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Reconstruction of magnetic field surges to the poles from sunspot impulses

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Abstract. The time-latitude diagram of the photospheric magnetic field of the Sun during 1975-2011 (Kitt Peak NSO, SOLIS NSO, SOHO MDI data) is analyzed using Gnevysvev's idea of impulsed structure of sunspot cycle and a flux transport concept. It is demonstrated that poleward migrations of magnetic trailing polarities are closely associated with the impulses of sunspot activity. We use a fitting procedure to reconstruct the sunspot impulses and poleward magnetic field surges. We compare our results for Cycle 22 model with the time-latitude diagram of the photospheric magnetic field of the Sun.

Keywords. Sun: activity, Sun: magnetic fields, (Sun:) sunspots.

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1. Introduction

1.1. *Sunspot impulses*

Gnevyshev(1938) proposed a hypothesis of spatio-temporal organization of sunspot activity over the solar surface based on impulses. The scale of these impulses is some tens of degrees in latitude and from 0.5 to 2 years in duration (Antalová & Gnevyshev 1983). The times at which impulses appear in both hemispheres may not be the same. The 11-year cycle consists of two or more superposed impulses, which peak at different times at different latitudes and do not always obey Spörer's law (Zolotova & Ponyavin 2011a). Additionally, the Gnevyshev gap can be observed separately in each hemisphere (Temmer *et al.* 2006; Norton & Gallagher 2010).

By means of a Gaussian random field approximation we modeled the solar cycle shape in the northern and southern hemispheres (Zolotova & Ponyavin 2011b; Zolotova & Ponyavin 2012). We specified the distribution parameters and overlapping proportions. Then, we designed different lengths, magnitudes of cycles, the presence of the Gnevyshev gap or a single-peaked activity cycle separately for each hemisphere. We have shown that even weak sunspot impulses can change the shape of the cycles — the declining phase becoming longer than the ascending one (the Waldmeier Effect). It was demonstrated that using only the convolution of activity over latitude (e. g., area or sunspot number data) makes it difficult to recognize impulses. Even a monotonic decay of activity may be consistent with them. The overlapping of impulses hides the internal structure of the cycle. Finally, why the solar cycle consists of impulses is still a puzzle.

1.2. *Magnetic field surges*

Leighton (1964) proposed that the polar magnetic field reversals are the result of trailing polarity transport by supergranular diffusion. On the contrary, Howard & LaBonte (1981) suggested that the transport of magnetic field poleward does not occur by diffusion, but by directed flow.

While the role of diffusion is annihilating the leading flux at low latitudes, that of the meridional flow is to transport the net surplus of trailing flux to the poles, with only a minor help from diffusion (Wang *et al.* 1989). These authors suggest that if supergranular diffusion did not exist, meridional flow would convect equal amounts of leading and trailing flux to the poles, producing no net change in the polar fields. A high diffusion itself (without meridional flow) is able to reverse the polar fields (Leighton 1964; Baumann *et al.* 2004).

Howard & LaBonte (1981) noticed that the polar field formation is not continuous but episodic by the movement of the magnetic field from the sunspot latitudes to the poles. Further, Wang *et al.* (1989) determined the magnetic field surges as poleward-moving streams (waves) of either polarity. In flux-transport models the surges are a result of meridional flow on the diffusion background (Wang *et al.* 1989; Baumann *et al.* 2004).

In this paper, we reconstruct magnetic field surges from sunspot impulses without diffusion assignment. Impulses are derived from observational data. Using the meridional flow and latitudinal separation between the leading and trailing spots, we model the poleward magnetic field surges.

2. Impulse–surge relation

Figure 1 shows the time-latitude diagram of the photospheric magnetic field of the Sun from 1975 to 2011 (Kitt Peak NSO, SOLIS NSO, SOHO MDI data — Scherrer *et al.* 1995; Keller 1998) with imposed sunspot impulses for Cycles 21 to 23. Black contours delineate impulses of sunspot activity and color gradation of impulses indicates sunspot density. To reconstruct sunspot impulses we used the RGO/USAF/NOAA daily data set of sunspot positions (http://solarscience.msfc.nasa.gov/greenwch.shtml). Sunspot impulses were derived independently for each cycle, from Cycle 21 to 23.

It is seen that each sunspot impulse produces the latitude migration of unbalanced flux (poleward magnetic field surge) of new polarity in each hemisphere, whereas waves of old polarity occur in gaps between impulses.

