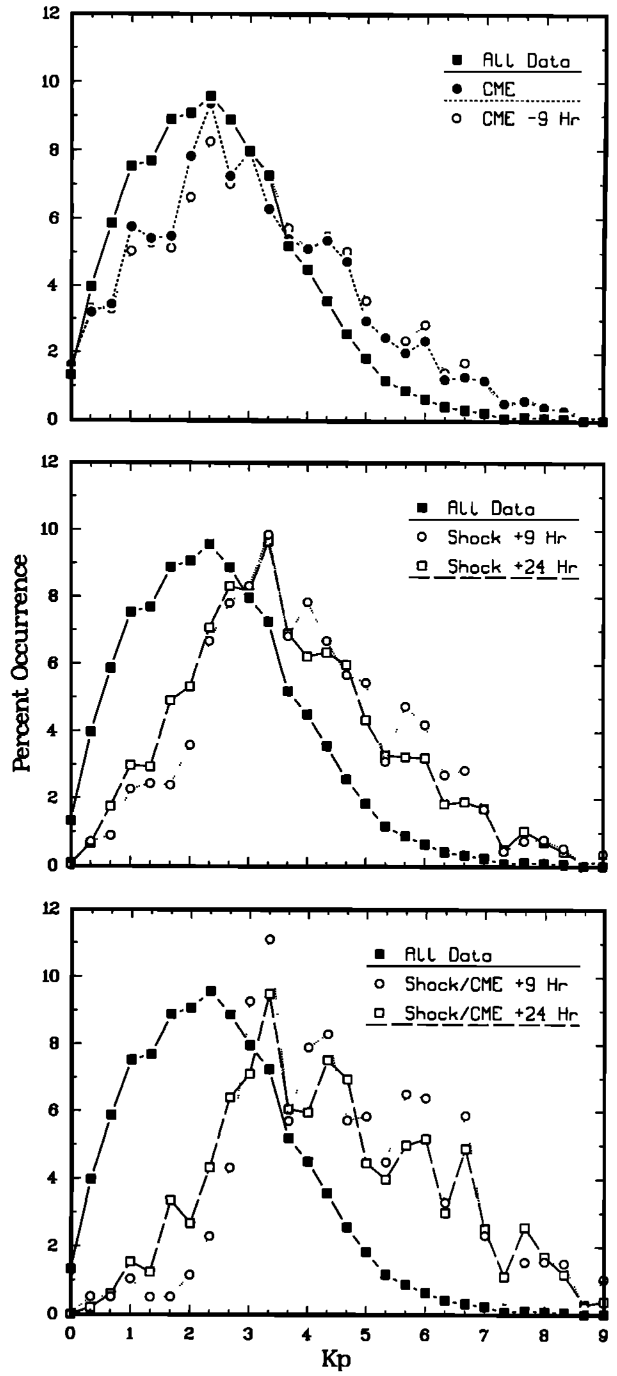

Fig. 5. Plots of the occurrence frequency of the geomagnetic index Kp for different interplanetary conditions in the interval spanning the last solar maximum. Event categories are not mutually exclusive from one panel to the next. See text for explanation.

Figure 5 provides an alternate approach to examining geomagnetic effects associated with Earth passage of interplanetary shock disturbances and CMEs. Each panel of Figure 5 shows a set of plots of the relative occurrence frequency of Kp values for different interplanetary conditions. (In constructing these plots we have not attempted to account for the lag between ISEE 3 and Earth because the lag was generally short compared to the 3-hour binning of Kp values. Typical lags were of the order of 30–45 min, depending on the actual spacecraft position relative to Earth and the instantaneous flow speed of the solar wind.) In each panel the distribution of Kp for all of the data, already presented in Figure 2, is indicated by the filled squares.

