CORONAL HOLES, SOLAR WIND STREAMS, AND RECURRENT GEOMAGNETIC DISTURBANCES: 1973–1976

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Abstract. Observations of coronal holes, solar wind streams, and geomagnetic disturbances during 1973–1976 are compared in a 27-day pictorial format which shows their long-term evolution. The results leave little doubt that coronal holes are related to the high-speed streams and their associated recurrent geomagnetic disturbances. In particular, these observations strongly support the hypothesis that coronal holes are the solar origin of the high-speed streams observed in the solar wind near the ecliptic plane.

1. Introduction

Using observations made during and prior to the Skylab mission (May 1973–February 1974), several authors have reported a measure of success in identifying coronal holes as the origin of solar wind high-speed streams and their associated recurrent geomagnetic disturbances (Krieger *et al.*, 1973, 1974; Neupert and Pizzo, 1974; Bell and Noci, 1975; Nolte *et al.*, 1976; Wagner 1975a, b, 1976a). In addition, Hansen *et al.* (1976) have extended the study to include a comparison of long-lived coronal structures and recurrent geomagnetic patterns in 1974. In general, these studies conclude that large, near-equatorial coronal holes are associated with high-speed streams in the ecliptic plane at 1 AU and their associated geomagnetic disturbances.

We have extended these studies to include the interval 1973–1976. Moreover, we have summarized our observations in a single, color-coded picture which compares the observations of coronal holes, solar wind streams, and geomagnetic disturbances in a familiar Bartels-type format. The striking similarity of the resulting patterns leaves little doubt that coronal holes are closely related to solar wind streams and their associated geomagnetic disturbances.

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2. The Observations

Although no single source of coronal hole observations was available for the entire interval January 1, 1973–February 8, 1976, most of the coronal hole data used in this study was derived from helium spectroheliograms. In general, this information was obtained either from Bohlin and Rubenstein's (1975) synoptic maps of coronal hole boundaries which were derived from NRL He II 304 Å spectroheliograms during the manned portions of the Skylab mission, or from KPNO He I 10 830 Å spectroheliograms which have been obtained since the end of the Skylab mission in February 1974. Both the He II 304 Å and He I 10 830 Å images indicate the location of coronal holes against the solar disk as areas in which the chromospheric network is relatively weak or absent (Tousey et al., 1973, 1974; Harvey et al., 1975a, b). Occasionally, wideband XUV images obtained with the NRL XUV monitor on Skylab were used to supplement the He II 304 Å observations. During the unmanned intervals (June 20–August 5, and September 22–November 26, 1973), coronal holes were identified using the published soft x-ray images obtained with the American Science and Engineering Corporation's ATM x-ray telescope (Nolte et al., 1975; Solodyna et al., 1976). Finally, Wagner's (1975a 1976b) synoptic maps of coronal holes, determined from Neupert's (1973) OSO-7 Fe xv 284 Å spectroheliograms, were used to fill in the interval between January 1, 1973 and the beginning of the Skylab mission in May 1973.

The bulk solar wind speed was measured with the Los Alamos Scientific Laboratory's plasma analyzers on the IMP 6, 7, and 8 spacecraft. Some of these data have already been published in another form (Bame et al., 1976; Gosling et al., 1976). Finally, geomagnetic activity was represented by the daily geomagnetic character figures, C9, published by the Institut Für Geophysik, Göttingen, Germany.

