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CORONAL INFLOWS AND THE SUN'S NONAXISYMMETRIC OPEN FLUX

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ABSTRACT

Wang et al. recently described white-light coronagraph observations of faint coronal features moving inward toward the Sun at heliocentric distances of 2–6 $R_\odot$. In a study of these inflows during 1996–2000, we have found that they occur along bends of the coronal streamer belt and are especially common when the magnetic field has a four-sector structure. The measured inflow rate is dominated by episodic bursts that are correlated with the occurrence of nonpolar coronal holes and other indicators of the Sun's nonaxisymmetric open flux. However, the inflow rate has only a broad long-term correlation with conventional indicators of solar activity like the sunspot number and coronal mass ejection rate. We conclude that most inflows indicate collapsing field lines that occur as nonpolar coronal holes are subjected to photospheric motions and the eruptions of new flux.

Subject headings: interplanetary medium — Sun: activity — Sun: corona — Sun: magnetic fields

1. INTRODUCTION

The Large-Angle and Spectrometric Coronagraph (LASCO) was launched on the *Solar and Heliospheric Observatory* (*SOHO*) in 1995 December and began taking routine observations of the white-light corona during the 1996 sunspot minimum. (For a description of the instrument, see Brueckner et al. 1995.) Since that time, LASCO has recorded many varieties of coronal ejecta, including blobs of material that seem to be torn from the tops of streamers by the passing solar wind (Sheeley et al. 1997) and an increasing number of coronal mass ejections (CMEs; St. Cyr et al. 2000). As the sunspot cycle progressed, we became aware of a new kind of coronal feature, moving inward toward the Sun rather than outward like all of the features we had seen previously (Wang et al. 1999). This Letter concerns one aspect of our follow-up study of these coronal inflows—their occurrence rate.

By measuring the occurrence rate, we expected to learn whether or not the inflows were associated with other forms of solar activity and thereby gain some insight into their origin. Because the inflows had become more common as the sunspot cycle progressed, we supposed that they were somehow related to solar activity, perhaps indicating the collapse of field lines that had been dragged open by CMEs. This conjecture seemed plausible because we sometimes observed inflows in the wake of CMEs.

However, there were numerous counterexamples. Frequently, inflows occurred without CMEs, and often CMEs occurred without inflows. Also, despite the lower observational cadence early in the mission, we found more inflows toward the end of 1996 (when the polar coronal holes had equatorial extensions) than in 1997 (when the streamer belt was relatively flat). In recent years, we noticed a pronounced difference in the occurrence of inflows at the east and west limbs of the Sun, as if they were occurring at preferred longitudes. Perhaps the most dramatic clue was an especially large increase in the inflow rate between Carrington rotations CR 1951 and 1952 (1999 June and July) as the magnetic field began to acquire a strong quadrupole moment.

In this Letter, we shall describe this evolution and show that the inflow rate is highest when the streamer belt is most convoluted and when nonpolar coronal holes contain a substantial amount of open flux. A high rate of magnetic field line reconnection ought to occur under these conditions since the holes are subjected to distortion and erosion by photospheric transport processes and the eruption of new flux. We conclude that such field line reconnections are responsible for most coronal inflows.

2. RESULTS

During 1996–2000, we have seen several kinds of features moving inward through the field of the C2 coronagraph (2–6 $R_\odot$). They include eruptive prominences that fell back to the Sun, inflow-outflow pairs that seemed to diverge from a common source, loops moving to lower heights, and portions of coronal rays apparently sinking along linear paths with depletion-like tails trailing behind them. Figure 1 shows one of these sinking columns on 2000 June 12. In the "background-subtracted" images (*left panels*), the inflow begins almost invisibly as a column whose brightness is comparable to that of the neighboring rays. However, a slight discontinuity produces an obvious two-toned signal in the running difference images (*right panels*), with white initially leading black. By the end of this sequence, the sinking column has developed a dark tail, which causes a "tone reversal" in the difference images, with black now leading white. In our preliminary measurements of the inflow rate, we have not attempted to distinguish between these different types of inflow. However, the measured rate is probably dominated by these sinking columns, which sometimes occurred as frequently as 10–20 day^{-1} and are the most common type by far.