The upper panel of Figure 5 compares the distribution of Kp values for all of the data with that for the intervals of Earth passage of CMEs (which, on the average, lasted for 18 hours) as well as that of the CMEs plus the preceding 9 hours. Our rationale for including the latter in the comparison is the recognition that the ambient plasma ahead of many CMEs is often compressed by motion of the CME relative to it (see Figure 1), and is also often geomagnetically effective (see, for example, *Gosling et al.* [1990]; *Gonzalez and Tsurutani* [1987]; *Tsurutani et al.* [1988]). There is nothing special about a 9-hour lead time other than it approximates the average delay from shock passage to CME arrival for shock/CME events. Roughly, the same result is obtained when we use lead times of (say) 6 or 12 hours. We note that the CME and CME - 9-hour distributions are nearly identical and that both peak at a Kp value of 2_+, as does that for all of the data. On the other hand, both the CME and CME - 9-hour distributions are skewed somewhat toward higher values of Kp, with approximately 22% of the Kp values being greater than or equal to 5_- for each (as compared to 8.7% for all of the data). Thus high values of Kp occurred 2.5 times more frequently during Earth passage of CMEs and the ambient plasma immediately ahead than for all of the data. Nevertheless, relatively low values of Kp were quite common during Earth passage of CME plasma and that immediately ahead. This clearly indicates that many CMEs, or portions thereof, were relatively ineffective in stimulating anything but very minor geomagnetic activity.

The middle panel of Figure 5 makes a similar comparison of the distribution of Kp values for all of the data with that following shock passage by 9 and by 24 hours respectively. Both of the postshock distributions peak at a Kp value of 3_+ and are much more strongly skewed toward high values of Kp than is that for all of the data. For example, values of Kp greater than or equal to 5_- occurred 3.9 times more frequently for the +9-hour data and 3.3 times more frequently for the +24-hour data than for all of the data. On the other hand, Kp values less that 2_+ occurred 3.6 times more frequently for all of the data than for the +9-hour data and 2.4 times more frequently for all of the data than for the +24-hour data. It thus is apparent that (1) geomagnetic activity was often substantially enhanced following shock passage, with the probability of enhanced activity being somewhat greater in the first 9 hours following shock passage than at later times, and (2) shock disturbances (which we assume were driven by CMEs) were more effective than CMEs in general in stimulating geomagnetic activity. Despite the above, it was nevertheless true that geomagnetic activity, as measured by Kp, was not always significantly enhanced in the hours following shock passage.

Finally, the bottom panel of Figure 5 provides a comparison of frequency of occurrence plots of Kp for all of the data and for shock/CME events. As in the middle panel, the plots for the latter events cover intervals extending 9 and 24 hours respectively following shock passage. Although the distributions for the shock/CME events peak at the same value (3_+) as did that for the entire shock set (middle panel), they are even more strongly skewed toward high values of Kp. Values of Kp greater than or equal to 5_- occurred 5.4 times as frequently for the +9-hour data and 5.0 times as frequently for the +24-hour data than for all of the data. On the other hand, values of Kp less than 2_+ occurred 10.3 times as frequently for all of the data than for the +9-hour data and 4.6 times as frequently for all of the data than for the +24-hour data. Clearly, shock disturbances in which the Earth also encountered the CMEs driving the shocks were highly effective in stimulating geomagnetic activity.

Figure 5 is useful for demonstrating the relative geomagnetic effectiveness of CMEs and shock disturbances as compared to all solar wind conditions, but, since the distributions displayed there are all normalized on a percent occurrence basis, they do not directly show the fraction of any particular Kp value that was associated with CMEs and shock disturbances in the 1978-1982 interval. The plots shown in Figure 6 provide that information for the same event categories as in Figure 5. Although CMEs accounted for approximately 10% of all the data, we see in the upper panel that they accounted, for example, for only 6.8% of all Kp values of 1_0, but for 14.4% of all Kp values of 5_0 and 50.0% of all Kp values of 9_-. Similarly, although the 24-hour intervals following passage of interplanetary shocks accounted for approximately 11% of all the data, they accounted for only 4.4% of all Kp values of 1_0, but 26.7% of

