A PICTORIAL COMPARISON OF INTERPLANETARY MAGNETIC FIELD POLARITY, SOLAR WIND SPEED, AND GEOMAGNETIC DISTURBANCE INDEX DURING THE SUNSPOT CYCLE

N. R. SHEELEY, JR.*
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20375, U.S.A.

J. R. ASBRIDGE and S. J. BAME
University of California, Los Alamos Scientific Laboratory, Los Alamos, N. M. 87545, U.S.A.

J. W. HARVEY
Kitt Peak National Observatory**, Tucson, Arizona 85726, U.S.A.

(Received 25 October, 1976)

Abstract. Observations of interplanetary magnetic field polarity, solar wind speed, and geomagnetic disturbance index (C9) during the years 1962–1975 are compared in a 27-day pictorial format that emphasizes their associated variations during the sunspot cycle. This display accentuates graphically several recently reported features of solar wind streams including the fact that the streams were faster, wider, and longer-lived during 1962–1964 and 1973–1975 in the declining phase of the sunspot cycle than during intervening years (Bame et al., 1976; Gosling et al., 1976). The display reveals strikingly that these high-speed streams were associated with the major, recurrent patterns of geomagnetic activity that are characteristic of the declining phase of the sunspot cycle. Finally, the display shows that during 1962–1975 the association between long-lived solar wind streams and recurrent geomagnetic disturbances was modulated by the annual variation (Burch, 1973) of the response of the geomagnetic field to solar wind conditions. The phase of this annual variation depends on the polarity of the interplanetary magnetic field in the sense that negative sectors of the interplanetary field have their greatest geomagnetic effect in northern hemisphere spring, and positive sectors have their greatest effect in the fall. During 1965–1972 when the solar wind streams were relatively slow (500 km s\(^{-1}\)), the annual variation strongly influenced the visibility of the corresponding geomagnetic disturbance patterns.

1. Introduction

In a recent paper, Sheeley et al. (1976) compared observations of coronal holes, solar wind speed, and geomagnetic activity during the declining phase of the sunspot cycle (1973–1975) in a Bartels-type format which emphasized the evolution of 27-day recurrent patterns. The striking similarity of the resulting patterns of coronal holes, high speed solar wind streams, and recurrent geomagnetic

* Visiting Scientist, Kitt Peak National Observatory, Tucson, Arizona.
** Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Solar Physics 52 (1977) 485–495. All Rights Reserved
Copyright © 1977 by D. Reidel Publishing Company, Dordrecht-Holland

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
disturbances reinforced the notion that coronal holes are the source of the streams and their associated geomagnetic disturbances.

Now this study has been extended into the past to include observations over an entire sunspot cycle. Observations of the polarity of the interplanetary magnetic field, the solar wind speed, and the geomagnetic activity during 1962–1975 are compared here, and x-ray and XUV photographic observations of coronal holes during 1963–1974 will be summarized in a following paper by Broussard et al. (1977).

The results of this paper in a sense serve to ‘calibrate’ the geomagnetic response to solar wind variations. By using the C9 index which has been tabulated since 1884, it may be possible to infer the presence of both the high-speed solar wind streams and the coronal holes in which they originated during the past eight sunspot cycles. In particular, by using the combined observations of interplanetary magnetic field polarity, solar wind speed, and C9 index during 1962–1975, it may be possible to deduce the presence of some coronal holes during the active phase of the last sunspot cycle when coronal hole observations were relatively sparse.

2. The Observations

Figure 1 compares observations of the polarity of the interplanetary magnetic field (left), the speed of the solar wind (center), and geomagnetic activity (right) in the well-known 27-day Bartels format. The measurements begin on August 27, 1962 in the upper left corner of each section, and proceed left-to-right in daily steps and downward in 27-day rows ending with February 8, 1976 in the lower right corner of each section. The uniformly-spaced marks along each section indicate the position of the first complete Bartels rotation of each year beginning with rotation 1772 (January 9, 1963) and ending with rotation 1948 (January 13, 1976).

In the left section, the polarity of the interplanetary magnetic field is indicated by one of three colors – light yellow for positive polarity (away from the Sun), light brown for negative polarity (toward the Sun), and light purple for mixed polarity. These observations were obtained through the courtesy of Dr. L. Svalgaard (1975, 1976).