We have not yet found a simple way of counting and recording coronal inflows in a completely objective and automatic way. They are just too faint and difficult to observe against the background of more dramatic transients and CMEs. Instead, we watched 1 day running difference image movies at a standard cadence, and we asked ourselves whether or not any inflows were visible in each of the six sectors of the field (NE, E, SE, NW, W, and SW). If there were inflows, the observer would enter a "1" in that slot; otherwise, a "0" was assigned. Thus, for each day, we ended up with a set of six numbers, which we used to construct relatively coarse east- and west-limb Carrington maps of inflow occurrence during 1996–2000.

The resulting maps were crude, with only three eye-estimated

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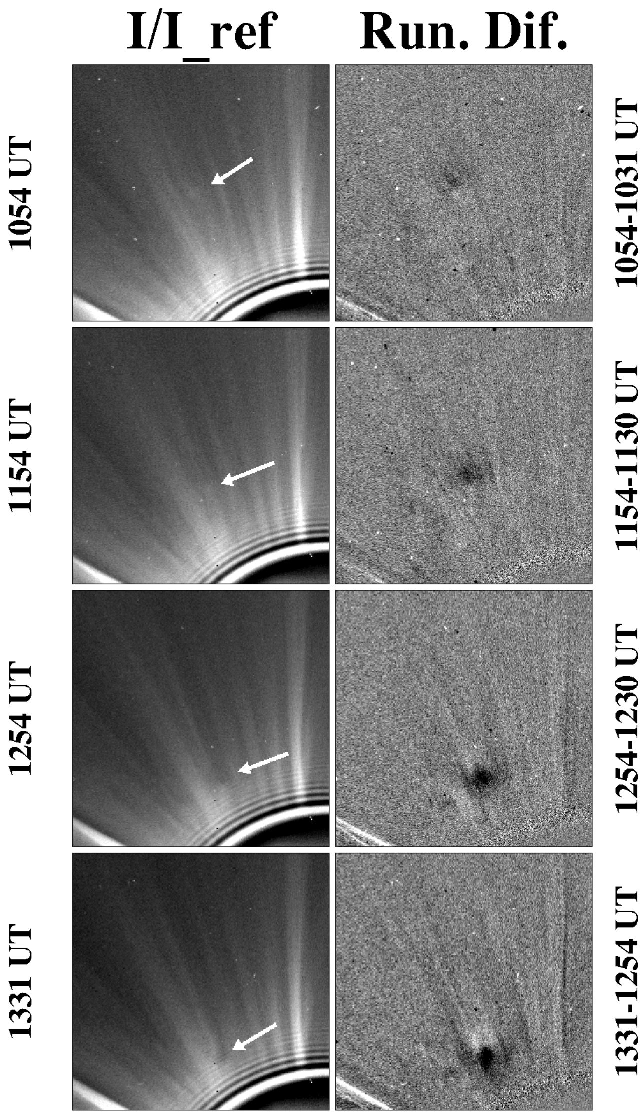

FIG. 1.—Time-lapse sequence of images showing the inward motion of a sinking column on 2000 June 12. The background-subtracted images (*left panels*) were obtained by dividing each frame by a minimum intensity reference image, and the running difference images (*right panels*) were obtained by subtracting a previous frame from each image (as indicated at the right edge). These images refer to identical 3 $R_\odot$ × 3 $R_\odot$ fields extending from the northwest edge of the C2 occulting disk, whose radius is approximately 2 $R_\odot$. The arrows indicate the top of the sinking column of material (*upper panels*) and the leading edge of the dark tail that follows it (*lower panels*).

