THE TRANSPORT OF PHOTOSPHERIC MAGNETIC FLUX

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ABSTRACT

This paper briefly describes our current model for transporting magnetic flux on the Sun’s surface and mentions some results that have been obtained with the model. Special focus is placed on the reversal of the polar magnetic fields of the Sun and the influence that meridional flow may have in regulating the reversal from one sunspot cycle to the next. As an introduction to a longer-term study of white-light images obtained at the Mount Wilson Observatory, a preliminary analysis of continuum images from the Michelson Doppler Interferometer (MDI) on the Solar and Heliospheric Observatory (SOHO) spacecraft is briefly described.

1. INTRODUCTION

The objective of this paper is to summarize our ideas about the origin and evolution of magnetic flux on the Sun’s surface and to review some of the consequences of these ideas.

Following Leighton’s (1964) original suggestion, we suppose that all of the Sun’s magnetic flux originates in balanced concentrations called bipolar magnetic regions, and that the flux spreads out on the surface through the dispersive action of the non-stationary convective cells called supergranules. The result is a gradually expanding reticulated pattern whose grid size matches the 30,000 km characteristic cell size of the supergranular cells. The expanding patterns are sheared by differential rotation and carried poleward by a very slow meridional flow whose 10-20 m s⁻¹ speed takes a few years to go from the sunspot belts to the poles. (The existence of a poleward meridional flow was not known when Leighton formulated the flux-transport model and has been added to the model since that time.) Positive and negative fluxes are assumed to spread out independently, and to be removed when supergranular diffusion brings them in contact. The net contribution of all of the bipolar magnetic regions during a sunspot cycle gives rise to the evolving large-scale field of the Sun.

There are two aspects of this model that we should appreciate. First, it is not a dynamo. It is only part of a dynamo. A complete dynamo requires a feedback mechanism to generate new bipolar magnetic regions from the expanding fields. Second, the model is a way of understanding the contributions of bipolar magnetic regions to the large-scale field, and our numerical simulations are just a procedure for keeping track of these contributions. In effect, the simulations are a magnetic bookkeeping technique.

But the magnetic-flux transport simulations are a very important bookkeeping technique because they allow us to compare theories about how the magnetic fields may vary with observations of how they do vary. By bringing these theories and observations together, these simulations have led to interesting results about the origin of the sector structure (Sheeley et al., 1985; Sheeley & Devore, 1986), the rigid rotation of the corona (Wang et al., 1988) and coronal holes (Nash et al., 1988; Wang et al., 1989b; Wang & Sheeley, 1993), the temporal fluctuations of open flux and interplanetary field strength (Wang & Sheeley 2002, Wang et al. 2000a, Wang et al. 2000b, Wang & Sheeley 2003a), and the 11-year reversal of the polar magnetic fields (Leighton, 1964; Devore & Sheeley, 1987; Wang et al., 1989a; Wang & Sheeley, 1991; Rabin et al., 1991; Wang & Sheeley, 2003b). In this paper, I will concentrate on the reversal of the polar magnetic fields.

2. THE POLAR FIELD REVERSAL

The beauty of Leighton’s original model was that it provided a way of reversing the polar magnetic fields without meridional flow, for which there seemed to be little observational evidence in 1964. Supergranular diffusion and the systematic properties of the sources of flux were sufficient: Newly erupted flux was arranged with its leading polarity closer to the equator and its trailing flux closer to the poles, as described by Hale’s Law of sunspot polarities and
Joy’s Law of sunspot group tilts (Hale et al., 1919). Under the influence of diffusion, the trailing-polarity flux would arrive at the nearby pole sooner than the leading-polarity flux, and would be less diluted when it arrived. Thus, the net effect was for trailing-polarity flux to diffuse to the poles and cancel the polar field left there from the prior sunspot cycle. Similarly, leading-polarity flux diffused to the equator and cancelled its counterpart from the opposite hemisphere.

However, as time passed, new observations pointed to the presence of a poleward meridional flow. In their analysis of magnetograms obtained at the Mount Wilson Observatory, Howard & Labonte (1981) discovered episodic surges of flux that moved toward the poles without diffusing. In their analysis of magnetograms obtained at the Wilcox Solar Observatory, Svalgaard et al. (1978) deduced that the field at the 1976 sunspot minimum was much more concentrated toward the pole than one would expect for a simple dipole structure, as if a poleward meridional flow were holding the flux there (Devore et al., 1984; Sheeley et al., 1989). Such topknot polar fields were consistent with the sizes of the polar coronal holes, whose 30-degree half angles are large compared to those found for low-latitude coronal holes, but are much smaller than the 50-degree half angles that would be expected for a dipole field (Sheeley et al., 1989).