Figure 1 compares the observations of coronal holes, solar wind streams, and geomagnetic disturbances in the well-known 27-day Bartels format. The right section shows the geomagnetic activity, and is similar to the conventional C9 diagram except that increasing levels of geomagnetic disturbance are represented by progressively lighter shades of yellow. In this section, daily information begins with January 1, 1973 in the upper left corner and ends with February 8, 1976 in the lower right corner. The middle section indicates the daily average solar wind speed (rounded off to the nearest 100 km s^{-1}) by various colors, with the white corresponding to 800 km s^{-1} and the blue corresponding to 300 km s^{-1}. Black areas without entries indicate days for which measurements were not available, either because the spacecraft were inside the Earth's bow shock or, more recently, because the observations have not yet been reduced. In both the right and middle sections, the daily entries have been shaped to indicate the polarity of the interplanetary magnetic field measured at 1 AU (Svalgaard, 1975, 1976). A slant to the upper right corresponds to a positive (outward from the Sun) polarity, a slant
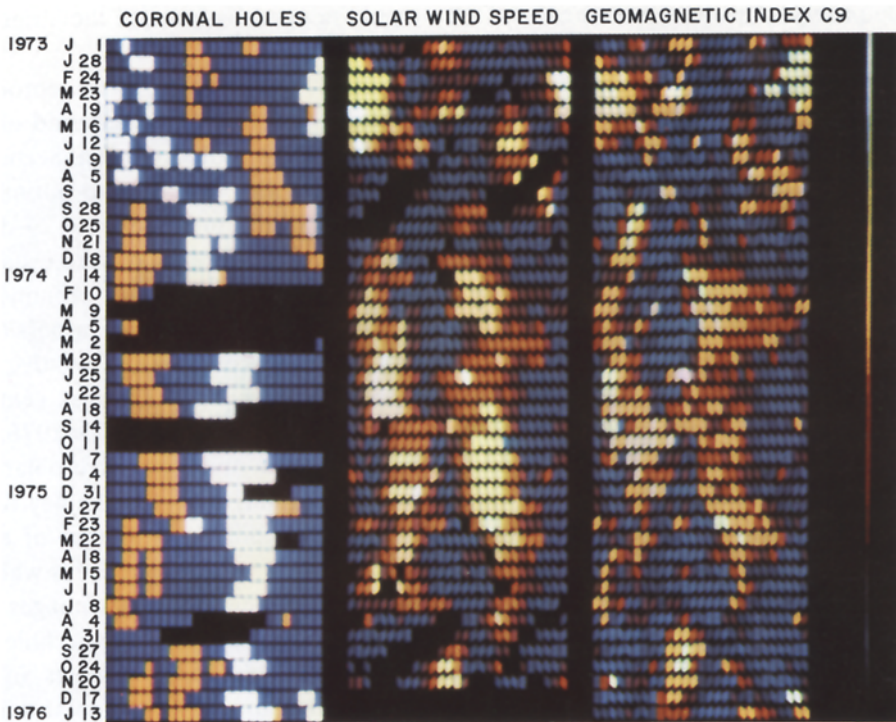
Fig. 1.   Comparison between coronal hole central-meridian-passage dates (plus 3 days), solar wind speed, and the C9 geomagnetic disturbance index for the interval January 1, 1973–February 8, 1976. The observations are presented as a sequence of 27-day Bartels rotations with coronal hole information on the left, wind speed in the center, and the C9 index on the right. The date of the first block in each 27-day row is indicated at the left of that row. On the left, only coronal holes within 40° of the solar equator have been included. Orange blocks refer to coronal holes associated with positive (directed out of the Sun) photospheric magnetic fields; white blocks refer to negative polarity. The sector polarity of the interplanetary magnetic field is indicated in the center and right sections by blocks slanted to the upper right (positive polarity), to the upper left (negative polarity), or not slanted (mixed polarity). In all three sections, black areas without entries refer to days for which observations either were not obtained or have not yet been reduced. The similarity of the large-scale patterns of holes, wind, and geomagnetic activity as well as the general agreement between the photospheric and interplanetary magnetic polarity during this 3-year interval leaves little doubt that these quantities are related.

to the upper left corresponds to a negative polarity, and a vertical rectangle corresponds to a mixed polarity.

In Figure 1, entries in the left section indicate the presence of a coronal hole within 40° of the solar equator at the central meridian 3 days prior to the specified date. Orange blocks indicate coronal holes that are associated with areas of the solar photosphere having a predominantly positive (outward from the Sun) magnetic field; white blocks are associated with areas of negative field. The blue shading

indicates the absence (or in a few cases the questionable presence) of a coronal hole. Again, the black areas without entries refer to intervals for which no coronal hole observations were obtained, and they do not necessarily indicate the absence of a coronal hole.

