CORONAL HOLES AS INDICATORS OF LARGE-SCALE MAGNETIC FIELDS IN THE CORONA

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Abstract. It is shown that coronal holes may be used as indicators to trace the location of the neutral line on the source surface in the corona. At the same time, coronal holes are shown to concentrate in regions of enhanced magnetic field at the source surface. This provides us with a simple method for predicting the interplanetary current sheet and sector structure which, in turn, determine the location of the proton complexes and the outflow regions of high-velocity streams. Rotation of coronal holes has been studied. Rather than being rigid, it displays the same reduced differentiallity as the rest of the corona. However, there are particular periods 2 or 3 years before the cycle minimum when the solid-body type of rotation is settled for both the coronal holes and the corona as a whole.

1. Introduction

According to a nowadays widespread concept, the coronal holes (CHs) are believed to possess a number of unique properties. It is known that coronal holes were initially identified as regions of reduced brightness in the corona in the soft X-ray range (Krieger, Timothy, and Roelof, 1973; Vaiana, Krieger, and Timothy, 1973). Later on (Harvey *et al.*, 1975; Zirin, 1975; Harvey and Sheeley, 1977; McCabe, Michey, and Sheeley, 1977), it was shown that coronal holes could be observed in the helium lines as regions of enhanced brightness. Afterwards, these purely photometrical definitions were expanded and now coronal holes are referred to as specific objects in the Sun, characterized by the solid-body type of rotation and connected with the outflow regions of high-velocity solar wind streams (HVS) and the regions of weak magnetic field of open configurations (Altschuler, Trotter, and Orral, 1972).

As shown below, the latter properties still need further corroboration.

2. Differential Rotation

Shortly after they were discovered, the coronal holes were found to display an apparently striking property – the solid-body type of rotation, i.e., a low angular velocity gradient in latitude (Wagner, 1975; Timothy, Krieger, and Vaiana, 1975; Bohlin, 1977). The differential rotation law written down in its convential form is:

$$\omega = \omega_0 + \omega_1 \sin^2 \varphi , \tag{1}$$

where ω is the angular velocity (synodic in our case) and φ is the latitude. In the case of coronal holes, it turned out that $\omega_1 \approx -0.4^\circ \text{ day}^{-1} \pm 0.4$, which sharply contradicted the well-known Newton–Nunn law for sunspots (Newton and Nunn, 1951), where $\omega_1 = -2.69^\circ \text{ day}^{-1}$.

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Since then, the 'solid-body' rotation of coronal holes has been recognized as valid and is widely cited in monographs and manuals. However, little attention has been paid to the following circumstances:

(1) Of course, the rotation law for coronal holes differs from that for sunspots. However, rather than with sunspots it should be compared with the corona, whose rotation is more rigid and depends both on the activity and on the phase of the cycle (Antonucci and Dodero, 1977; Letfus and Sýkora, 1982; Fischer and Sime, 1984; Parker, 1987).

(2) All evidence available of the rigid rotation of X-ray coronal holes (Wagner, 1975; Timothy, Krieger, and Vaiana, 1975; Bohlin, 1977) is based on one and the same series of Skylab data relevant to a short observation interval in 1973, i.e., two or three years before the sunspot minimum.

The only paper we are aware of to contain an analysis of CH rotation for another phase of the cycle (1982) (Shelke and Pande, 1985) provides rough estimates of the rotation periods at different latitudes suggesting a significant differentiallity. Schröter (1985) used these estimates to obtain $\omega_1 = -1.5$. A direct processing of the synoptic charts from Shelke and Pande (1985) performed by ourselves provided $\omega_1 = -1.04$.

Proceeding from these considerations, we have analyzed the differential rotation of the coronal holes marked on the synoptic charts in *Solar Geophysical Data* for 1978–1986. For this period, 489 coronal holes were recorded to cross the solar disk, 423 of them being recurrent and 66 non-recurrent.