We reproduced magnetic field surges as a result of meridional transport of a net surplus to the poles. The surplus is the difference between distributions of leading and trailing

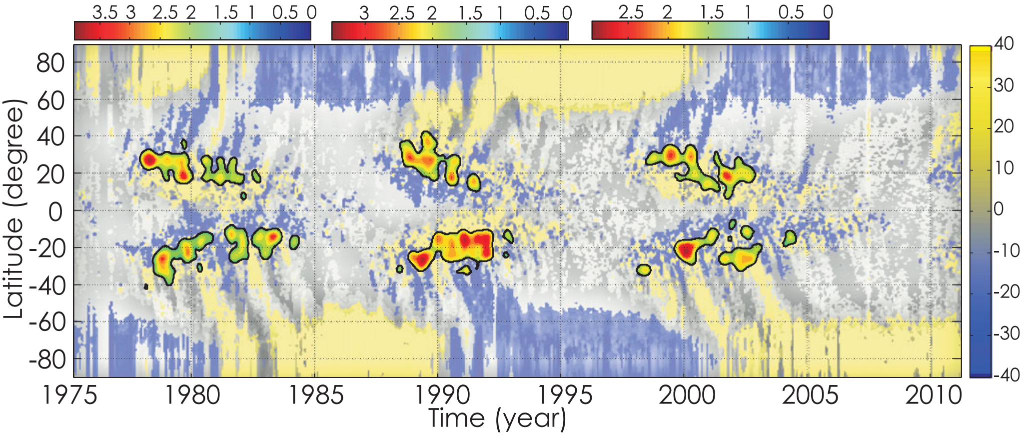

Figure 1. A magnetic butterfly diagram with imposed sunspot impulses from 1975 to 2011. Impulses are inside of the black contours.

polarities of bipolar sunspots. Thus, for surge reconstruction we required: sunspot impulses, meridional flow, and the value of the latitudinal separation between leading and trailing sunspots.

In models, it is usual to consider the effective turbulent diffusivity as a constant value (typically 600 $\mathrm{km}^2/\mathrm{sec}$) within a wide range (50–1500 $\mathrm{km}^2/\mathrm{sec}$) (see e.g., Wang *et al.* 1989; Baumann *et al.* 2004). However, there are not experimental measurements of diffusion on the Sun. Fortunately, the use of distributions permits modelling without diffusion assignment.

We defined the meridional flow pattern using an inverse proportionality to the cycle shape. To specify the north-south asymmetry of the meridional flow (Hathaway & Rightmire 2010) we modulated the meridional flow profile back in the past separately by hemisphere:

$$\upsilon = \begin{cases} (\upsilon_m - A_n/1000)\sin(\pi l/l_0), & for \quad 0^\circ < l < 90^\circ; \\ (\upsilon_m - A_s/1000)\sin(\pi l/l_0), & for \quad -90^\circ < l < 0^\circ, \end{cases} \tag{2.1}$$

where υ_m is the maximal value of the meridional flow (we use 2.74^0 in latitude per solar rotation, corresponding to $\sim$14 m/sec), A_n and A_s are the average sunspot areas in each hemisphere, l is the latitude, and l_0 is the latitude at which the meridional flow vanishes.

We determined the latitudinal separation Δl between leading and trailing sunspots using:

$$\Delta l = \Delta d \tan(0.5l). \tag{2.2}$$

where $\Delta d = 10^\circ$ is the longitudinal separation and $\alpha = 0.5l$ is the tilt angle.

Figure 2a shows sunspot impulses from 1985 to 1997. By means of latitudinal separation Δl we calculated the distributions of leading and trailing polarities of bipolar sunspots and the surplus. Applying the meridional flow pattern (Fig. 2b) to the surplus, we reconstructed poleward magnetic field surges of new and old polarities (Fig. 2c). Notice the absence of magnetic polarity cancellation across the equator. Figure 2d shows the observed photospheric magnetic field of the Sun during Cycle 22. It follows from