Several additional factors were considered in the preparation of the coronal hole data in Figure 1. First, we excluded small coronal holes that required only one day or less to be carried across the central meridian by solar rotation. Second, we arbitrarily chose 40° as the cutoff latitude because this appeared to optimize the correlation between the holes and streams during the first complete 27-day rotation in June 1973. In this way, we excluded the polar holes that were usually present at latitudes greater than 60°, but included some of the more prominent low-latitude lobes of the polar holes. We did not attempt to eliminate a possible seasonal effect associated with the 7°.25 tilt of the Sun's rotation axis relative to the ecliptic; of course this could have been done by referring to the disk center rather than the solar equator. Third, in a few, rare cases during 1973–1976, a positive-polarity coronal hole in the northern hemisphere and a negative-polarity coronal hole in the southern hemisphere overlapped in longitude. On the day that the overlap was at the central meridian, the assigned polarity was that of the coronal hole extending to the lower latitude. Fourth, we omitted 5 cases for which the presence of a coronal hole was questionable due to degraded solar images or due to the difficulty of identifying a newly-emerging or decaying coronal hole.

We began our comparison of coronal holes and solar wind streams in a Carrington rotation coordinate system located at the Sun. Since the solar wind speed was measured as a function of time near the Earth, it was first necessary to transform this speed profile back to the Sun to eliminate Sun-Earth transit-time effects. We used the well-known transformation first described by Synder and Neugebauer (1966) in which the solar wind is plotted versus the time that it would have left the vicinity of the Sun (20 solar radii) in order to reach the Earth at the observed time and speed (assumed constant over this distance). In this way, the central-meridian-passage date of a coronal hole was directly comparable with the date of occurrence of a solar wind stream. To test the validity of this solar wind speed transformation, we cross-correlated the resulting temporal patterns of coronal holes and solar wind streams during the interval 1973–1976. This statistical test revealed no systematic delay between the patterns of holes and streams within our measurement accuracy of $\frac{1}{2}$ day. Of course, individual holes and streams did not always overlap with this precision. Finally, to compare the temporal patterns of coronal holes and solar wind streams near the Sun with the geomagnetic disturbance patterns, we added 3 days to the times of occurrence of both the holes and the streams, and plotted the results in the Bartels format in Figure 1. We selected 3 days to maximize the correlation of the holes and streams with the geomagnetic disturbances. (In fact, 2.5 days gave a better correlation than 3 days, but the display format required the use of an integral number of days.)

3. Results and Discussion

A comparison between the observations of coronal holes, solar wind streams, and geomagnetic disturbances in Figure 1 reveals both similarities and differences. In general, similarities occur on a large scale, and are associated with long-lived recurrence patterns. Differences occur on a small scale, and are most visible in a detailed superposition of the data.

A cursory examination of Figure 1 reveals that long-lived patterns of coronal holes, high-speed solar wind streams, and geomagnetic disturbances appear remarkably alike. The left section shows that during 1973–1976 the distribution of coronal holes was organized into a pattern of several large-scale features, each of which was either predominantly orange (positive) or predominantly white (negative), depending on the polarity of the associated photospheric magnetic field. Corresponding features are visible in the patterns of high-speed solar wind streams and their associated geomagnetic disturbances in the center and right sections, respectively. Moreover, the polarity of each of the large-scale features in the center and right sections generally agrees with the polarity of the corresponding features in the left section. (In the center and right sections, large-scale features composed almost entirely of daily entries that are slanted toward the upper right (positive) correspond to predominantly orange (positive), large-scale features in the left section. In the center and right sections, large-scale features composed of entries slanted to the upper left (negative) correspond to white (negative), large-scale features in the left section.) This is consistent with the idea that the polarity of the magnetic field emerging from the base of a coronal hole is the same as the predominant polarity of the interplanetary magnetic field carried by the corresponding high speed stream.

Finally, we note that Figure 1 includes intervals during which the patterns were changing with time as well as intervals during which the patterns were relatively stable. In particular, the major changes that occurred in mid-1973 and mid-1975 are separated by the very long-lived leftward- and rightward-weaving patterns that are known to be characteristic of the declining phase of the sunspot cycle just prior to sunspot minimum (Bartels, 1963).

A detailed comparison between the three sections of Figure 1 reveals certain differences, some within the errors of measurement. The different sources of coronal hole observations might well lead to inaccuracies in the identification of coronal holes or in the precise determination of their boundaries, especially prior to the Skylab mission. Furthermore, occasionally it was difficult to identify a coronal hole in the He I 10 830 Å spectroheliograms, particularly during the seemingly transitional period in late 1975 and early 1976.