With meridional flow added to the model, we are faced with the question of how fast it is. Inferences based on our simulations suggest a speed on the order of 10–20 m s$^{-1}$, which is near the observational limit of Doppler measurements. If the speed were too fast, the leading-polarity flux would not diffuse across the equator to annihilate its counterpart in the other hemisphere, and instead would be carried to the poles with the following-polarity flux, causing the polar fields to oscillate, but not reverse. If the speed were too slow, then a large amount of leading-polarity flux would diffuse across the equator, and the excess of unbalanced trailing-polarity flux in each hemisphere would cause the new-cycle polar fields to be too strong.

Furthermore, a particular flow speed that successfully reverses the polar field in one sunspot cycle may not necessarily reverse the polar field in another sunspot cycle. In particular, Schrijver et al. (2002) and Lean et al. (2002) found that when a series of increasingly stronger sunspot cycles is followed by a weaker one (as happened during sunspot cycles 16-20), the meridional flow speed used in the strong cycles was insufficient to reverse the field during the weak sunspot cycle, contrary to observations. Schrijver et al. (2002) wondered if something might be missing from the flux-transport model, and noted that the reversal could be recovered if all of the Sun’s flux emerged with a life expectation on the order of 5 years.

Wang et al. (2002) took a different approach, noting that the unmodified flux-transport model would reverse the polar field if the meridional flow speed varied systematically with the level of solar activity. In particular, a slower flow during a weak cycle would produce more trans-equatorial diffusion and cancellation of leading-polarity flux and leave an excess of trailing-polarity flux in each hemisphere. If the flow speed were not too weak, it would carry this flux to the poles in a timely manner and reverse the polar fields. A faster flow speed during an active cycle would have the opposite effect, lessening the amount of trans-equatorial diffusion and leaving a smaller amount of unbalanced trailing-polarity in each hemisphere. Thus, the relevant question was not how fast the polar field reversed, but how much unbalanced trailing-polarity flux was available to reverse the field.

Fig. 1 summarizes Wang et al.’s (2002) calculations during the 100-year interval 1890–1990. When a constant speed of about 21 m s$^{-1}$ was used in the model, the polar field failed to reverse at times, as shown in the longitudinally averaged field plotted in the bottom panel. However, when the flow speed was increased by 6 m s$^{-1}$ in strong cycles and reduced by 6 m s$^{-1}$ in weaker cycles, the 11-year reversal persisted through the entire interval, as shown in the middle panel. This periodic reversal is also shown in the corresponding map of observations during the past 30 years, indicated in the top panel. Such modest speed variations are comparable to the variations that Wang et al. (1989a) deduced from their comparison of the observed and simulated field during sunspot cycle 21.

If meridional flow regulates the polar-field reversal, then it must be a link to the solar dynamo. By adjusting the flow speed according to the level of solar activity, we are involved in a feedback mechanism, and not just keeping track of flux. A number of speculations come to mind, including the possibility that a slower poleward flow speed during a weaker sunspot cycle would have a correspondingly slower subsurface return flow, and that this slower return flow might allow the subsurface field to wind up for a longer time and thus create more toroidal flux for the next cycle. However we think of it, this link to the dynamo provides strong motivation for studying indicators of poleward meridional flow during past sunspot cycles when high-quality magnetic observations were unavailable.

One source of historical data on magnetic-flux transport is the collection of white-light solar images obtained daily at the Mount Wilson Observatory since 1905. In addition to sunspots and low-latitude faculae that the Sun rotates into our view, there are faculae visible near the poles of the Sun during the years around sunspot minimum. Figure 2 shows the results of systematically counting the numbers of polar faculae during the times of year that they are
most visible from Earth (August-September for the north pole and February-March for the south pole) (Sheeley, 1964, 1976, 1991). Since 1952, the numbers of faculae have been assigned the polarities of the associated polar magnetic fields. Prior to 1952, the polarities were simply reversed when the numbers of faculae reached zero. For comparison, the sunspot numbers have been assigned the polarity of the trailing sunspots in each hemisphere.
Like the polar magnetic fields, the numbers of polar faculae show a cyclic variation, reaching their largest values around sunspot minimum and passing through zero near sunspot maximum in each cycle. The net effect is that the signed numbers of faculae and sunspots oscillate about 90 degrees out of phase, consistent with the idea that in each hemisphere the sunspot flux is responsible for the polar field 5 years later.

In addition to the overall cyclic variation of the numbers of polar faculae, there are some short-lived sporadic fluctuations. Notable examples occurred in the northern hemisphere during 1940–1942 and 1959–1961, and in the southern hemisphere during 1959–1960. In these cases, the numbers of polar faculae decreased suddenly, as if the buildup of the polar fields were interrupted by the arrival of opposite-polarity flux at the poles. These would be opportune times to examine the historical data for bursts of activity and episodic poleward surges of flux that might indicate variations of meridional flow speed. We intend to do this as the Mount Wilson Observatory (MWO) white-light images are digitized.

