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THE LATITUDINAL EXCURSION OF CORONAL MAGNETIC FIELD LINES IN RESPONSE TO DIFFERENTIAL ROTATION: MHD SIMULATIONS

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ABSTRACT

Solar energetic particles, which are believed to originate from corotating interacting regions (CIRs) at low heliographic latitude, were observed by the *Ulysses* spacecraft even as it passed over the Sun's poles. One interpretation of this result is that high-latitude field lines intercepted by *Ulysses* connect to low-latitude CIRs at much larger heliocentric distances. The Fisk model explains the latitudinal excursion of magnetic field lines in the solar corona and heliosphere as the inevitable consequence of the interaction of a tilted dipole in a differentially rotating photosphere with rigidly rotating coronal holes. We use a time-dependent three-dimensional magnetohydrodynamic (MHD) algorithm to follow the evolution of a simple model of the solar corona in response to the differential rotation of the photospheric magnetic flux. We examine the changes of the coronal-hole boundaries, the redistribution of the line-of-sight magnetic field, and the precession of field lines in the corona. Our results confirm the basic idea of the Fisk model, that differential rotation leads to changes in the heliographic latitude of magnetic field lines. However, the latitudinal excursion of magnetic field lines in this simple "tilted dipole" model is too small to explain the *Ulysses* observations. Although coronal holes in our model rotate more rigidly than do photospheric features (in general agreement with observations), they do not rotate strictly rigidly as assumed by Fisk. This basic difference between our model and Fisk's will be explored in the future by considering more realistic magnetic flux distributions, as observed during *Ulysses* polar excursions.

Subject headings: MHD — solar wind — Sun: activity — Sun: corona — Sun: magnetic fields

1. INTRODUCTION

Solar energetic particles (SEPs) were observed by the *Ulysses* spacecraft as it passed over the polar regions of the Sun (Keppler et al. 1995; Maclennan et al. 1995; Posner et al. 2000; Zhang et al. 2003). This was surprising because SEPs are believed to be accelerated in corotating interacting regions (CIRs), which are present only at low latitudes (McDonald et al. 1976; Barnes & Simpson 1976). One mechanism that might account for this phenomenon is the perpendicular transport of SEPs from lower latitudes, where the CIRs are found, to higher latitudes (Jokipii 2001; Giacalone 2001). A second explanation was proposed by Fisk (1996) and Fisk et al. (1999), who argued that there is an organized meridional component of the heliospheric magnetic field connecting the lower latitude distant heliosphere with the spacecraft at high latitudes. The assumptions of the Fisk model, as it is known, are summarized succinctly in Fisk et al. (1999): (1) the heliospheric magnetic field is attached to a differentially rotating photosphere; (2) the high-speed solar wind expands nonradially from coronal holes; and (3) the expansion of the solar wind in polar coronal holes is around an axis that is offset from the solar rotation axis and that also rotates rigidly at approximately the equatorial rotation rate. This last assumption is equivalent to assuming that coronal holes rigidly rotate. The almost rigid rotation of some coronal holes, as well as the differential rotation of the photosphere, is supported by observation (Timothy et al. 1975) and has been studied with potential (Wang et al. 1996) and MHD (Lionello et al. 2005) models. Both studies concluded that magnetic field lines undergo magnetic reconnection as their footpoints enter and exit coronal-hole boundaries, which may remain relatively unchanged.

From the assumptions given above, Fisk and coworkers concluded that in the frame of reference that corotates with the equatorial rotation rate, heliospheric field lines will rotate about a new axis that is determined by the heliographic latitude of the field line that originates from the pole of the solar rotation axis. Because of the nonradial expansion of the magnetic field, this axis will, in general, be offset from both the axis of solar rotation and the axis of the dipole. The heliographic latitude of field lines will therefore change over time. A graphical representation of the assumptions and consequences of the Fisk model is given in Figures 1 and 3 of Fisk et al. (1999).