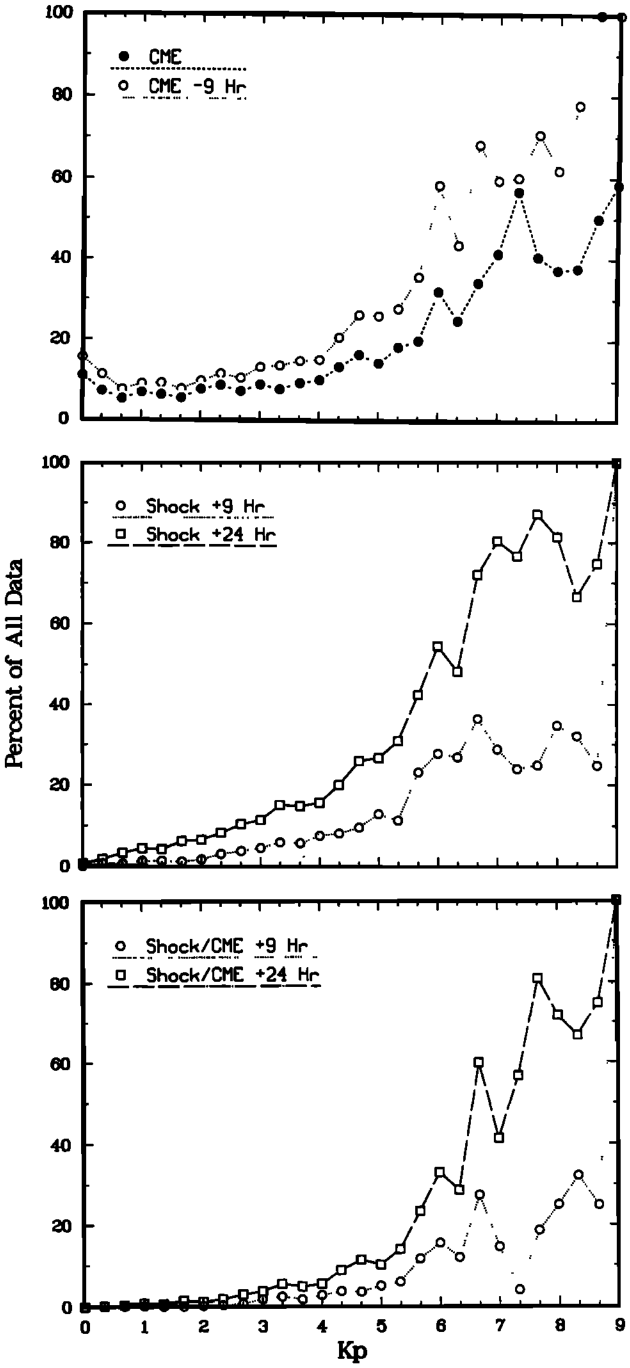

Fig. 6. Plots of the percent of all Kp values associated with different transient interplanetary disturbance event intervals. Event categories are as in corrresponding panels of Figure 5 and are not mutually exclusive from one panel to the next.

all Kp values of 5_0 and 74.8% of all Kp values of 9_-. In general, an increasing fraction of all Kp values were associated with Earth passage of CMEs and shock disturbances as Kp increased. However, CMEs and shock disturbances accounted for a nonzero fraction of any Kp value at all levels of geomagnetic activity.

Examination of the detailed solar wind plasma and field data for transient shock disturbances and CME events reveals why some of these events were geomagnetically effective while others were not. In general, geomagnetically effective interplanetary events had high flow speeds and strong magnetic fields, with the field being strongly southward at least some of the time. Figures 7 and 8 show plots of the occurrence frequency of different solar wind speeds, magnetic field magnitudes, and north-south field components (GSM coordinates) for CME events plus the preceding 9-hour intervals (Figure 7) and for 24-hour intervals following shocks (Figure 8). In constructing these figures we have used 1-hour averaged solar wind data obtained from the Omni solar wind data base provided by the National Space Science Data Center. In each panel the data have been binned on the basis of the storm categories previously defined. That is, the events have been separated according to whether they produced a major storm, a large storm, a medium or small storm (other storm), or no storm at all. For comparison purposes, occurrence frequency distributions for all of the solar wind data for the entire solar maximum interval are also shown. Similar plots were constructed for the other event intervals used in constructing Figures 5 and 6. However, all of these plots have roughly the same appearance as the ones presented in Figures 7 and 8 and thus are not reproduced here.

In both figures the speed distributions are skewed toward ever higher flow speeds as the severity of the geomagnetic disturbances produced by the interplanetary events increased. For example, speeds above 550 km s^{-1} were common for events which produced major and large geomagnetic storms. Such speeds occurred 6.0 times as frequently for CME events that produced major geomagnetic storms and 5.6 times as frequently for shock events that produced such storms than for all of the data. The occurrence frequency distribution for those shock disturbances that did not produce storms (Figure 8) is nearly identical to that for all of the data, while the occurrence frequency distribution for those CMEs that did not produce storms (Figure 7) is actually shifted to lower speeds than is the distribution for all of the data. The latter result is consistent with the observation previously reported [*Gosling et al.*, 1987] that many CMEs, as distinguished by the counterstreaming electron signature, are found in the low-speed solar wind and have speeds comparable to or less than that of the ambient solar wind ahead. The present result indicates that such CMEs are generally geomagnetically ineffective, as expected.