The results of the analysis are represented in Table I and in Figure 1. Owing to a small number of coronal holes recorded during 1986, the data for that year are not very

TABLE I

Synodic angular velocity (deg day^{-1})

Year Latitude	1978	1979	1980	1981	1982	1983	1984	1985
0–10	12.93	13.25	–	13.49	13.24	13.40	13.40	13.29
10–20	12.93	13.20	13.20	–	13.27	13.31	13.37	13.09
20–30	12.75	13.04	12.71	13.03	13.08	13.13	13.23	13.27
30–40	12.20	13.02	12.65	12.78	12.76	12.99	12.92	13.06
40–50	12.60	12.67	12.53	12.71	12.70	12.84	12.79	13.12
50–60	12.16	–	12.58	12.64	12.69	12.69	12.84	12.89

reliable, but within the large errors ω_1 is close to zero at all latitudes. The dashed lines in the figure represent the rotation laws for the green corona according to Antonucci and Dodero (1977): the lower dashed line corresponds to the synodic law $\omega = 13.42 - 1.9 \sin^2 \varphi$ obtained for the maximum solar activity in 1956–1958; the upper one, $\omega = 13.34 – 0.34 \sin^2 \varphi$, corresponds to the quiescent corona at the decay phase in 1972–1974, i.e., 2 or 3 years before the minimum (1976.5).

Table II contains the values of ω_0 and ω_1 for the law (1) obtained by the least-square

TABLE II

ω_0 and ω_1 parameters of the CH differential rotation

Year	1978	1979	1980	1981	1982	1983	1984	1985
ω_0	12.70	13.04	12.73	12.93	13.25	13.37	13.38	13.25
	± 0.05	± 0.03	± 0.08	± 0.07	± 0.04	± 0.02	± 0.04	± 0.04
ω_1 ($0 \leq \varphi \leq 60°$	-1.04	-1.10	-0.88	-1.21	-0.98	-1.05	-0.99	-0.44
	± 0.22	± 0.18	± 0.39	± 0.30	± 0.19	± 0.07	± 0.19	± 0.11
ω_1 ($\varphi \leq 30°$)	-1.15	-1.25	-4.34	-2.71	-1.03	-1.02	-1.03	$+0.11$
ω_1 ($\varphi \geqslant 30°$)	-1.90	-1.02	-0.20	-0.40	-0.20	-0.88	-0.23	-0.50

method for each year at all latitudes and separately for $\varphi \leq 30°$ and $\varphi \geq 30°$. From the tables and Figure 1 it may be concluded that: (a) the simple linear dependence on $\sin^2 \varphi$ does not satisfactorily describe the observed data. At the latitudes $\geq 30°$ deviations from the law (1) towards smaller differentiallity are very strong; and (b) the statement that coronal holes rotate like a solid body is an incorrect generalization of a particular case. In fact, near the maximum and at the beginning of the decay phase the rotation of coronal holes has a pronouncedly differential character. Note that in 1982 $\omega_1 \approx -1.0$ as shown by our estimates, as well as by the data reduced from Shelke and Pande (1985).

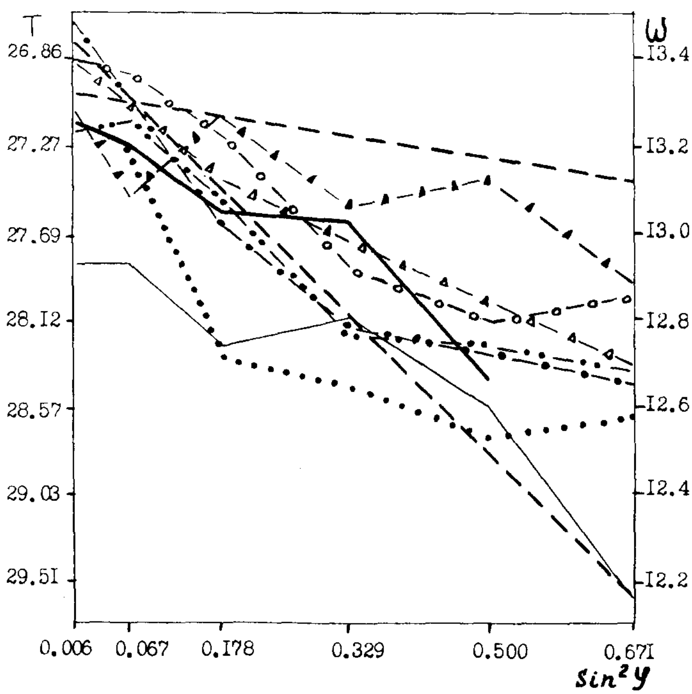

Fig. 1. Periods and angular velocities of CH rotation as a function of heliographic latitude: 1978 ——; 1979 ▬▬; 1980 · · ·; 1981 – · –; 1982 – · · –; 1983 – △ –; 1984 – ◦ –; 1985– ▲ –; Antonucci and Dodero (1977) ▬ ▬ ▬.