In this Letter we expand from the work of Lionello et al. (2005) and apply a three-dimensional, time-dependent MHD model (Mikić et al. 1999) to study the changes in the coronal magnetic field in response to differential rotation at the photosphere. We follow the evolution of the photospheric flux distribution (initially corresponding to a tilted dipole), identify the modifications in the coronal-hole boundaries, and determine any changes to the latitude of coronal magnetic field lines. We find that the basic idea of Fisk (1996) is confirmed by our computations; open magnetic field lines do indeed undergo latitude excursions. However, we find that the latitudinal excursion found in the simulations is not sufficient to explain a connection between low-latitude CIRs and the high-latitude regions traversed by *Ulysses*.

2. RESULTS FROM THE MHD MODEL

We have used the same MHD model that is described in detail in Lionello et al. (2005). On the solar surface we have imposed the differential flow of Newton & Nunn (1951):

$$\omega(\theta) = -2\overset{\circ}{.}77 \cos^2 \theta \ \mathrm{day}^{-1}. \qquad (1)$$

The overall rigid rotation rate of the Sun ($13\overset{\circ}{.}39$ day^{-1}) has been neglected.

On the solar surface we have prescribed a magnetic flux distribution corresponding to a 1 G dipole inclined by 30° from the

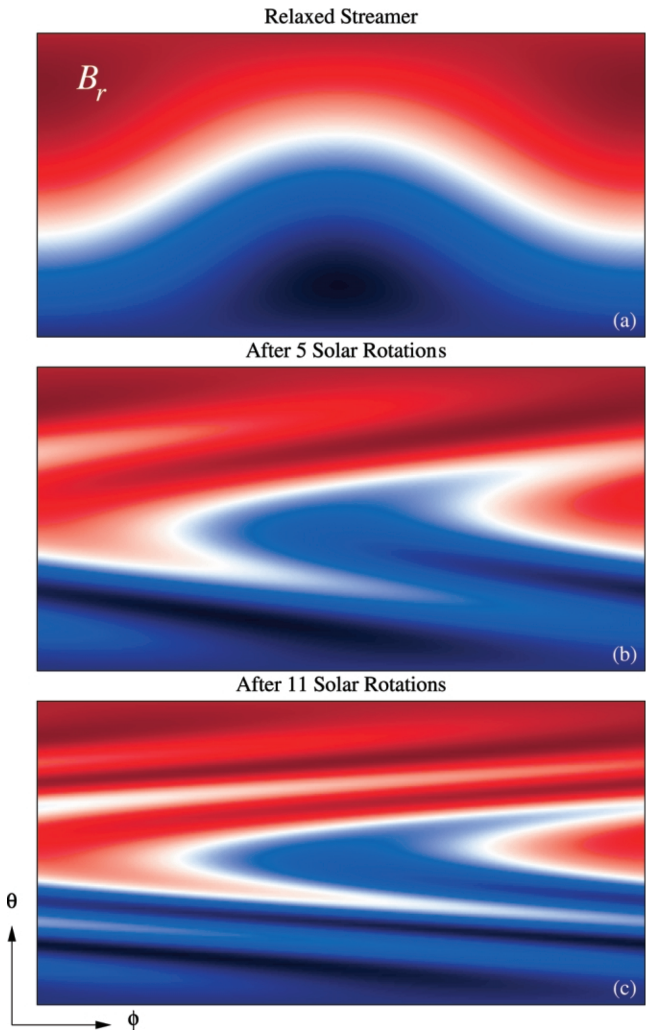

FIG. 1.—Radial component of the magnetic field, B_r, (*a*) at the beginning of the simulation, (*b*) after five solar rotations, and (*c*) after 11 solar rotations.

