Reproducing the Photospheric Magnetic Field Evolution During the Rise of Cycle 24 with Flux Transport by Supergranules

David H. Hathaway[1] & Lisa Upton[2]

[1]NASA Marshall Space Flight Center, Huntsville, AL

[2]The University of Alabama in Huntsville, Huntsville, AL

ABSTRACT

We simulate the transport of magnetic flux in the Sun's photosphere by an evolving pattern of cellular horizontal flows (supergranules). Characteristics of the simulated flow pattern match observed characteristics including the velocity power spectrum, cell lifetimes, and cell pattern motion in longitude and latitude. Simulations using an average, and north-south symmetric, meridional motion of the cellular pattern produce polar magnetic fields that are too weak in the North and too strong in the South. Simulations using cellular patterns with meridional motions that evolve with the observed changes in strength and north-south asymmetry will be analyzed to see if they reproduce the polar field evolution observed during the rise of Cycle 24.

Introduction

Models of the 2D transport of magnetic flux in the solar photosphere have been produced by several investigative groups starting with the NRL group in the mid 1980s (e.g. Sheeley, DeVore, & Boris 1985 *Solar Phys.* 98, 219). These models had their roots in 1960s with the work of Horace Babcock and Bob Leighton. The central hypothesis is that magnetic flux emerges through the photosphere in Bipolar Magnetic Regions – sunspot groups – and is then transported across the surface by the near surface flows – Differential Rotation, Meridional Flow, and Supergranular (cellular) Flows. This transport leads to flux cancelation where opposite polarities meet and to the build-up and reversals of the polar fields.

Early models parameterized the transport by supergranules with a diffusivity and a Laplacian operator and used Meridional Flow profiles only loosely based on observations. We now have accurate measurements of the Meridional Flow and its variations since mid-1996 (Hathaway & Rightmire 2010 *Science* 327, 1350; Hathaway & Rightmire 2011 *ApJ* 729, 80) as well as detailed models of the supergranular flows and their temporal variations (Hathaway et al. 2010 *ApJ* 725, 1082; Hathaway 2012 *ApJL* 749, L13; Hathaway 2012 *ApJ* 760, 84).

We have constructed a Surface Flux Transport model which employs these observed flows without recourse to free parameters.

We have found that it is critically important that the supergranules themselves move with the observed Meridional Flow and Differential Rotation. Without this, the magnetic elements do not exhibit the observed Meridional Flow and Differential Rotation. (The magnetic elements are rapidly carried to the boundaries of the supergranules. If those boundaries don't move properly then the magnetic elements also don't move properly.)

Flux Transport and Synchronic Maps

We use our Surface Flux Transport model to construct Synchronic Maps (Fig. 1) of the magnetic field at 15-minute intervals from March 1999 to October 2012. The magnetic flux is transported by supergranule flows which are also constructed at 15-minute intervals. Data is assimilated from MDI magnetograms at 96-minute intervals or, when available, HMI magnetograms at 60-minute intervals.

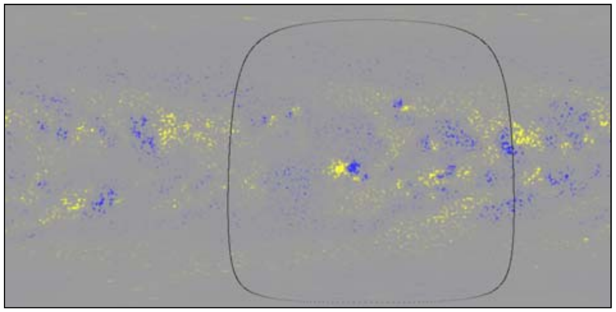

Figure 1. A Synchronic Map of the Sun's photospheric magnetic field for 2001/01/01 00:00UT. Data from *SOHO*/MDI has just been assimilated in the area outlined in black. The evolving pattern of supergranules transports vertical magnetic flux (yellow-up, blue-down) across the entire solar surface.