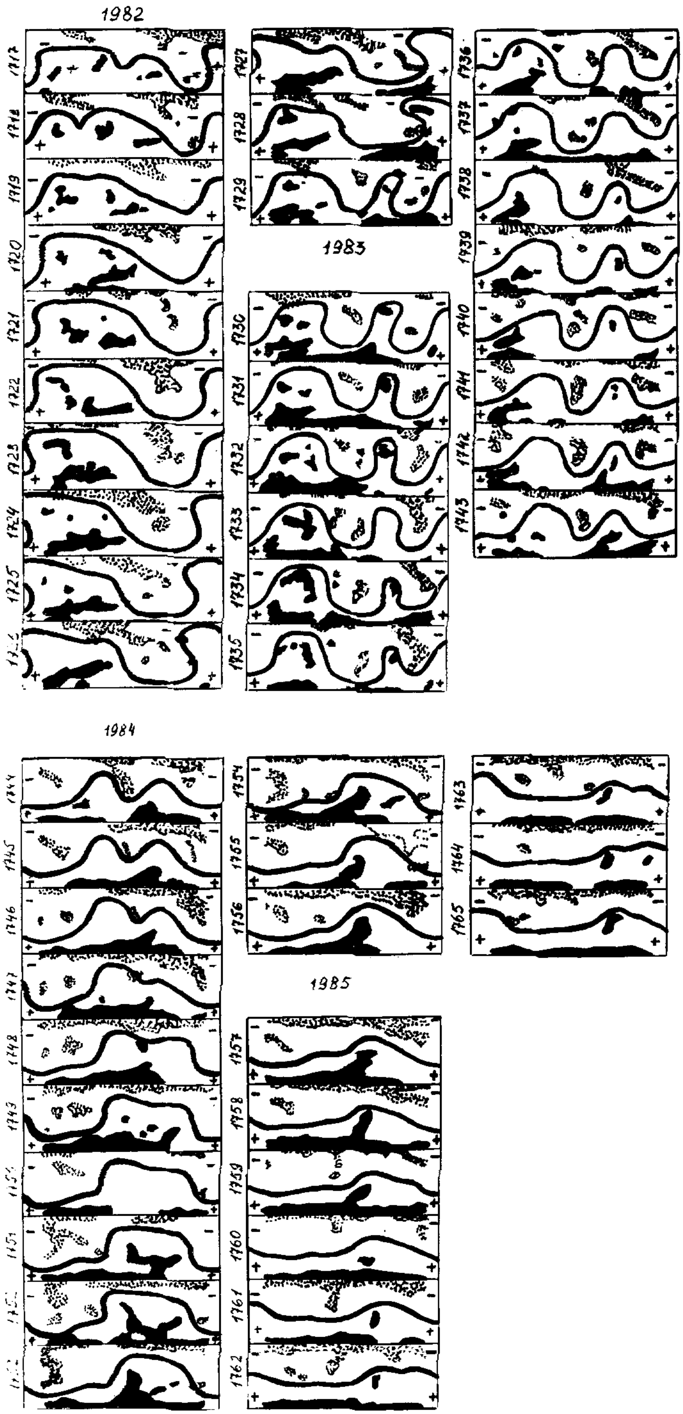

Fig. 2. Coronal holes and the magnetic field neutral line on the source surface as calculated in Hoeksema and Scherrer (1986) for Carrington rotations 1717–1743 (a) and 1744–1765 (b). Black spaces correspond to the coronal holes of positive polarity, dotted spaces to those of negative polarity.

Afterwards the differentiality decreases gradually. As seen from the figure, this process starts at higher latitudes, i.e., the high-latitude parts of the coronal holes begin to rotate faster. Several years before the minimum, the rotation becomes nearly rigid with $\omega_1 \approx -0.4$. This fact has been established in Wagner (1975), Timothy, Krieger, and Vaiana (1975), Bohlin (1977) for 1973 and in the present work for 1985. For 1986, no ω_1 values differing from 0 have been established at all.