In the center section, daily solar wind bulk speed (rounded off to the nearest hundred km/sec) is displayed with the color coding:

<table>
<thead>
<tr>
<th>Color</th>
<th>Speed (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dark blue</td>
<td>300</td>
</tr>
<tr>
<td>light blue</td>
<td>400</td>
</tr>
<tr>
<td>reddish brown</td>
<td>500</td>
</tr>
<tr>
<td>dark yellow</td>
<td>600</td>
</tr>
<tr>
<td>light yellow</td>
<td>700</td>
</tr>
<tr>
<td>white</td>
<td>800</td>
</tr>
<tr>
<td>black</td>
<td>no observations</td>
</tr>
</tbody>
</table>
Fig. 1. Comparison of the polarity of the interplanetary magnetic field, the speed of the solar wind, and geomagnetic activity (C9) during the years 1962–1976. The color coding is explained in the text. This figure shows the dominance of large-scale patterns of solar wind speed and recurrent geomagnetic activity during the declining phase of the sunspot cycle in 1973–1975 and in 1962–1964. This figure also shows that the correlation between geomagnetic activity and solar wind speed is modulated by an annual variation whose phase depends on the direction of the interplanetary field. Negative streams have their greatest geomagnetic effect in the spring and positive streams have their greatest effect in the fall.
In this section, all of the solar wind observations since July 1964 were obtained with Los Alamos Scientific Laboratory plasma analyzers on Earth-orbiting satellites, either in the Vela 2–6 series (1964–1972) or in the IMP 6–8 series (1971–1976).

In order to study the important interval 1962–1964 during the declining phase of the previous sunspot cycle, it was necessary to supplement this uniform set of Los Alamos measurements with observations obtained by other laboratories. The observations during 1962 were obtained with the Jet Propulsion Laboratory’s positive-ion spectrometer on the Mariner 2 flight to Venus (Neugebauer and Snyder, 1966). The observations during November 1963–February 1964 were obtained with the Massachusetts Institute of Technology’s ‘Faraday cup’ on the Earth-orbiting Satellite IMP 1 (Olbert, 1968). These measurements appear to be systematically lower than the other spacecraft measurements of solar wind speed. Consequently, in this study we have increased the IMP 1 values by 30% to obtain the same quantitative relation to geomagnetic activity that Snyder et al. (1963) found for the Mariner 2 observations.

Finally, we note for completeness that in Figure 1 of this paper the solar wind observations have been included directly without any Sun–Earth transformation. In contrast, in Figure 1 of Sheeley et al. (1976), the solar wind speed profile had been transformed back to the Sun for comparison with coronal holes before it was plotted in the Bartels-type format for comparison with geomagnetic disturbances. We have not yet compared these alternate presentations of solar wind speed in detail because the 1973–1975 and 1962–1975 observations have different display scales. Although it is possible that some temporal shifts by one day may be present, the large-scale patterns appear to have the same size and shape in both displays. Thus, either display technique would appear to be satisfactory for our present purposes.

In the right section of Figure 1, geomagnetic activity is represented by the daily geomagnetic character figures, C9, published by the Institut für Geophysik, Göttingen, Germany. This section is similar to the conventional C9 diagram except that values of the C9 index are indicated by a color code:

- light blue 0 or 1
- dark blue 2
- purple 3
- reddish brown 4
- yellowish brown 5
- dark yellow 6
- light yellow 7
- white 8 or 9

Since the same colors have been used to represent both the solar wind speed and the (larger) values of the C9 index, a general tendency for the patterns of solar wind speed to have the same color as the recurrent patterns of geomagnetic
activity would indicate an approximate quantitative correlation between these quantities. We shall see in Figure 1 that although corresponding patterns of solar wind streams and geomagnetic activity do tend to have the same color, in detail this color correspondence is modulated by an annual variation in the response of geomagnetic activity to solar wind conditions with a phase that depends on the polarity of the interplanetary magnetic field.