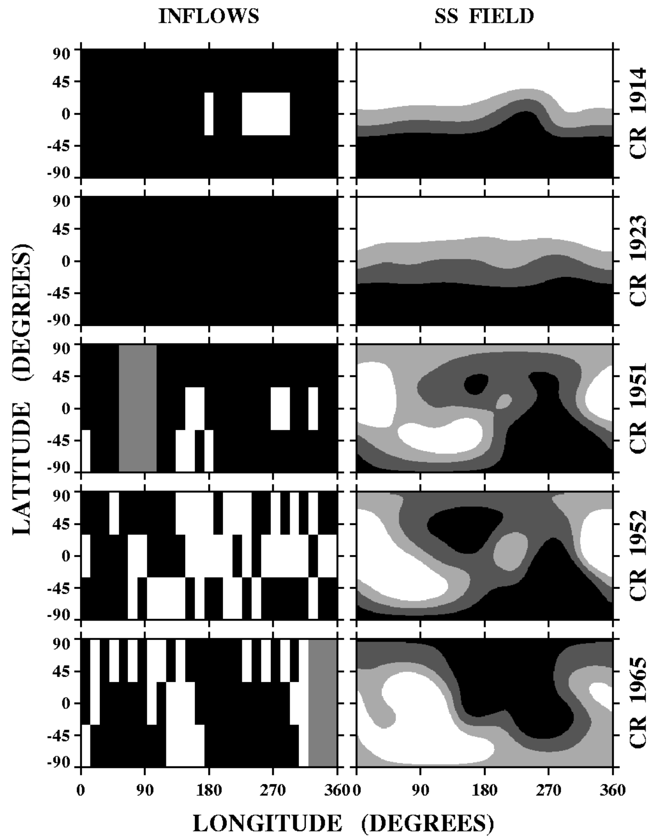

FIG. 2.—Carrington maps of west-limb coronal inflows (*left panels*) and SS fields at 2.5 $R_\odot$ (*right panels*), obtained by potential-field extrapolations of the MWO photospheric measurements. Inflow occurrences are indicated by white spaces and data gaps by gray. The magnetic field contours are ±0.1 G, with white denoting positive polarity (directed outward from the Sun).

pixels spanning 180° of latitude and 27 pixels spanning 360° of longitude. Nevertheless, they were remarkably reproducible, showing only minor differences when another observer (or the same observer) repeated the measurements. As the sunspot cycle advanced, we often encountered several (and sometimes many) inflows in a given sector, but we did not modify the measurements to allow for this enhanced flow. Thus, the rate reported here refers to the number of days that we saw inflows, not to the number of inflows that occurred.

Figure 2 shows a sample of west-limb Carrington maps of the inflow rate (*left panels*) compared with the corresponding maps of the source-surface (SS) magnetic field at 2.5 $R_\odot$ (*right panels*). The SS maps were derived using a potential-field extrapolation of Mount Wilson Observatory (MWO) photospheric field measurements (corrected for saturation effects as described by Ulrich 1992 and Wang & Sheeley 1995). The map for CR 1914 (beginning 1996 September 18) shows a few inflow days concentrated around the bend of the SS neutral line. Inflows also occurred here during CR 1912–1916 but disappeared later as the streamer flattened out. The map for CR 1923 (1997 May 22) shows no inflows when the neutral line was relatively flat. By CR 1951 (1999 June 24), there were more inflows, but not nearly as many as in the next rotation CR 1952 (1999 July 21). This sudden jump in mid-1999 is a real effect, confirmed by repeated measurements, and occurred at a time that the SS field was acquiring a strong four-sector pattern. By CR 1965 (2000 July 10), the rate had become smaller and the SS field had returned to a two-sector pattern, but the inflows still tended to be concentrated along the bends of the neutral line.

Next, we computed an average inflow rate for each Carrington rotation by counting the number of "1's" in each map and averaging the east-limb and west-limb values. As mentioned above, this rate refers to the average number of sectors that had inflows and does not account for multiple inflows that sometimes occurred in each sector. Nevertheless, we hoped that this "sector rate" would provide some clues when compared with solar activity indicators like the sunspot number.

Figure 3 compares the inflow rate with the monthly averaged sunspot number provided by the National Solar and Geophysics Data Center. The sunspot number shows an overall increase during 1996–2000 with several fluctuations per year. Some of these fluctuations coincide with peaks in the inflow rate, but