The field magnitude distributions in Figures 7 and 8 are also generally skewed toward ever higher field strengths as the severity of the geomagnetic disturbances produced by the events increased. For example, field strengths above 10 nT were common for events which produced major and large storms, but were uncommon for the data set as a whole. Such field strengths occurred 5.6 times as frequently for the CME events that produced major geomagnetic storms and 5.8 times as frequently for the shock events that produced such storms than for all of the data. The occurrence frequency distributions for those events which did not produce

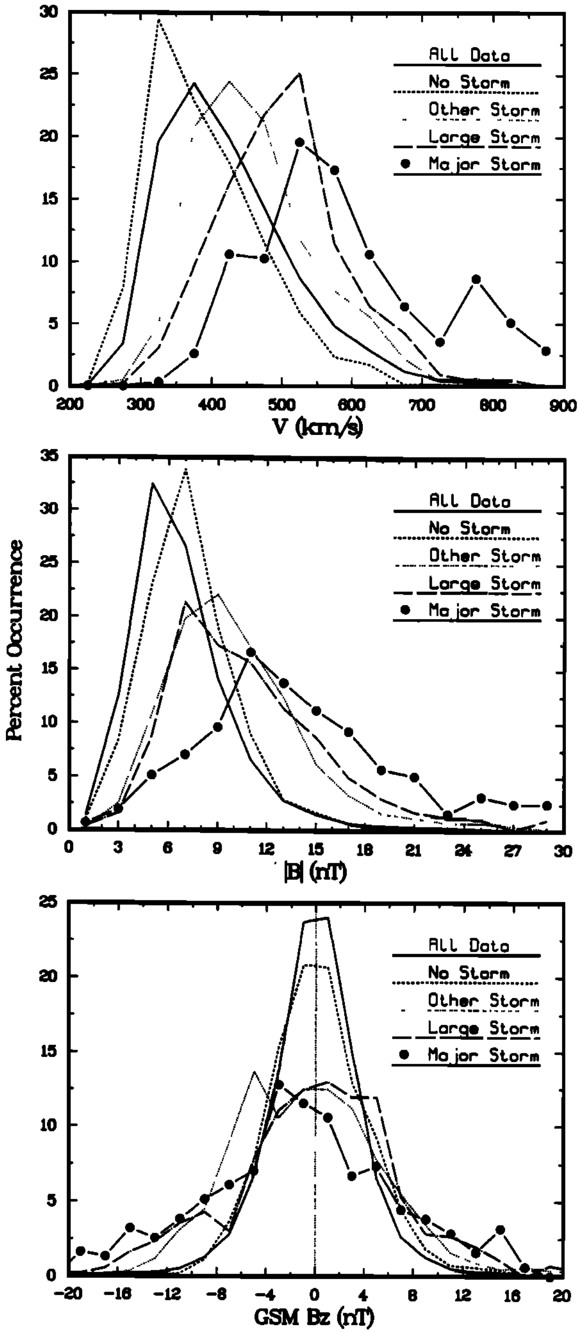

Fig. 7. Plots of the occurrence frequency of different solar wind speeds, interplanetary magnetic field strengths, and values of the north-south component of the field (GSM coordinates) for all CME events plus the preceding 9 hours of data. The CME events have been separated according to the type of geomagnetic disturbance they produced. For comparison, occurrence frequencies for all the solar wind data are also shown. The plots utilize 1-hour averages of the interplanetary data.

geomagnetic storms are both slightly more skewed toward higher field strengths than is that for all of the data. The small skewing of the no storm, CME distribution (Figure 7) is consistent with the observation that even slow CMEs which do not interact strongly with the ambient solar wind ahead generally have somewhat higher than normal internal field strengths at 1 AU [*Gosling et al.*, 1987], while the small skewing of the no storm, shock distribution (Figure