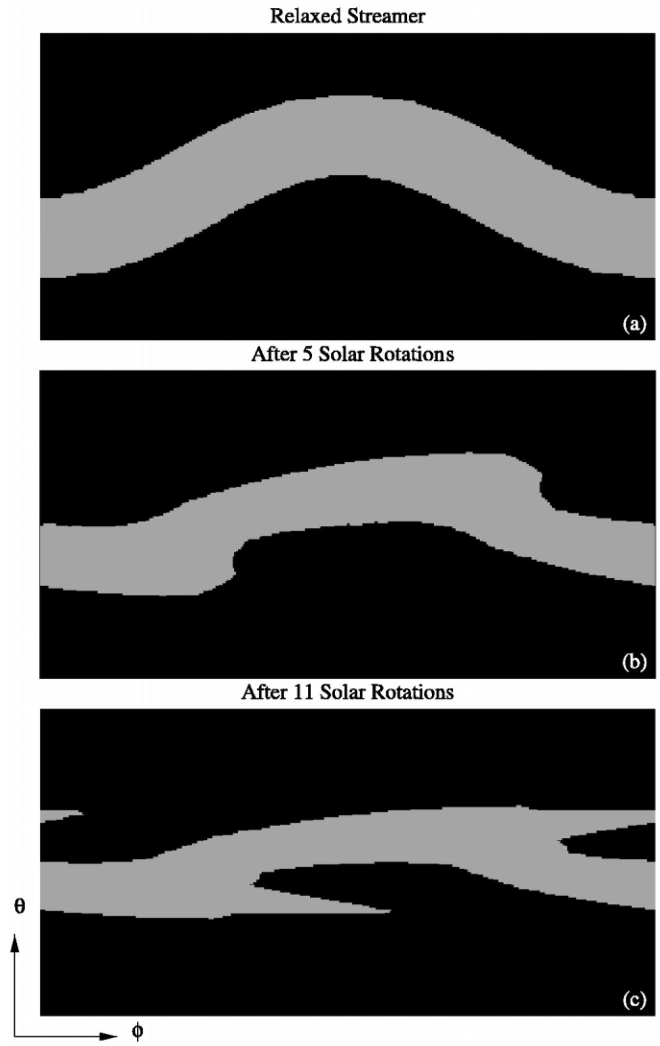

FIG. 2.—Coronal-hole boundaries (*a*) at the beginning of the simulation, (*b*) after five solar rotations, and (*c*) after 11 solar rotations. Gray areas are closed field regions, and black areas have open magnetic fields (coronal holes).

rotation axis. After a relaxation period of 64.5 hr, during which the initial field relaxed to a configuration with a streamer and a current sheet, we initiated differential rotation according to equation (1). We integrated the equations for about 11 solar rotations. Differential rotation distorts the original magnetic flux distribution significantly. Figure 1 shows the evolution of B_r at three instants in time: (1) the initial tilted dipole (Fig. 1*a*); (2) after five rotations (Fig. 1*b*); and (3) at the end of the simulation (11 rotations; Fig. 1*c*). The effects of differential rotation on the magnetic flux are more evident at higher latitudes, where the flow is larger.

Given the global magnetic field we can produce a "coronal-hole" map by tracing magnetic field lines from the solar surface. We distinguish between regions of open magnetic flux, which we define as coronal holes, and regions of closed magnetic flux. In Figure 2 we show the evolution of coronal-hole boundaries at the same times as Figure 1. Gray areas represent closed field regions, while black areas indicate coronal holes. Although the coronal-hole pattern is far less distorted than the magnetic flux distribution, the rotation of coronal holes is not completely rigid. This is evident in Figure 3, where we use crosses to indicate the rotation rates for different latitudes of coronal-hole boundaries as calculated with our model. These rates are compared with the rotation rate of photospheric magnetic features, as prescribed in equation (1), and with three best-fit curves obtained from observations of rotation of coronal holes (Timothy et al. 1975; Antonucci & Dodero 1977; Insley et al. 1995). Since the Fisk model assumes that coronal holes rotate strictly rigidly, its differential rotation rate is uniformly zero. The observations show considerable variability in the rotation rate of coronal holes but are certainly compatible with departures from strictly rigid rotation. In order to reconcile the rapid changes in the surface flux with the much slower evolution of coronal holes, magnetic reconnection must occur such that the footpoints of magnetic field lines are advected through the boundaries separating a coronal hole from the closed field region (Lionello et al. 2005).