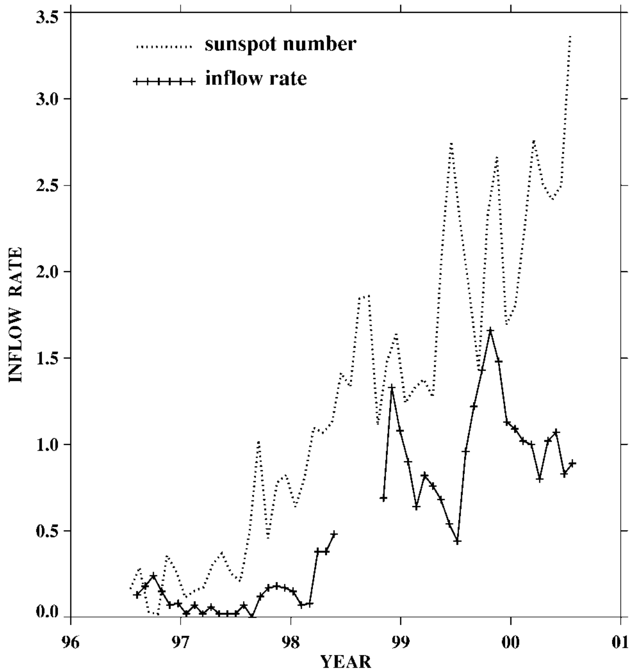

FIG. 3.—Comparison of the average inflow rate (expressed in observed sectors per day) and the monthly averaged sunspot number. Although each index shows an overall increase, the inflow rate shows episodic bursts that are not well reproduced by the sunspot number.

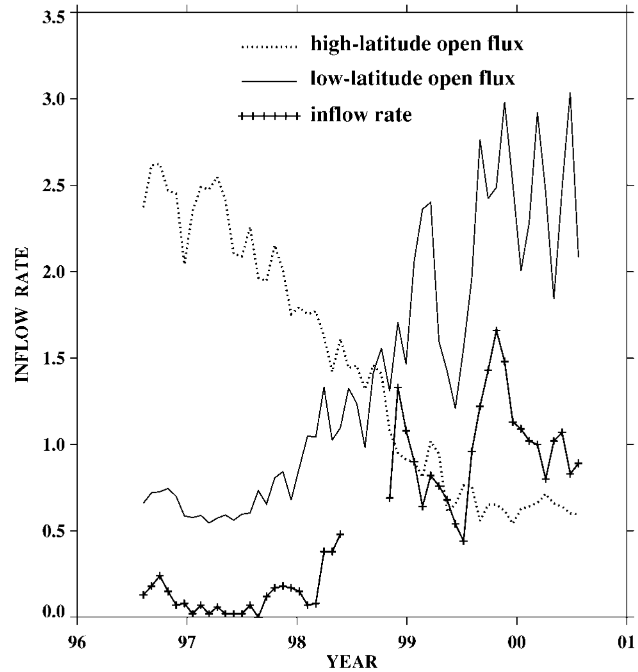

FIG. 4.—High- and low-latitude open flux compared with the inflow rate (sectors per day). The low-latitude flux shows episodic bursts approximately matching those of the inflow rate, whereas the high-latitude flux follows a different overall decrease with time.

others do not. The correspondence was particularly bad in mid-1999 (when the sunspot number was high and decreasing while the inflow rate was low and increasing) and in early 2000 (when the inflow rate tapered off while the sunspot number continued to climb). Thus, the episodic variation of the inflow rate is not well reproduced by the sunspot number.

Much better correlations were obtained with indicators of the Sun's nonaxisymmetric open flux, such as the Sun's mean line-of-sight field, the flux in low-latitude coronal holes, and the magnetic quadrupole moment. Figure 4 compares the inflow rate with the flux that originated in coronal holes located above and below latitude 45°, respectively. These fluxes were derived using potential-field extrapolations of the MWO photospheric field measurements. The low-latitude open flux shows a "bursty" rise with peaks in rough agreement with those obtained for the inflow rate. In contrast, the high-latitude open flux shows a monotonic decrease during 1996–1999, apparently indicating the shrinking and disappearance of the polar coronal holes. (The nonzero base level in the year 2000 is an artifact caused by the vertical shift that we introduced to separate the open flux curves from the inflow rate.)

The separation of the open flux into high- and low-latitude components effectively distinguishes the flux that originates in the long-lived, longitudinally symmetric polar coronal holes from the shorter lived open flux that is strongly affected by flux emergence and by transport processes such as photospheric differential rotation. A more general—but essentially equivalent—separation would be in terms of the axisymmetric and nonaxisymmetric components of open flux.