Some of our results showing that coronal holes rotate very much like the corona as a whole agree with the results reported by Sheeley, Nash, and Wang (1987), Wang *et al.* (1988), Nash, Sheeley, and Wang (1988).

3. Location of Coronal Holes with Respect to the Large-Scale Magnetic Field Structure on the Sun

Illustrated in Figure 2 are the coronal holes and the neutral line of the solar magnetic field in the corona on the source surface as calculated in Hoeksema and Scherrer (1986).

(1) If we assume the coronal holes to have the same magnetic polarity as the underlying photospheric magnetic field, it will practically in all cases coincide with that of the coronal magnetic field on the source surface over the coronal hole. Exceptions are very scarce and are obviously associated with incorrectly mapped or misidentified coronal holes. Thus, out of 184 isolated coronal holes recorded during 1982–1985, only 3 CHs did not follow this regularity. Two of them crossed the neutral line when projected onto the source surface, but fell entirely within the unipolar cell in the photosphere. The first CH had a large lifetime (of about 20 rotations) and was located on the neutral line only in the last two rotations (NN 1747 and 1748) before the disappearance. The second one was non-recurrent and survived for only one rotation (N 1754). Another recurrent coronal hole crossed the neutral line in the photosphere in two rotations (NN 1738 and 1739), but was projected onto the source surface at the center of the magnetic hill. These effects may be due to incorrect mapping of the coronal holes.

(2) Coronal holes are always located in the bays and bends formed by the neutral line. One cannot help having an impression that coronal holes repel the neutral line as a source of intensive magnetic field would do. Figures 3 and 4 illustrate typical examples of the CH arrangement. One can see that coronal holes are located at the hills of the coronal magnetic field. The totality of the data available for 1982–1985 show that 85% of coronal holes are entirely or partly located in the regions of maximum field intensity for a given rotation.

Thus, the statement that coronal holes are located in the regions of weak field holds true only with respect to the photospheric magnetic field. The situation is opposite where the coronal field on the source surface is concerned. The relatively strong bipolar fields in the photosphere do not contribute to the source-surface field, which is dominated by the weaker, large-scale components of the photospheric field, and the coronal holes arise at the local maxima of the remaining large-scale field. So, a bend of the neutral line or a magnetic hill on the source surface indicate that a coronal hole is likely to exist at that place. Its size and location can be determined more exactly by using photospheric

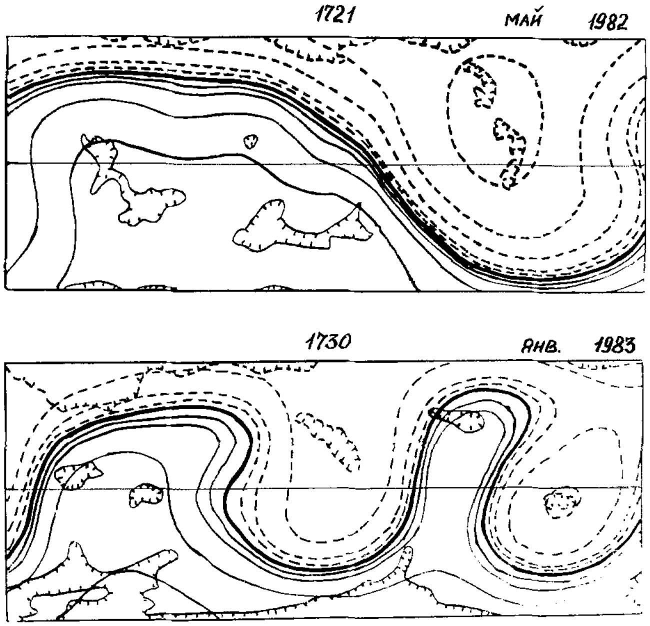

Fig. 3. CH location with respect to the magnetic field on the source surface. Thin solid and dashed lines are the isogausses of the positive and negative magnetic fields, respectively; the thick solid line is the magnetic field neutral line; thin solid and dashed crossed lines are the CHs of positive and negative polarity, respectively.