In Figure 4 we plot the evolution of magnetic field lines on a surface at $r = 15\ R_\odot$, which is well beyond the Alfvén point. In the top sequence we show magnetic field lines intersecting the $r = 15\ R_\odot$ surface, which we follow to the upper boundary at $r = 30\ R_\odot$. The field lines are colored according to their latitude on the photosphere. The thick red field line starts from the north pole of the Sun, while other field lines are spaced 5° in latitude. The z solar rotation axis is in black. The bottom sequence shows the same surface ($r = 15\ R_\odot$) colored according to the latitude on the solar surface of the field lines connecting each point on that surface with the photosphere. A

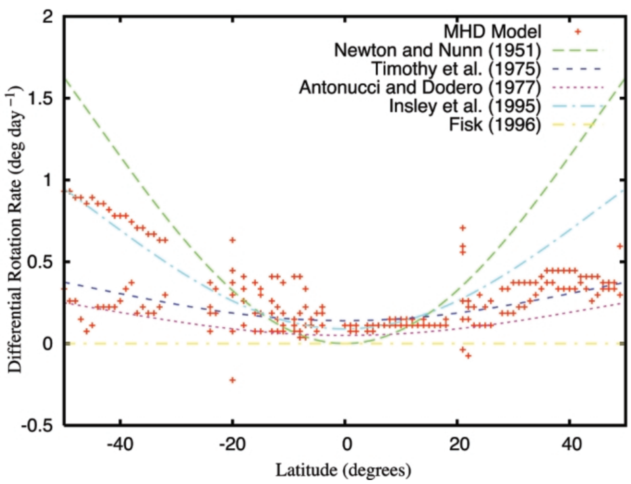

FIG. 3.—Differential rotation rates vs. latitude. The crosses indicate the angular velocities for the coronal-hole boundaries in our model. The differential rotation rate of Newton & Nunn (1951) was deduced from sunspot observations and has been prescribed in eq. (1). The best-fit curves to the coronal-hole rotation periods of Timothy et al. (1975), Antonucci & Dodero (1977), and Insley et al. (1995) are shown. The model of Fisk (1996) assumes strictly rigid rotation of coronal holes (i.e., zero differential rotation), and its curve coincides with the *x*-axis.

sharp discontinuity is noticeable at the current sheet, separating field lines that connect to the northern hemisphere of the Sun from those connecting to the southern hemisphere. Complete circles are made by field lines that evolve through differential rotation but never reconnect, since their footpoints are located at high latitudes and they never enter the closed field regions. In contrast, partial circles indicate field lines whose footpoints enter and exit the closed field region. The northern coronal hole expands into the solar wind around the magnetic field line that connects to the north pole of the Sun (Fisk et al. 1999).

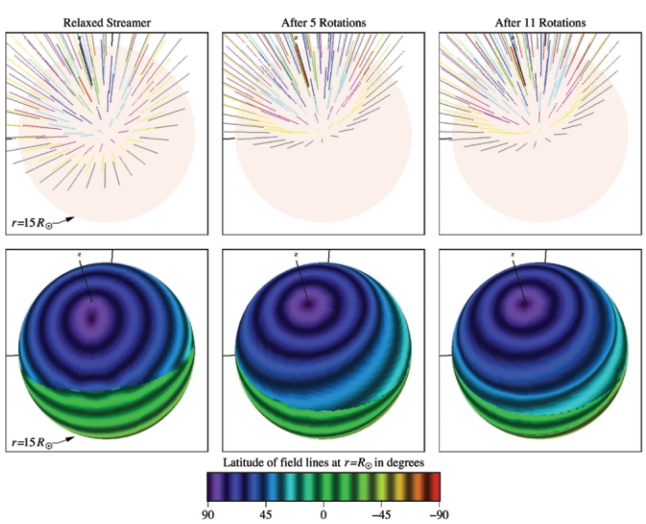

FIG. 4.—Evolution of differentially rotating field lines at 15 $R_\odot$. A surface at 15 $R_\odot$ is depicted in all frames. The top sequence shows field lines emanating from the solar surface and intersecting the r = 15 $R_\odot$ surface in the corona. Different colors correspond to different latitudes on the photosphere: the thick red field line starts from the Sun's north pole, the green field lines start from 85° of latitude, and the successive field lines are spaced at an interval of 5° in latitude on the solar surface. The bottom sequence shows the surface at 15 $R_\odot$, colored according to the photospheric latitude of the footpoint of the field lines intersecting it. Therefore, rings indicate field lines starting from the same latitude on the solar surface.