However, many differences are real, and reflect a lack of perfect agreement between the central meridian passage of coronal holes and the onset of high-speed streams and their associated geomagnetic disturbances at 1 AU. Next, we shall examine some of these differences and consider possible reasons for them.

First, Figure 1 shows that the detailed temporal agreement between the recurrence patterns of coronal holes, solar wind streams, and geomagnetic disturbances is not exact, even allowing for observational and display accuracies of approximately one day. The onset of some high-speed streams (as observed at 1 AU, but corrected for the expected transit time from 20 solar radii) comes sometimes before and sometimes after the central meridian passage of their associated coronal holes. Similar, small, temporal disagreements between the high-speed streams and geomagnetic disturbances are also visible. This close, but inexact, relation between recurrent solar wind streams and geomagnetic disturbances has been recognized for some time (Snyder *et al.*, 1963; Gosling *et al.*, 1967).

We should expect such detailed timing differences between the central meridian passage of the chromospheric base of a coronal hole and the onset of a high-speed stream at 1 AU if the boundary of the coronal hole extends non-radially from its base in the chromosphere into the outer corona. Not only might the onset of the stream be advanced or retarded relative to the passage of the base of the coronal hole, but the stream might be missed entirely. Furthermore, some coronal holes poleward of our arbitrary 40° cutoff latitude might produce high-speed streams observable near the ecliptic plane at 1 AU.

There is some evidence for such non-radial extensions of coronal hole boundaries. We have compared the pattern of coronal holes in Figure 1 with Howard and Koomen's (1974) observations of coronal streamers at 3–10 $R_\odot$ made with the OSO-7 coronograph during 1973. The results of this comparison suggest that during 1973 the long-lived coronal streamers indicated the extension of coronal hole boundaries into the outer corona. Moreover, the spatial appearance of such streamers suggests that the photospheric magnetic flux emerging from a low-latitude coronal hole may fan out considerably with distance from the Sun. This expanding low-latitude flux seems to join similarly expanding flux from the polar coronal hole having the same magnetic polarity to form a large-scale interplanetary magnetic sector.

Second, Figure 1 shows some 2–3 day intervals of non-recurrent geomagnetic disturbances, such as July 4–6, 1974 and November 21–22, 1975, for which there were no corresponding coronal holes. The onset of such non-recurrent geomagnetic disturbances usually occur 1–2 days following major flares at the Sun (Akasofu and Chapman 1972), and these July 1974 and November 1975 disturbances were not exceptions. It is interesting that some of these major flares occurred on days such as July 29, September 7, and November 3, 1973 for which their subsequent geomagnetic effects overlapped in time with the expected geomagnetic effects from coronal holes

Third, Figure 1 shows a recurrent coronal hole for which the geomagnetic field is only moderately disturbed (C9 = 4). This small, positive-polarity coronal hole is visible in the lower-left corner of the left section of Figure 1. The corresponding polarity of the interplanetary field is predominantly negative, although some days of positive and mixed polarity are present. We can only speculate that this

disagreement between the polarity of the coronal hole and the dominant polarity of the interplanetary magnetic field may be related to the fact that the geomagnetic field is disturbed only moderately.

In summary, it appears that major solar flare events and the non-radial extension of coronal holes into the outer corona can account for most of the specific, small-scale differences between the patterns of coronal holes, high-speed solar wind streams, and enhanced geomagnetic disturbances. This fact together with the remarkable similarity between these large-scale patterns during this 3-year interval leads us to conclude that the coronal holes are indeed the solar origin of most recurrent, high-speed solar wind streams observed in the ecliptic plane at 1 AU.

We complete our discussion by noting that coronal hole observations can be used to forecast the occurrence of solar wind streams and geomagnetic disturbances at the Earth. Since coronal holes are visible from the Earth several days before they are carried across the central meridian by solar rotation, and since 2–3 days remain before the wind from the hole would reach the Earth, we should expect to be able to predict the arrival of the high-speed streams and their associated magnetic effects approximately a week in advance. In fact, the He I 10 830 Å spectroheliograms are currently being used by NOAA as an aid in the forecasting of geomagnetic disturbance conditions (Sutorik, 1976). Whether such observations will continue to be useful during intervals of increased solar activity such as generally occur during sunspot maximum must await future study.

Acknowledgements

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