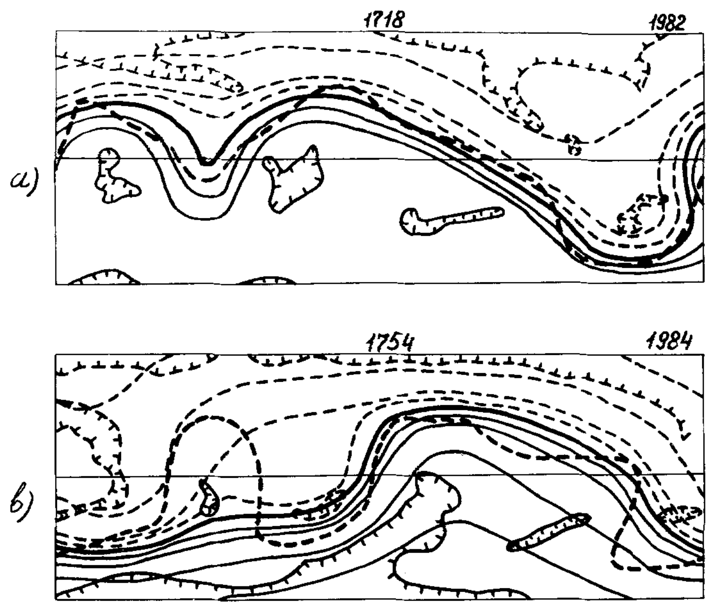

Fig. 4. Same as Figure 3. The thick dashed line is the magnetic field neutral line calculated by our simplified method.

magnetic charts. It turns out that isolated coronal holes rest on the isolated magnetic cells in the photosphere. In 50% of the cases in 1982 and in 80% of the cases in 1985, the CH areas were approximately equal to the area enclosed within $2\ \mathrm{G} < B < 5\ \mathrm{G}$ isogausses in the photosphere. The coronal holes are usually located over photospheric regions with $B \approx 1$–5 G. By 1985, they are seen to have entirely moved to the region of weaker fields, $B \leq 2$ G.

(3) Proceeding from the conclusion of a close connection between the CH location and the behaviour of the magnetic field neutral line on the source surface, one can make an attempt to reconstruct the location of the neutral line without applying the method suggested by Hoeksema and Scherrer (1986). It provides an independent method based on coronal-hole observations rather than photospheric magnetic field observations. The simplest way is to draw the neutral line midway between the coronal holes of opposite signs. Examples are given in Figure 4. Figure 4(a) illustrates a typical case and Figure 4(b) shows the case of worst agreement with calculations in Hoeksema and Scherrer (1986). One can see that the agreement on the whole is rather good, the discrepancies being probably due to uncertainties in mapping the coronal holes.

Since the IMF sector structure is determined by the Earth's passage across the interplanetary current sheet, it may be calculated with the aid of our simple algorithm. Figure 5 shows the IMF sector structure determined by exact calculations (a) (Hoeksema and Scherrer, 1986), by direct measurements (b), and by using our rough algorithm (c). All three 'carpets' coincide in 75% of the cases, the discrepancies being mainly due to errors in the original data rather than to the calculation method applied.