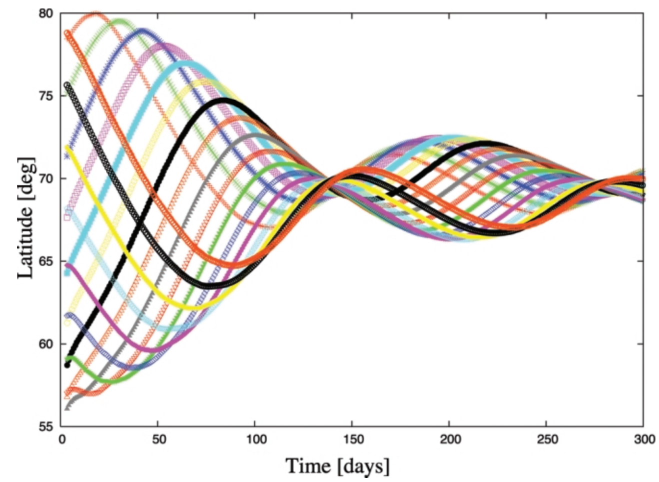

FIG. 5.—Field line latitude at the r = 15 $R_\odot$ surface vs. time. The field lines all start with a photospheric latitude of 75° and have a range of longitudes. The heliospheric latitude of the field lines changes over time, as predicted by Fisk (1996).

Note that the polar field line is distinct from the rotation axis and that it is not stationary; it precesses around the rotation axis. However, at the end of the simulation, the polar field line almost coincides with the polar axis. The panels in Figure 4 can be compared with Figures 1 and 3 in Fisk et al. (1999), which also show the motions of magnetic field lines in the corona. In the Fisk model the polar field line is much more separated from the rotation axis than shown by our results.

The latitudinal excursion of the magnetic field lines in the solar corona is shown in Figures 5 and 6. Figure 5 shows the latitudinal evolution of field lines (at 15 $R_\odot$) starting at 75° north on the solar surface as their footpoints are advected by differential rotation. These field lines initially span a range in latitude of approximately 25°. As the magnetic flux distribution changes in response to the differential flow, the excursion in latitude is damped, and the field lines migrate to approximately 70° heliographic latitude. In Figure 6 we plot the latitude at 15 $R_\odot$ as a function of time for field lines whose initial latitude was 35° at 15 $R_\odot$ in the relaxed streamer. These field lines

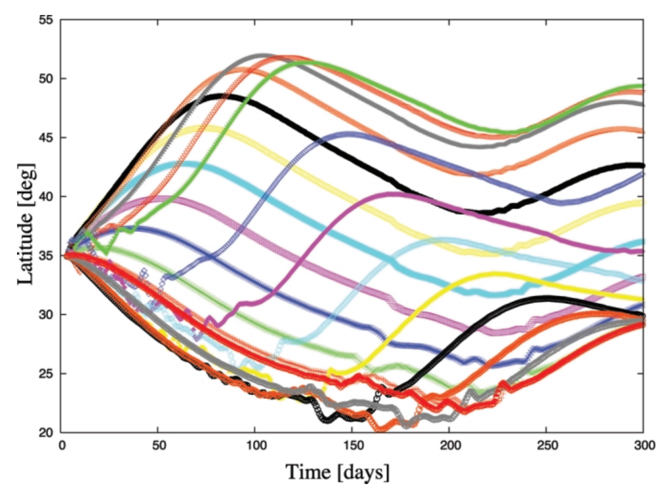

FIG. 6.—Field line latitude at the r = 15 $R_\odot$ surface vs. time. The field lines have a latitude of 35° at the r = 15 $R_\odot$ surface in the relaxed initial configuration and originate from a range of latitudes and longitudes. The variation of heliographic latitude of the field lines as a result of differential rotation can be seen.

originally at 35° at 15 $R_\odot$ may experience a maximum change in latitude of $+20°$ or $-15°$. In the later stages of the simulation, field lines tend to have small oscillations around a fixed heliographic latitude.