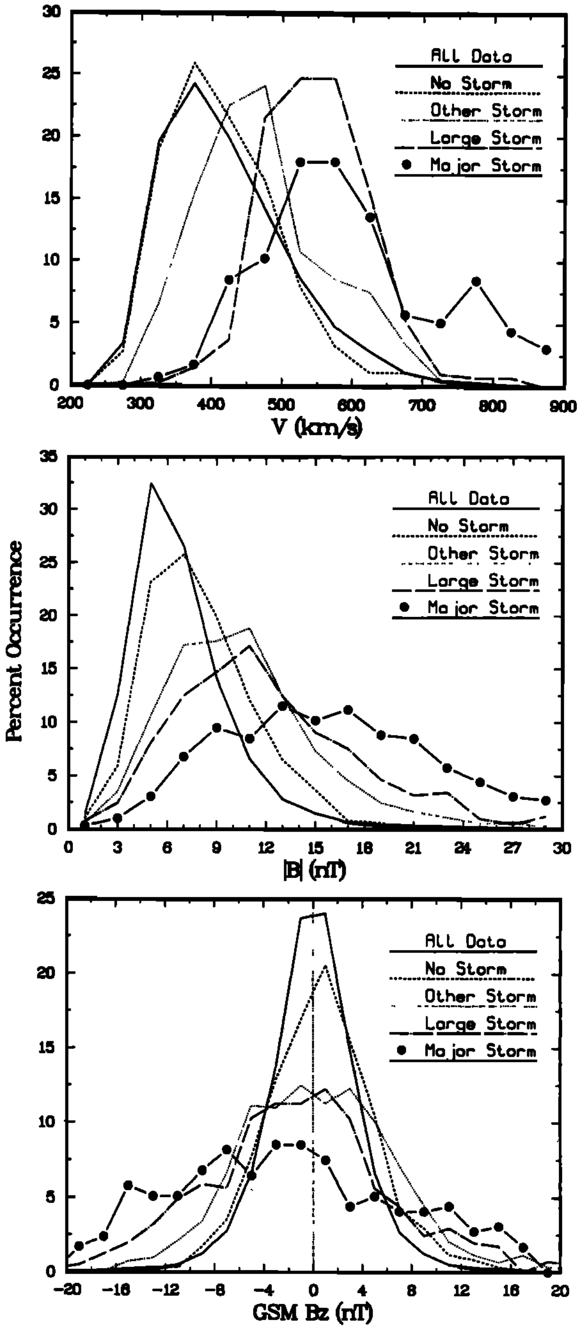

Fig. 8. Same as Figure 7, but for the 24-hour intervals following shock passages.

8) reflects the fact that all shocks produce at least some compression of the interplanetary magnetic field.

Finally, the B_z occurrence frequency distributions in Figures 7 and 8 tend to be skewed toward ever higher field strengths, both positive and negative, as the severity of the geomagnetic disturbances produced by the events increased. For example, values of $|B_z| > 8$ nT occurred 7.1 times as frequently for the CME events that produced major geomagnetic storms and 10.0 times as frequently for the shock events that produced such storms than for all of the data as a whole. What is perhaps surprising to those accustomed to relating geomagnetic activity to strong negative B_z is the lack of a strong asymmetry in the distribution of large negative and large positive values of B_z for events which produced geomagnetic storms, although an asymmetry does in fact exist for both the CME and the shock disturbance events for all storm categories. The explanation for the relatively modest asymmetry lies in the fact that events which produce geomagnetic storms generally do not contain strong southward (negative B_z) fields throughout (see also *Gonzalez and Tsurutani* [1987]). Although most events which produced geomagnetic storms, and virtually all events which produced major and large storms, contained some regions with strong negative B_z, the field orientation typically was variable, particularly within the compressed ambient plasma behind the shocks [e.g., *McComas et al.*, 1989] but also within the CMEs themselves.

DISCUSSION

In the present paper we have explored the overall geomagnetic effectiveness of shock disturbances and CMEs in the 1978-1982 interval spanning the last solar maximum. The study has taken advantage both of a newly appreciated capability for distinguishing CMEs in solar wind data (counterstreaming solar wind halo electron events), as well as the availability of an extensive and nearly complete solar wind data set for the years of interest.

We have found that all but one of the 37 largest geomagnetic storms in the 1978-1982 era were associated with Earth passage of either a shock disturbance or a CME or both. (See also *Gosling et al.* [1990], as well as *Gosling et al.* [1987], *Gonzalez and Tsurutani* [1987], *Tsurutani et al.* [1988] for discussions of the more limited 1978, 1979 interval.) Events in which the Earth encountered both a shock and the CME driving it (shock/CME events) were particularly effective in producing very large storms. In general, shock disturbances and CMEs were increasingly the cause of geomagnetic activity as the level of geomagnetic disturbance increased. Nevertheless, we have also found that many of these interplanetary events were relatively ineffective in stimulating geomagnetic activity. As might be expected on the basis of previous studies relating geomagnetic activity to solar wind variations in general (see, for example, reviews by *Russell and McPherron* [1973], *Akasofu* [1981], and *Baker et al.* [1984]), the level of geomagnetic activity stimulated by Earth passage of a shock disturbance or CME was related directly to the magnitude of the flow speed, magnetic field strength, and southward field component associated with the event.

