Role of sunspots in the polar magnetic field reversal on the Sun

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Abstract

Using Greenwich catalogue of sunspots and magnetic field observations it was shown that impulses of sunspot activity during a course of solar cycle are responsible for residual magnetic flux transported by meridional circulation toward the poles. This, in turn, is related to the polarity reversal of the axisymmetric magnetic fields. Magnetic field reversals at solar poles during 1875-2012 are reconstructed. Asymmetric strength of surges in hemispheres, relationships between the strong cycles 18 and 19 with the strength of the polar magnetic field at solar minimums are discussed. Asynchronous reversals in both hemispheres are related also to the phase differences between northern and southern activities.

Method

1) Use the observational RGO/USAF/NOAA daily data set of sunspot area and positions. Define the magnetic flux from individual sunspot equal to:

-- magnetic field strength (Houtgast and Sluiters 1948):

$Flux = 6247 + 475 \cdot \log(A + 0.00002)$, where A is area;

-- area.

2) Derived impulses by means of average of flux distribution from sunspots on time–latitude plane. The magnetic flux from sunspot impulse is equal to its magnitude.

3) Calculate the latitudinal separation between leading and trailing spots of Bipolar Magnetic Region (BMR):

$\Delta l = 10 \cdot \tan(0.5 \cdot l)$, l is latitude.

4) Separate fluxes of leading and trailing spots:

$Flux_{\text{trailing}}(l, t) = Flux_{\text{leading}}(l + \Delta l, t) \cdot 1.01.$

1.01 is flux imbalance in absence of diffusivity (see Motivation).

5) Calculate the latitudinal profile of meridional flow:

$$\upsilon(l) = \begin{cases} \upsilon_0 \sin\left(\dfrac{\pi l}{l_0}\right), & if\ |l| < |l_0|; \\ 0, & otherwise. \end{cases}$$

5) Calculate flus surplus: $S(l, t) = Flux_{\text{leading}}(l, t) - Flux_{\text{trailing}}(l, t)$

6) Use autoregression to reconstruct surges:

$S_{\text{Result}}(l_{n+1}, t_{n+1}) = S(l_{n+1}, t_{n+1}) + S(l_{n+1} - \upsilon \cdot (t_{n+1} - t_n), t_n)$.

Due to flux imbalance a poleward surges in hemispheres have new (trailing) polarity.

Conclusions

- Strong surges of the magnetic field to the poles originate from powerful sunspot impulses. The polar field reversals are intimately related to the sunspot impulses. Their behaviour exhibits long-term dynamical evolution.
- The weakening of the polar fields during the recent minimum is more associated with decrease in the field strength of sunspots (Livingston and Penn, 2009) and the decrease in nominal sunspot counts (decrease in sunspot impulses intensity) along the cycle 23 with respect to the cycles 21 and 22.
- We suggest that an alternation of old and new polarity surges, current weakness of polar magnetic field are not result of speed variations of the meridional flow.