Figure 5 compares the inflow rate with the total open flux and its nonaxisymmetric component, derived by integrating the absolute value of the radial field and its nonaxisymmetric component over a source surface at 2.5 $R_\odot$ and by taking one-half of the result. Like the low-latitude open flux, the nonaxisymmetric open flux shows a variation similar to the inflow rate, effectively reproducing the increase in the first half of 1998, the large peaks near the beginning and end of 1999, and the smaller peaks in late 1996 and 1997. Also, the nonaxisymmetric open flux shows a minimum in the second half of 1998 when

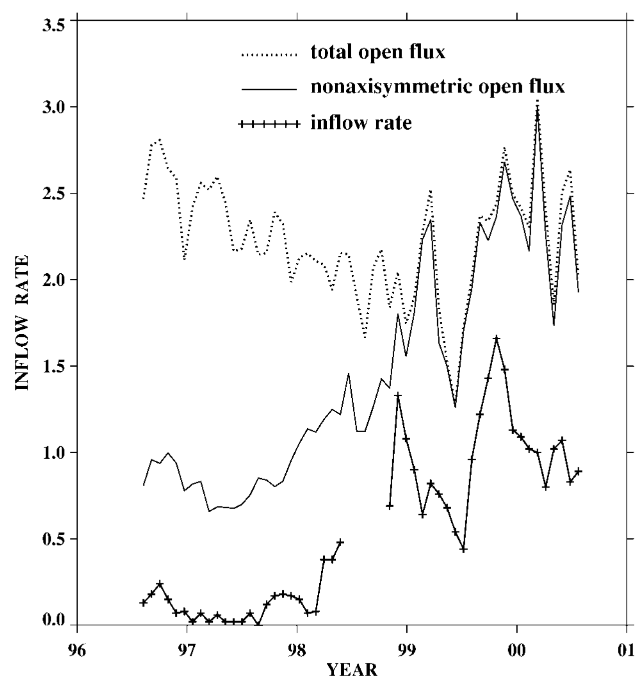

FIG. 5.—Total open flux and its nonaxisymmetric component compared with the inflow rate. The nonaxisymmetric component resembles the inflow rate, whereas the total open flux does not, until 1999 when its axisymmetric part has virtually disappeared.

communication with *SOHO* was temporarily lost and no coronal observations were taken. This suggests that the inflow rate may have decreased during this time despite a large increase in the sunspot number (see Fig. 3). By comparison, the total open flux decreased during 1996–1998 and did not begin to match the inflow rate until 1999, when its axisymmetric part had virtually disappeared.

The low-latitude open flux and the nonaxisymmetric open flux are dominated by the nonaxisymmetric dipole and quadrupole moments of the Sun's magnetic field. Figure 6 compares the inflow rate with these individual moments. The quadrupole provides a better fit than the dipole, especially during 1998–2000 when it reproduces the three major peaks and the subsequent decline in 2000.

3. DISCUSSION

We found that inflows occur along the bends of the streamer belt and are especially common when the magnetic field has a strong, four-sector structure. What is special about a convoluted streamer belt that would produce inflows? One possibility is that the inflows are present all of the time but are only visible when the streamer belt is seen face-on, as would happen when folds of a convoluted streamer rotate through the sky plane. A four-sector field would present twice as many face-on views as a two-sector pattern, effectively doubling the number of "inflow days" observed during each Carrington rotation. However, this simple increase in the number of face-on views would not produce multiple inflows like the ones that "rained down" at the rate of 10–20 per "quadrant" on some days in 1999 and 2000. Thus, we think it is more likely that the inflows are physically related to the bending.

Another property of a convoluted streamer is its intimate relation to nonpolar coronal holes. These holes are continually subject to distortion and erosion by flux transport processes, such as differential rotation, and by the emergence of new flux in active regions. Thus, it is possible that the coronal inflows are related to the magnetic field line reconnections that are thought to accompany the evolution of nonpolar coronal holes.

As Nash, Sheeley, & Wang (1988) illustrated for the coronal holes of a nonaxisymmetric dipole field, the reconnection occurs in two phases. There is an initial phase in which the hole maintains its shape and rotates almost rigidly without an appreciable loss of open flux. In this case, open field lines reconnect with closed ones, shifting open flux along the boundary of the hole to oppose the distortion. However, eventually this process is insufficient to prevent the distortion, and the reconnection enters a second phase in which the hole becomes deformed and loses open flux. In this case, the reconnection occurs between open field lines, and newly formed closed loops collapse from high in the corona as open flux is removed from the Sun. Further examples are described by Wang & Sheeley (1993) and by Wang, Hawley, & Sheeley (1996)

We cannot say which of these types of reconnection may be related to coronal inflows. It is possible that both types of reconnection occur and have signatures that correspond to some of the different kinds of inflow that we have observed. However, we suspect that most inflows (and especially the raining inflows with the sinking column structure) occur while open flux is being removed from the Sun. This hypothesis is supported by the fact that the nonpolar coronal holes were short-lived and longitudinally sheared when the inflow rate was high. Also, differential rotation would shear the coronal holes of a four-sector pattern twice as fast as those of a two-sector pattern and would reduce the time that they spend in the footpoint-switching phase of reconnection.