Photospheric Magnetic Field Evolution

NSO/Kitt Peak has constructed Synoptic Maps of the Sun's magnetic field from daily observations with few gaps since 1970. (Synoptic Maps insert fields observed daily near the central meridian into each map at the appropriate Carrington longitude.) Longitudinal averages of the magnetic field in each map can be used to construct a magnetic "butterfly diagram" (Fig. 2) which reveals the poleward transport of magnetic flux from the active latitudes. Averaging these latitudinal profiles of magnetic field over latitudes poleward of 55° gives a measure of the polar fields which reveals the polar field reversals and their asymmetries (Fig. 2).

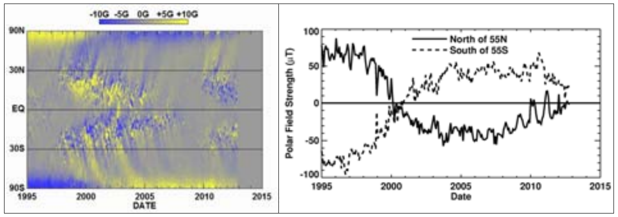

Figure 2. Left: The magnetic butterfly diagram constructed from NSO/Kitt Peak Synoptic maps. Right: The polar fields derived from the magnetic butterfly diagram. The polar fields at Cycle 22/23 Minimum in 1996 were nearly twice as strong as those at Cycle 23/24 Minimum in 2008.

Flux Transport Experiments

We ran two flux transport experiments with our Surface Flux Transport model using two different Meridional Flow profiles:

1. The time averaged and symmetric Meridional Flow
2. The time varying and asymmetric Meridional Flow

Experiment Results

The evolution of the photospheric magnetic field when the average and symmetric Meridional Flow is used for the flux transport is shown in Fig. 3. The evolution when the time-varying and asymmetric Meridional flow is used is shown in Fig. 4. The Meridional Flow profiles (as input to the supergranule pattern and as measured from magnetic element motions in the synchronic maps) for early 2006 are shown in Fig. 5.

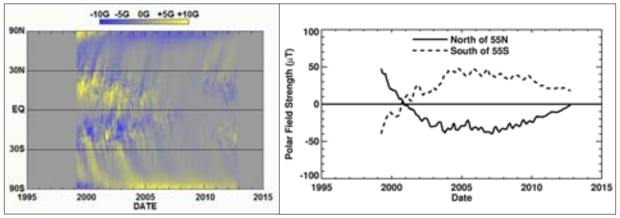

Figure 3. Magnetic field evolution from MDI/HMI Synchronic maps with flux transport by the average/symmetric Meridional Flow.

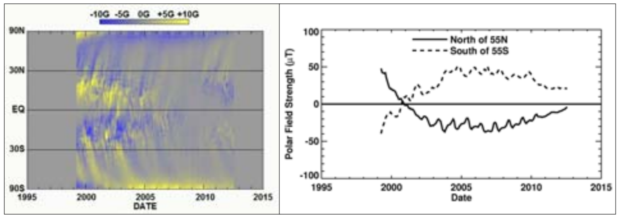

Figure 4. Magnetic field evolution from MDI/HMI Synchronic maps with flux transport by the time-varying, asymmetric Meridional Flow. The polar field is weakened in the north and strengthened in the south.

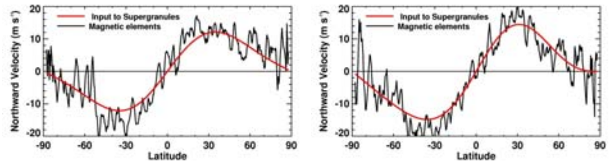

Figure 5. Meridional Flow profiles for early 2006. The profiles imposed on the supergranules are shown in red. The profiles measured by the magnetic element motions in the unassimilated areas are shown in black. The average/symmetric profiles are on the left. The variable/asymmetric profiles are on the right.

Conclusions

The polar fields react to even small changes in the meridional flow. The north-south asymmetry in the meridional flow (faster at high latitudes in the south from 2000 to 2010) is reflected in the strengthened polar fields.

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