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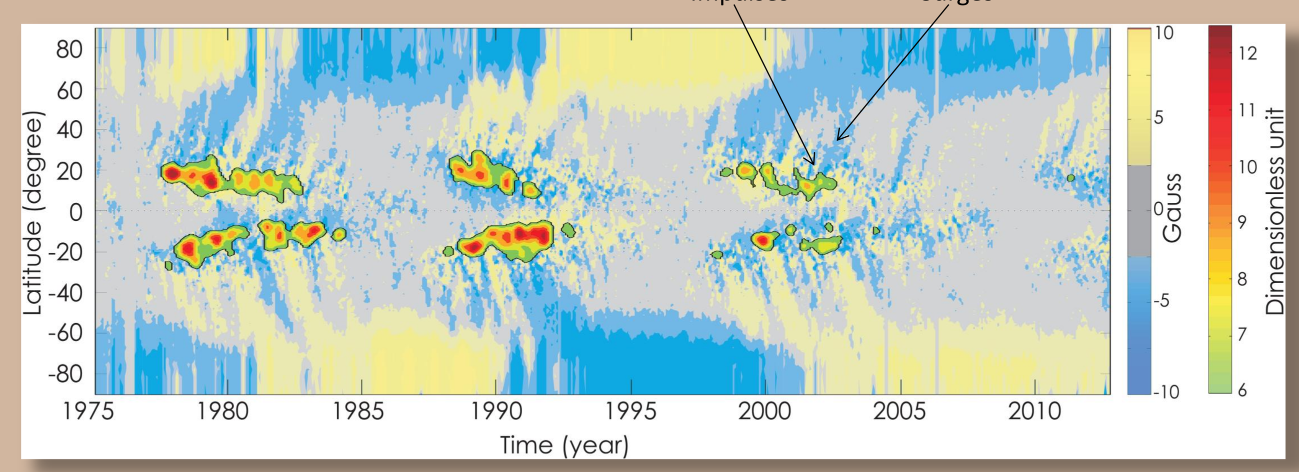
Motivation

<u>Sunspot impulse is</u> concentration of sunspots on latitude-time plane. The scale of impulse is some tens of degrees in latitude and in duration from 0.5 to 2 years (Antalova and Gnevyshev 1983).

<u>The magnetic surge</u> is poleward moving streams of either polarity (Wang et al. 1989) .

<u>Relation</u>: Each impulse generates both old and new polarity surges, but superposition of impulses suppresses old polarity surges. Thereby, the surges of old polarity are observed in gaps between impulses (Zolotova and Ponyavin 2012). Svalgaard and Kamide (2013) found that asynchronous reversals in hemispheres are a consequence of sunspot asynchrony (Zolotova and Ponyavin 2009, 2010).