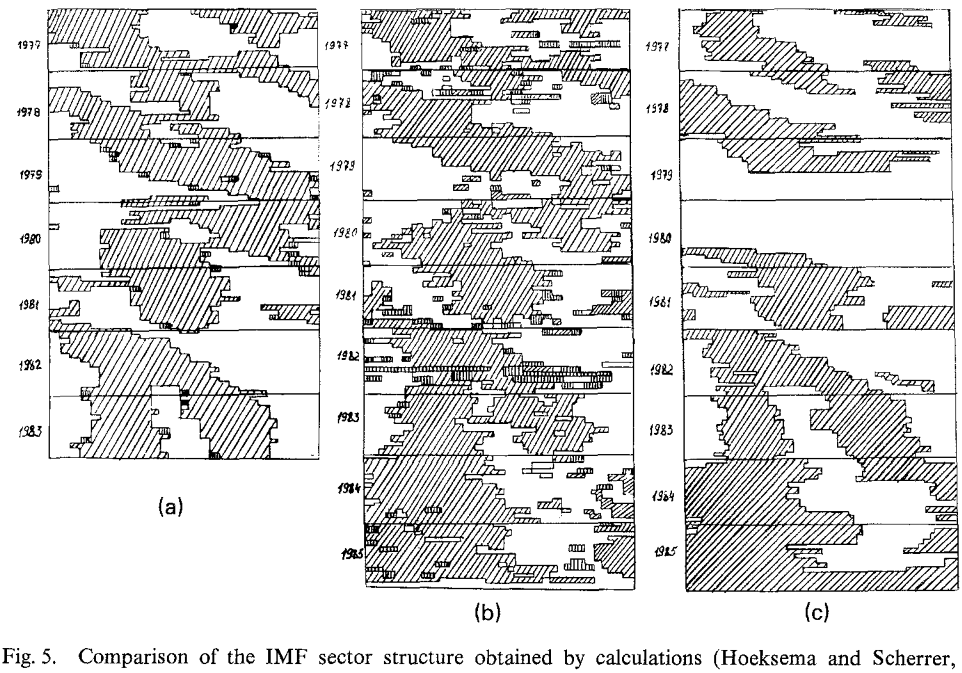

Fig. 5. Comparison of the IMF sector structure obtained by calculations (Hoeksema and Scherrer, 1986) (a), by direct measurements (b), and by using the simplified method (c).

4. Discussions

Thus, the coronal holes can be considered a fairly reliable indicator of the large-scale field structure in the corona. Here, an analogy with sunspots suggests itself. Sunspots indicate the most intensive parts of local fields in the photosphere, and coronal holes do the same as far as the large-scale coronal fields are concerned. The sunspot and the coronal hole are regions of open field in the photosphere and the corona, respectively. If the sunspot is fairly good a tracer for the rotating photospheric plasma, the coronal hole is the same for the upper corona (Obridko and Shelting, 1988). The sunspot is a region of reduced brightness with respect to the ambient photosphere and has a lower temperature and pressure. The same is true for the coronal holes with respect to the corona.

To conclude with, it should be mentioned that since the large-scale magnetic field on the source surface is most likely connected with deep subphotospheric layers, the analysis of coronal holes may help us specify some characteristics of the magnetic field distribution with depth.

References

Altschuler, M. D., Trotter, D. E., and Orral, F. Q.: 1972, *Solar Phys.* **26**, 354.
Antonucci, E. and Dodero, M. A.: 1977, *Solar Phys.* **53**, 179.
Bohlin, J. D.: 1977, *Solar Phys.* **51**, 377.
Fischer, R. and Sime, D. G.: 1984, *Astrophys. J.* **287**, 959.
Harvey, J. W. and Sheeley, N. R.: 1977, *Solar Phys.* **54**, 343.
Harvey, J. W., Krieger, A. S., Davis, J. M., Timothy, A. F., and Vaiana, G. S.: 1975, *Bull. Am. Astron. Soc.* **7**, 358.
Hoeksema, J. T. and Scherrer, P. H.: 1986, Report UAG-94, WDC-A, p. 352.
Krieger, A. S., Timothy, A. F., and Roelof, E. C.: 1973, *Solar Phys.* **29**, 505.
Letfus, V. and Sýkora, J.: 1982, *Hvar Obs. Bull.* **6**, 117.
McCabe, M. K., Mickey, D. L., and Chesley, S. E.: 1977, *Bull. Am. Astron. Soc.* **9**, 371.
Nash, A. G., Sheeley, N. R., Jr., and Wang, Y.-M.: 1988, *Solar Phys.* **117**, 359.
Newton, H. W. and Nunn, M. L.: 1951, *Monthly Notices Roy. Astron. Soc.* **111**, 413.
Obridko, V. N. and Shelting, B. D.: 1988, *Soln. Dann.* No. 1, 89.
Parker, G. D.: 1987, *Solar Phys.* **108**, 77.
Schröter, E. H.: 1985, *Solar Phys.* **100**, 141.
Sheeley, N. R., Jr., Nash, A. G., and Wang, Y.-M.: 1987, *Astrophys. J.* **319**, 481.
Shelke, R. N. and Pande, M. C.: 1985, *Solar Phys.* **95**, 193.
Timothy, A. F., Krieger, A. S., and Vaiana, G. S.: 1975, *Solar Phys.* **42**, 136.
Vaiana, G. S., Krieger, A. S., and Timothy, A. F.: 1973, *Solar Phys.* **32**, 81.
Wagner, W. J.: 1975, *Astrophys. J.* **198**, L141.
Wang, Y.-M., Sheeley, N. R., Jr., Nash, A. G., and Shampline, L. R.: 1988, *Astrophys. J.* **327**, 427.
Zirin, H.: 1975, *Astrophys. J.* **199**, L63.