It is worth emphasizing that our results pertain only to the interval near solar maximum. We have not yet had the opportunity to extend this type of analysis to other phases of the solar cycle. In fact, such an extension is not possible with the ISEE 3 data since the spacecraft spent most of 1983 in the geomagnetic tail and was then directed ahead of the Earth in orbit about the Sun toward an encounter with comet Giacobini-Zinner. On the basis of much previous work, we would expect to find that shock disturbances and CMEs are much less important causes of geomagnetic activity during the declining phase of solar activity and near solar activity minimum. In those years geomagnetic storms tend to be recurrent at the rotation period of the Sun and are associated primarily with Earth passage of quasi-stationary, corotating high-speed solar wind streams [e.g., *Snyder et al.*, 1963] which originate in coronal holes [e.g., *Krieger et al.*, 1973]. The present work does establish that such streams made a relatively unimportant contribution to overall geomagnetic activity in the years surrounding the last solar maximum.

It is, of course, by now no mystery why fast CMEs and associated shock disturbances can be so effective in creating large geomagnetic disturbances. Solar wind energy is transferred into the magnetosphere primarily via magnetic reconnection at the dayside magnetopause [e.g., *Dungey*, 1961], which favors strong southward directed interplanetary magnetic fields. Compression in interplanetary space, which results when fast-moving CMEs overtake slower moving ambient plasma ahead, serves to elevate the magnetic field strength both within the ambient plasma as well as within the leading portion of the CME itself (see Figure 1). A large southward IMF component, the essential element in enhanced dayside reconnection, is more likely, of course, when the total IMF is strong. In addition, the rate of reconnection at the magnetopause is thought to depend upon the magnitude of the interplanetary convective ($\mathbf{V} \times \mathbf{B}$) electric field. Since both the solar wind velocity $\mathbf{V}$ and the interplanetary magnetic field $\mathbf{B}$ tend to be high within the leading portions (first ~24 hours) of interplanetary disturbances driven by fast CMEs, so too does the convective electric field. Finally, the speed differential between a fast CME and the ambient solar wind ahead is essential for producing draping of the ambient IMF about the CME. As illustrated in Figure 1, such draping can help produce a strong southward directed IMF in the compressed ambient plasma ahead of a fast CME even when the ambient plasma ahead of the shock does not contain a substantial out-of-the-ecliptic component [e.g., *Gosling and McComas*, 1987; *McComas et al.*, 1989]. (*Tsurutani et al.* [1988] mention additional possibilities.) All of these effects should be strongest near the centerlines of CME-driven disturbances, thus explaining why shock/CME events are so effective in exciting geomagnetic disturbances. Given the above, it also should be no mystery why slow CMEs and relatively minor shock disturbances fail to stimulate any significant geomagnetic activity.

It should be apparent from the above that it is the initial speed of a CME relative to the ambient solar wind ahead that ultimately is probably the most important factor in determining if an earthward directed CME will be geomagnetically effective. As we have noted, a speed differential appears to be essential for producing very strong magnetic fields in transient interplanetary disturbances at 1 AU. It is also essential for allowing draping to proceed ahead of CMEs. Measurements of initial CME speed and direction should therefore be the crucial elements in any attempt to make accurate real-time predictions of the geomagnetic consequences of solar activity. CME speeds close to the Sun are relatively easy to determine from observations with spaceborne coronagraphs. Unfortunately, as coronagraphs observe CMEs projected against the plane of the sky, it is extremely difficult even to detect earthward directed CMEs, much less determine their speeds, with coronagraph observations near Earth. This barrier to the accurate, long-term (one or more days) prediction of geomagnetic disturbances associated with solar activity could be overcome by placing coronagraphs in orbit about the Sun well ahead of and behind the Earth in its orbit, possibly at the L4 and L5 Lagrange points. Such a system, when coupled with in situ solar wind measurements at L1, would allow quite accurate long and short term prediction of geomagnetic activity.

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