3. Results

Perhaps the most striking characteristic of the solar wind observations in the center section of Figure 1 is the presence of large-scale patterns of very high speed (600–800 km s\(^{-1}\)) during 1973–1975 (see also Bame et al., 1976; Gosling et al., 1976). Corresponding patterns of geomagnetic activity are visible in the right section of Figure 1, as has been discussed in detail by Sheeley et al. (1976). Such large-scale patterns of recurrent geomagnetic disturbances are characteristic of the declining phase of the sunspot cycle just prior to sunspot minimum (Bartels 1963). In fact, the right section of Figure 1 shows similar patterns of geomagnetic activity in 1962–1964 during the declining phase of the previous sunspot cycle. In the center section, the solar wind measurements during this earlier time are not complete, but they show that the corresponding large-scale patterns of very high speed (600–800 km s\(^{-1}\)) were also present during 1962–1964, as previously reported (Bame et al., 1976). This result suggests that pronounced patterns of very high-speed solar wind streams (and the coronal holes in which they originate) have accompanied the large-scale recurrent patterns of geomagnetic activity that have been observed during the declining phase of every sunspot cycle since 1884.

Figure 1 shows that recurrent patterns of high-speed solar wind and geomagnetic activity were also present during 1965–1972. However, these solar wind streams were generally slower, shorter-lived, and narrower than the ones observed during 1962–1964 and 1973–1975 (Bame et al., 1976; Gosling et al., 1976). Numerous gaps in the solar wind observations contribute to the difficulty of identifying these relatively slow and short-lived streams. The identification of these recurrent patterns is made even more difficult by the sporadic variations in both solar wind speed and geomagnetic activity that are produced by numerous solar flares during this active phase of the sunspot cycle.

To clarify these points, let us consider some specific examples in Figure 1. The center section shows two solar wind streams of comparable speed (500–600 km s\(^{-1}\)) during the fall of 1966. The left section shows that one of these streams occurred in a negative magnetic sector and the other occurred in a positive sector. The right section shows that the geomagnetic activity associated with the positive stream was more intense than the geomagnetic activity associated with the negative stream. A two-day interval of relatively intense flare-associated geomagnetic activity tends to connect the two recurrent patterns near their beginning.
A high-speed stream whose corresponding pattern of recurrent geomagnetic activity was relatively weak is visible during the late summer and early fall of 1965 in a negative magnetic sector. In contrast, the most prominent recurrent high-speed stream during 1965-1972 occurred during the spring of 1971 in a negative sector. Its associated geomagnetic activity was comparable to that obtained during the 1962-1964 and 1973-1976 eras. Remarkably, a 500 km s$^{-1}$ stream that was visible at this ‘longitude’ two Bartels rotations earlier produced relatively little geomagnetic activity (C9 $\sim$ 2). This stream was associated with the X-ray coronal hole observed by the American Science and Engineering Corporation rocket on November 24, 1970 (Krieger et al., 1973).

In summary, Figure 1 shows that when the speed of a recurrent solar wind stream is relatively high (600-800 km s$^{-1}$) as was common during 1962-1964 and 1973-1976, the corresponding pattern of recurrent geomagnetic activity is always clearly visible. However, when the speed is relatively low (500 km s$^{-1}$), the associated recurrent geomagnetic activity is sometimes intense enough to be clearly visible, but at other times so weak that it is lost in the background of ambient fluctuations of the field. Thus, the correlation of recurrent geomagnetic activity with solar wind streams must depend on the solar wind speed plus other factors.

One of these factors appears to be an annual variation of geomagnetic activity (Arnoldy, 1971; Burch, 1973; Russell and McPherron, 1973; Burton et al., 1975). Perhaps this effect is described most clearly by Paulikas and Blake (1976) who summarize: “The interaction between the solar wind and the magnetosphere is expected to be strongest when the magnetosphere is immersed in a southward-pointing interplanetary field. This occurs during northern hemisphere spring, when the Earth is in a negative sector of the interplanetary field, and in the fall when the Earth is in a positive sector of the interplanetary field.”

The sense of this correlation accounts for the behavior of the specific examples described in the paragraphs above: During the fall of 1966 a greater degree of geomagnetic activity was associated with the positive stream than with the similar negative stream. During the late summer and early fall of 1965 the negative stream was associated with relatively weak geomagnetic activity, whereas the relatively high-speed stream of negative polarity during the spring of 1971 was associated with intense geomagnetic activity. In the ecliptic, the AS&E coronal hole 'produced' a relatively low-speed (500 km s$^{-1}$) stream of negative polarity, which in November 1970 was associated with very weak geomagnetic activity.