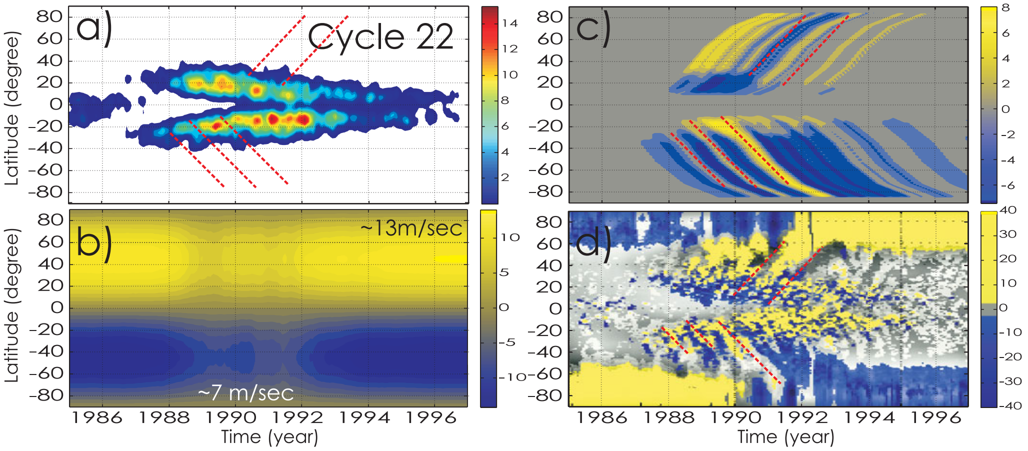

Figure 2. (a) Sunspot activity impulses of Cycle 22, reconstructed for a smoothing window $dx \times dy = 0.3 \times 0.2$ and iteration steps $i = 10$. (b) Pattern of meridional flow. (c) Reconstructed magnetic field surges. (d) Magnetic butterfly diagram for Cycle 22. Red (see the online version of the paper) dashed lines mark surges of old polarity.

comparison between model simulations and observations that waves of leading polarity to the poles correspond to gaps between sunspot impulses. Red (see the online version of the paper) dashed lines mark old polarity waves. The positions of these lines and their slopes are identical in Figures 2c and 2d. In addition, variations of meridional flow lead to variations of the magnetic field surge slopes in the time-latitude plane, but not of the surge intensities, which are determined by the intensities of the impulses (Fig. 2a).

Weak impulses in the northern hemisphere before 1990 (Fig. 2a) are not able to produce the magnetic field polarity reversal (Fig. 2d — northern hemisphere between 1988 and 1991). In comparison, activity as the impulses in the southern hemisphere (Fig. 2a) are stronger, hence, the first sunspot impulse between 1989 and 1990 already produced the polarity change (Fig. 2d — southern hemisphere between 1990 and 1991).

3. Conclusions

In this paper, we used a data set of sunspot positions to reconstruct activity impulses for Cycles 21 to 23. We showed that each sunspot impulse produces a poleward wave of new (trailing) polarity with unbalanced magnetic flux. Old (leading) polarities do not annihilate across the equator, but are transported to the poles. The meridional flow plays the role of transporting the net magnetic surplus. Due to bipolar sunspot tilts the old polarity surplus is located closer to the equator, whereas the new polarity surplus is at higher latitudes. As long as the tilt vanishes towards the equator, the old surplus is weaker than the new surplus (a geometric effect). While moving towards the poles, the old polarity surplus is cancelled by the new one. Thus, impulses of bipolar sunspots cause only new polarity poleward spike-like waves. Gaps between impulses create old polarity magnetic field surges. This is also due to the heliographic location of impulses and their occurrence rate during a solar cycle. We will demonstrate this effect in a coming paper. Impulses for Cycles 10 to 23 have been already reconstructed (Zolotova & Ponyavin 2012). Finally, we stress that variations of the meridional flow magnitude lead to variations of the surge slope in the time-latitude plane, but not of the surge intensity, which is determined by the intensity of the impulses.

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Discussion

Emre Işik: The latitude dependence of the tilt angle is a critical ingredient in your model. Recent data analysis by Dasi-Espuig *et al.* (2011) gives a coefficient which is a factor two smaller than what you assume. Have you tried different values for the coefficient in Joy's law?

Nadezhda Zolotova: We started from the usually used ratio $\alpha = 0.5l$. In a future work we will consider tilt variations according to newer findings.

Andrés Muñoz: I think you are on to something regarding the fact that when you have high concentrations of active regions that will be more important for determining surges in the sense that that will make a chain and produce a net flux separation. But, I think that diffusion is an important ingredient as is seen in the flux transport simulations of Wang and Sheeley where they look at the slope of the surges, and what it would be if only meridional transport is included, and what it would be if diffusion is included. What they find is that to match the slope of what you observe at the Sun you have to include diffusion.

Nadezhda Zolotova: I said that we do not use diffusion in the simulations because we work in terms of distributions. Such trick lets us make our simulations without a parameter for the effective diffusivity.