Meanwhile, we have begun to experiment with the 6767 Å continuum images obtained routinely since 1996 by the Michelson Doppler Interferometer (MDI) on the Solar and Heliospheric Observatory (SOHO) spacecraft (Sheeley & Warren, in preparation).
Figure 3. Comparison of an MDI 6767 Å continuum image (left) and a Mount Wilson Observatory white-light image (right) obtained on July 21, 2000. In each case, the solar limb darkening was removed prior to raising the contrast to emphasize faculae near the east and west limbs. Some of these east-limb and west-limb faculae are linked by a very faint stream of faculae trailing poleward across the southern hemisphere.

Figure 3 compares an MDI image with a digitized MWO white-light image obtained on August 21, 2000 near sunspot maximum. The limb darkening has been removed from these images and the contrast has been enhanced to show faculae at the east and west limbs. No polar faculae are visible. However, because the southern hemisphere of the Sun is tipped slightly away from the Earth (and SOHO) in August, a poleward migrating stream of faculae lies close to the south limb and parts of it are barely visible linking its leading and trailing ends at the west and east limbs.

Solar rotation ultimately carries the entire stream of faculae past our observational windows at the east and west limbs so that our limited views eventually span the entire stream. The top panel of Figure 4 shows the stream in a Carrington map, made from a series of east-limb glimpses. The stream of faculae lies near 180 degrees longitude in the southern hemisphere. For comparison, the middle panel shows the line-of-sight magnetic field obtained from central-meridian-weighted MDI magnetograms, and the bottom panel shows the corresponding faculae distribution obtained from west-limb glimpses. By comparing these maps, one can see a variety of evolutionary changes, including the eastward drift of the stream of faculae. The magnetic-field map helps to distinguish the white, trailing-polarity flux of this stream from black, leading-polarity flux that is following behind it at a lower latitude.

These maps refer to Carrington rotation 1966 (August 6–September 2, 2000), when the polar magnetic fields were weak and about to reverse. Consequently, the maps do not show polar faculae or their associated magnetic fields. However, Figure 5 contains maps obtained during Carrington rotation 1922 (April 24–May 22, 1997) when the polar fields were strong. These maps show faculae and concentrations of magnetic flux at high latitudes in both hemispheres.

We do not expect detailed agreement between the polar faculae in the east-limb and west-limb maps because the time difference of about 14 days greatly exceeds the one- or two-day lifetime of the supergranular cells that confine them. Similarly, we do not expect detailed agreement between the locations of the east-limb (west-limb) faculae and the flux elements observed at the central meridian 7 days later (earlier).

However, another factor that determines the locations of the faculae in these maps is the rate of differential rotation used in the map construction. For Figure 4 and 5, we used the Newton & Nunn (1951) rate, extrapolated to high latitudes from the sunspot belts where the measurements were made. At high latitudes, these maps are far superior to the ones we obtained using a latitude-independent Carrington rate, which blurred the polar faculae so much that they were not visible. On the other hand, the polar faculae in these Newton-and-Nunn-based maps are shifted slightly from the polar faculae in maps we constructed using the Snodgrass (1983) rate, which was determined by cross correlating magnetic fields below 60 degrees latitude and therefore required less...
Figure 4. Carrington maps generated from east-limb faculae (top), central-meridian-weighted magnetic fields (middle), and west-limb faculae (bottom) for rotation 1966 (August 6 – September 2, 2000) near sunspot maximum. The stream of faculae trailing toward the south pole near 180 degrees longitude is the same region that is only marginally visible in Figure 3. At this time, the polar fields are weak and polar faculae are not visible.
Figure 5. Carrington maps generated from east-limb faculae (top), central-meridian-weighted magnetic fields (middle), and west-limb faculae (bottom) for rotation 1922 (April 24 – May 22, 1997) near sunspot minimum. At this time, large numbers of polar faculae and their unipolar flux elements are visible.
of an extrapolation. Our plan is to determine the high-latitude rotation rate using MDI images of polar faculae and then to use this rate to construct improved Carrington maps of faculae.

3. SUMMARY AND CONCLUSIONS

The magnetic-flux transport model has been used to study a variety of solar and heliospheric problems and has led to discoveries in areas of sector structure, coronal holes and their rotation, open flux and interplanetary field strength, and the reversal of the polar fields. In particular, flux-transport simulations over several sunspot cycles have led to the question of whether the polar field reversal is regulated by a systematic variation of meridional flow speed with the level of sunspot activity. To answer this question, we plan to look for inferences of meridional flow speed in historical synoptic observations such as the white-light images obtained at the Mount Wilson Observatory. A prototype examination of the MDI continuum images during the present sunspot cycle is already revealing new facts about the Sun.

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