We have attempted to place these results on a more rigorous semi-quantitative basis by considering all of the recurrent solar wind streams of at least 500 km s$^{-1}$ during 1962-1975, any part of which occurred in ‘equinoctial quarters’ centered on the dates March 21 and September 21. A solar wind stream was considered recurrent if it was visible on three or more consecutive Bartels rotations and if it had the same magnetic polarity on each appearance. (We chose three appearances rather than two appearances to decrease the number of cases resulting from the
chance alignment of sporadic, flare-related events.) Streams that appeared to be 'slanted' in the Bartels format were included provided that, in addition to the above criteria, their occurrence on consecutive Bartels rotations overlapped by at least one day.

We did not undertake the laborious task of systematically identifying all of the geomagnetic disturbances that were associated with solar flares, and excluding the corresponding solar wind streams from our list. However, we did exclude streams that overlapped in time with geomagnetic disturbances which we happened to know were associated with major flares, or which we suspected were associated with flares because the value of the C9 index was either excessive (C9 ≥ 8), or large (C9 ≥ 6) on one day but small (C9 ≤ 1) on the preceding and following days.

For each solar wind stream, we calculated an average speed for the duration of each Bartels rotation that the speed was at least 500 km s⁻¹. In each case, we calculated the corresponding average value of the C9 index for the same time interval. The averages obtained on consecutive Bartels rotations were treated independently despite the fact that they corresponded to the same solar wind stream. We separated the data into two classes depending on whether the annual effect of geomagnetic activity was likely to be large (negative IMF in the spring or positive IMF in the fall) or small (positive IMF in the spring or negative IMF in the fall). Finally, we plotted the average value of the C9 index versus the average wind speed in Figure 2.

Figure 2 supports our visual impression from Figure 1 that the intensity of the geomagnetic activity for a given solar wind stream depends on both the wind speed and the phase of the annual geomagnetic variation. In particular, there is a clear tendency for the closed circles that correspond to the phase of maximum geomagnetic response to be separated from the open circles that correspond to the phase of minimum geomagnetic response. We have sketched dashed straight lines independently through the sets of closed and open circles. These lines have the same slope, but are separated by almost two units of the C9 index. One can see that this two-unit difference is relatively important when the average wind speed is low. Thus, in Figure 1 the annual variation can significantly affect the visibility of recurrent geomagnetic disturbances associated with relatively slow solar wind streams.

Although we find Figure 2 useful for verifying our visual impressions of Figure 1, we place little value in the quantitative relations themselves for two reasons. First, the scatter of the points in Figure 2 is appreciable despite the separation of data into two independent classes. Second, it is undoubtedly an oversimplification to describe the solar wind-magnetosphere interaction in terms of any two parameters, much less in terms of our average values of C9 index and solar wind speed which were chosen for their convenience rather than their physical significance. This oversimplification may contribute as much scatter to the points in Figure 2 as other sources of error such as the inclusion of some flare-produced
Fig. 2. The average C9 index for a given solar wind stream plotted versus the average speed of that stream in units of 100 km s\(^{-1}\). These data have been separated into two classes depending on whether the annual effect of geomagnetic activity is expected to be large (closed circles – negative IMF in spring or positive IMF in fall) or small (open circles – positive IMF in spring or negative IMF in fall). This figure verifies our qualitative conclusion from Figure 1 that during 1962–1975 the geomagnetic effect of solar wind streams depended on both the stream speed and the phase of the annual geomagnetic variation.

geomagnetic disturbances and the artificial subdivision of the year into broad, quarterly phases of geomagnetic activity.

4. Discussion

Taken individually, most of the results described here are not new. In fact, the behavior of high-speed solar wind streams during the sunspot cycle has been studied recently by Bame et al. (1976) and Gosling et al. (1976) using the same measurements. The variation of geomagnetic activity during the sunspot cycle has been known for some time (for example, see Bartels, 1963), and its annual variation has been discussed extensively. (See Paulikas and Blake (1976) and references contained therein.) The approximate relation between solar wind speed and geomagnetic activity has also been known for some time (Snyder et al., 1963).
The new contribution of this paper is the combining of observations of IMF polarity, solar wind speed, and geomagnetic activity in a single display that emphasizes their associated variations during the sunspot cycle. Furthermore, as will be shown in a following paper by Broussard et al. (1976), this display is a useful format for studying the relationship between coronal holes and their interplanetary and terrestrial effects during an entire sunspot cycle.