FIGURE 6

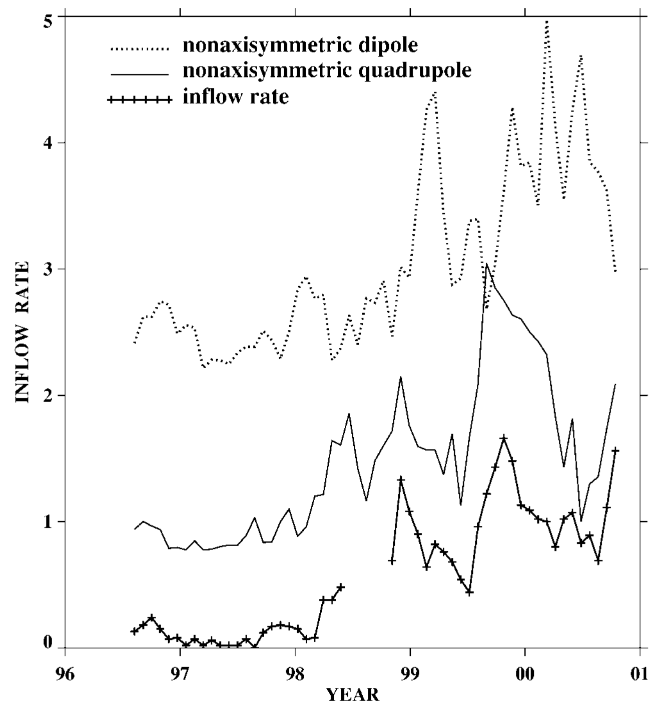

FIG. 6.—Nonaxisymmetric dipole and quadrupole moments of the photospheric field compared with the coronal inflow rate during 1996–2000 through Carrington rotation 1968 (September 30–October 27). The episodic increases of the inflow rate are matched better by the quadrupole than by the dipole, whose curves are expressed in arbitrary units and have been offset to reduce overlap.

On the other hand, Figure 5 seems to provide some evidence against this interpretation. The long-term decrease of the total open flux during 1996–1998 was not accompanied by a high rate of inflow. Also, the observed increases of the inflow rate were not accompanied by decreases of total flux or its nonaxisymmetric component. We think that these discrepancies reflect the difference between the relatively small net change and the relatively large total change of open flux each day. It took 3 years for the flux in the polar holes to disappear, whereas only five solar rotations are required for differential rotation to reduce the open flux in a nonaxisymmetric dipole field by one-half (Nash et al. 1988). And only 2.5 rotations are required for a quadrupole field. This suggests that much more open flux is lost each day from the erosion of nonpolar holes than from the gradual erosion of the polar holes. Also, as Sheeley, DeVore, & Boris (1985) described previously for the mean field, active regions tend to replace these relatively large decreases of open flux in a kind of "random walk" that depends on their longitudes of eruption. Thus, it seems likely that the relatively small net changes of open flux in Figure 5 are lost in the noise of the daily changes associated with coronal inflows and outflows.

It is interesting to consider some implications of the correlation between the inflow rate and the mean field strength for other epochs. In the previous two sunspot cycles, the mean field became unusually strong just after sunspot maximum, obtaining its largest values in 1982 and 1991. Apparently, this was caused by longitudinal fluctuations in the rate of magnetic flux eruption ("active" and "quiet" longitudes) as activity began

to decline (Sheeley et al. 1985; Wang, Sheeley, & Lean 2000). Thus, it is possible that a similar enhancement of the mean field strength and coronal inflow rate will occur a few years from now as the present sunspot cycle starts into its declining phase.

In the course of this work, we became aware that the cosmic-ray flux at Earth had significant decreases in 1982 and 1991 when the mean field was strong as well as in late 1996 and mid-1999 (H. Cane 2000, private communication). This planted the thought in our minds that a common factor might be responsible for these vastly different coronal and cosmic phenomena. Now, it appears that the nonaxisymmetric open flux is this common factor. In the corona, it is responsible for the field line reconnection that is apparently related to the inflows. In the heliosphere, it is responsible for the part of the field that solar rotation winds into a spiral structure that may shield the Earth from cosmic rays.

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