3. DISCUSSION

Our results confirm the validity of the basic idea of the Fisk model, namely, that open magnetic field lines in the corona undergo a variation in latitude in response to solar differential rotation. However, our simulations do not agree quantitatively with the predictions of Fisk (1996). Specifically, the maximum change in latitude is only about 25°, and this is much less than the ≈50° required by the *Ulysses* observations. After several rotations, the latitudinal range sampled by field lines actually diminishes.

The first important physical difference between our solutions and those of Fisk (1996) is that assumption 3 of the Fisk model, that coronal holes rotate strictly rigidly, is not satisfied in the actual simulations. The coronal holes are far less distorted than the underlying photospheric field, but the coronal streamer belt does change. Our computed differential rotation rates for coronal holes are compatible with those provided by observations (Timothy et al. 1975; Antonucci & Dodero 1977; Insley et al. 1995). Moreover, our coronal-hole distortion pattern is qualitatively similar to that calculated from source-surface models (Wang et al. 1996; Wang & Sheeley 2004). However, further analysis and comparisons between MHD simulations (with more realistic flux distributions) and observations are required to verify or refute our model. Because of the distortion of the coronal-hole pattern, the field line emanating from the solar rotation axis does not stay at the same latitude at $15R_s$ but instead precesses around its original position. The second important difference is that as the simulation proceeds, differential rotation smears the photospheric flux into bands, pushing the underlying photospheric magnetic field closer to azimuthal symmetry. This has the effect of reducing the "dipole" tilt over time. The maximum latitudinal excursion of the coronal field progressively decreases, and by the end of the simulation, field lines tend to oscillate around a fixed heliographic latitude. The "beating" of the latitude change observed in Figures 5 and 6 corresponds to the time period for a field line at a given latitude to circumvent its axis of precession.

The first effect discussed above, while different than what was envisioned by Fisk (1996), alters the evolution of the magnetic field but still leads to latitudinal excursions of field lines. The second effect limits this latitudinal excursion of field lines but is unrealistic; for the real Sun, differential rotation does not distort the underlying photospheric magnetic field to the extent seen in the simulations. That is because other flux evolution processes on the Sun such as flux emergence, dispersal, and meridional motions are not accounted for here. These processes replenish and redistribute the photospheric magnetic field and tend to mitigate the distortion by differential rotation over many rotations.

While our results call into question whether the Fisk model can quantitatively account for the presence of SEPs at high latitudes, they do not rule it out as an explanation. An important consideration is the expansion factor of the open field lines in the calculation. Magnetic flux distributions derived from solar magnetograms near solar minimum tend to produce fields with much larger expansion factors than the dipole field assumed by Fisk (1996) and used in this calculation. The larger the nonradial expansion of the field, the more the field line passing through the solar rotation axis is tilted away from that axis in this model, the effect that is necessary for differential rotation to yield large changes in the heliographic field lines. However, we note that our simulations used a dipole tilt of 30° away from the solar rotation axis while Fisk (1996) considered a 15° tilt. Reducing the dipole tilt to the value used by Fisk (1996) will decrease the range of latitudinal excursion further. Of course, a tilted dipole is only a rough approximation to the true heliospheric magnetic field. Determining whether the Fisk mechanism can quantitatively account for the *Ulysses* observations of SEPs requires simulations like those we have described here, but for initial configurations more closely related to those during the *Ulysses* spacecraft's passage to the southern heliospheric pole. We plan to perform such simulations in the near future.

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