We have seen that the response of the geomagnetic field to solar wind conditions is modulated by an annual variation whose phase depends on the polarity of the interplanetary magnetic field. This annual variation seems to be associated with the changing orientation of the geomagnetic dipole axis relative to the average spiral direction of the interplanetary magnetic field lines as the Earth orbits the Sun during the year (Burch, 1973). Thus, we would expect the annual variation to occur even under hypothetically constant conditions of solar wind speed and interplanetary magnetic field polarity at the Earth. However, these environmental conditions do not remain constant, but vary systematically in such a way that the geomagnetic response to them includes both $\frac{1}{2}$-year and 22-year periods in addition to the 27-day, 1-year, and 11-year periods that we have already discussed. These ideas have been summarized by Russell (1974).

It is possible to describe Figure 1 in terms of several phases of the sunspot cycle rather than simply the ‘declining years’ (1962–1964 and 1973–1975) and the ‘intervening years’ (1965–1972). In fact, the observations themselves suggest a subdivision of the ‘intervening years’ into three intervals, two of which (1965–1967.5 and 1970.5–1972) are characterized by relatively weak, narrow, short-lived recurrent patterns and one of which (1967.5–1970.5) is characterized by relatively sporadic variations. This latter interval coincided with the years of greatest sunspot activity and the years that the polar fields were apparently undergoing their 11-year reversal. Hence, this subdivision may well have a physical basis worthy of further study.

However, it is important to recognize that during the decade of the 1960’s the magnetic cycles of the northern and southern hemispheres were significantly out of phase with each other compared to their relative behavior during the past century (White and Trotter, 1977). Not only did the sunspot activity decline sooner in the southern hemisphere than in the northern hemisphere during the early 1960’s, but also the new activity started sooner in the northern hemisphere than in the southern hemisphere during the mid–1960’s. Similarly, the north polar field began its 11-year reversal sooner than the south polar field (Sheeley, 1976), as one might expect if the polar fields are produced by the transport of flux from its origin in bipolar magnetic regions of the sunspot belt (Babcock, 1961; Leighton, 1964). Furthermore, as will be shown in a following paper by Broussard et al. (1976), the intermittent disappearance of the polar coronal holes began almost two years earlier at the north pole than at the south pole. In summary, these facts place a limit on the temporal resolution with which it is possible to define phases of the sunspot cycle for the interpretation of Figure 1.
We conclude our discussion by noting that present theories of the solar wind-magnetosphere interaction are based on observations that were obtained primarily during 1964–1972 in the relative absence of the very high-speed solar wind streams that are characteristic of the declining phase of the sunspot cycle. Thus, it is not surprising that these theories stress the importance of the southward component of the interplanetary magnetic field (in magnetospheric coordinates) rather than the speed with which the solar wind convects this field to the magnetosphere (for example, see Garrett et al., 1974). In Figure 1, the striking correlation between the high-speed solar wind streams and the recurrent geomagnetic disturbances during the recent interval 1973–1975 suggests that the solar wind speed may be very important when it is large. Whether the speed itself is physically important, or whether the high-speed streams simply correlate with times of excess southward-directed field must await detailed studies of the 1973–1975 observations.

Acknowledgements

Two of us (N.R.S. and J.W.H.) began this research as participants in the Skylab Solar Workshop Series on Coronal Holes. The workshops are sponsored by NASA and NSF and managed by the High Altitude Observatory, National Center for Atmospheric Research. One of us (N.R.S.) would like to acknowledge the hospitality and support provided during his visit to the Kitt Peak National Observatory as well as to Dr R. Tousey and members of his staff at NRL for making this visit possible. Support for this work at NRL was received from NASA under DPR-S 60404 G. The work at Los Alamos was performed under the auspices of the U.S. Energy Research and Development Administration and supported in part by NASA. The Vela data were obtained from a joint program of the U.S. Department of Defense and ERDA, managed by the U.S. Air Force. We are grateful to Dr L. Svalgaard (Stanford) for observations of the sector polarity of the interplanetary magnetic field as well as for numerous helpful discussions. Finally, we appreciate the encouragement and interest of Dr W. C. Feldman (LASL) without which this work might never have been started.

References