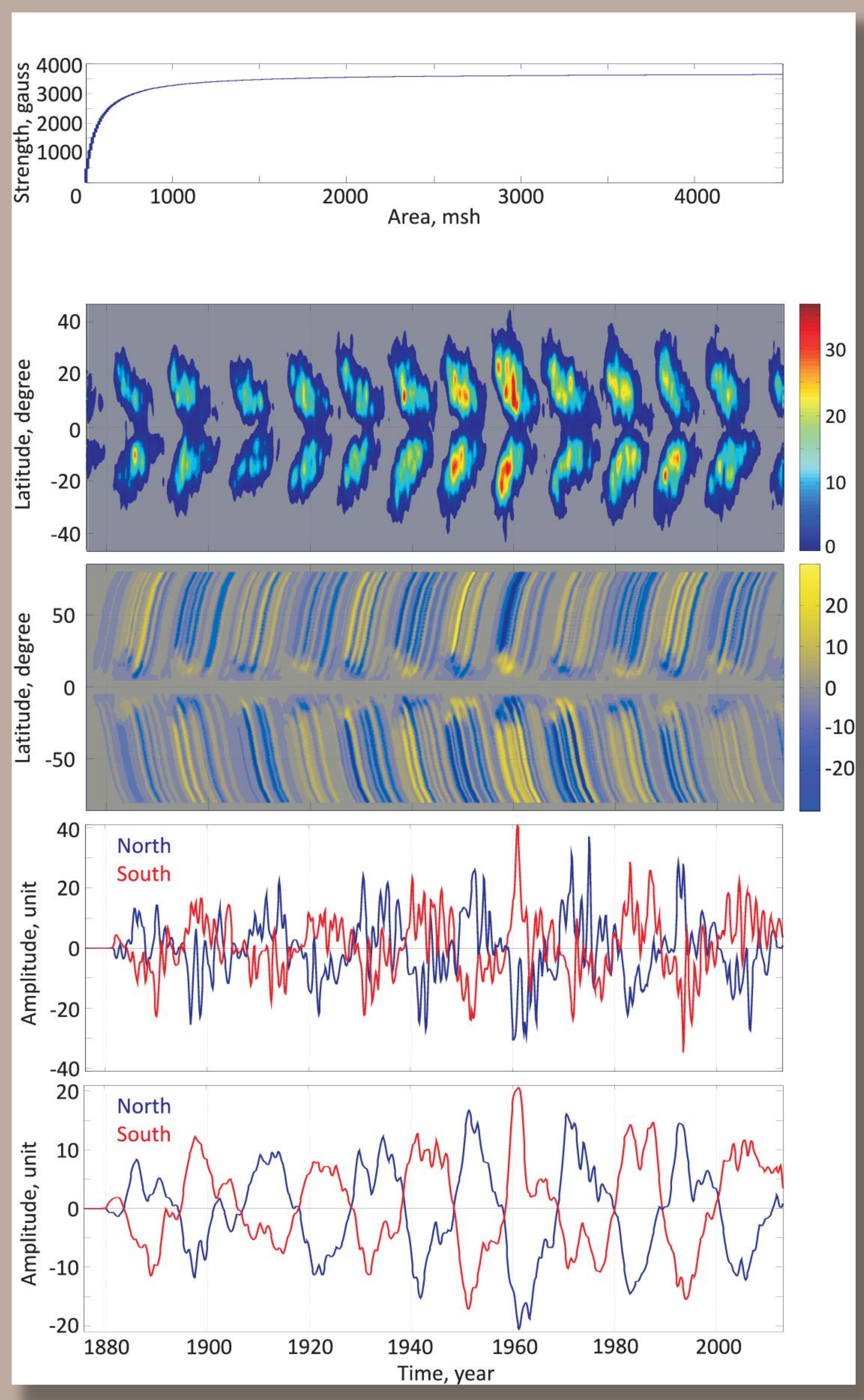


To consider impact of only sunspot population to the surge strength and avoid influence of competition between the meridional flow and diffusion at different latitudes, we perform modeling without explicit diffusivity assignment and without time variations of speed of meridional flow. In absence of diffusivity we specify a slight imbalance between leading and trailing fluxes of BMR --- less then 10% for benefit of total flux of trailing spots in each hemisphere (total flux over the whole solar surface is zero in each moment of time). That leads to the so-called surplus of imbalanced flux. Finally, we use autoregressive procedure to transport a both polarity surplus to the poles.

In flux-transport models a competition between the meridional flow and diffusion defines the surge strength (Wang et al. 1989, Sheeley 2010). Due to speed dependence of the meridional flow from latitude (Hathaway and Rightmire 2010), an emerged sunspot at different latitudes are exposed to different joint action of the meridional flow and diffusion. Even a ~15% increase of flow speed is enough to dramatically change the surge strength and, in turn, suppress the strength of polar field up to 40-50% (Schrijver and Liu 2008; Wang et al. 2009; Sheeley 2010; Nandy et al. 2011).

Diffusion also is a crucial parameter influencing on cycle characteristics. There are different diffusivity estimations: for sunspots decay 10 km^2 s^{-1} (Hathaway and Choudhary 2008); for the quiet Sun 100 km^2 s^{-1} (Rüdiger et al. 2012); typically 600 km^2 s^{-1} used to fit simulations on solar surface and synoptic magnetic data (Baumann et al. 2004).

Modeling strength of poleward magnetic surges

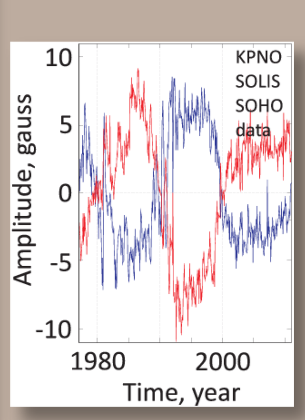


--- Normalization function – to transform area to the magnetic field strength of a spot (Houtgast and Sluiters 1948). It is known, that during the cycle 18 there were observed five history's biggest sunspots with magnetic field strength more then 3000 G (Pevtsov et al. 2013). However, normalization does not account large sunspots.

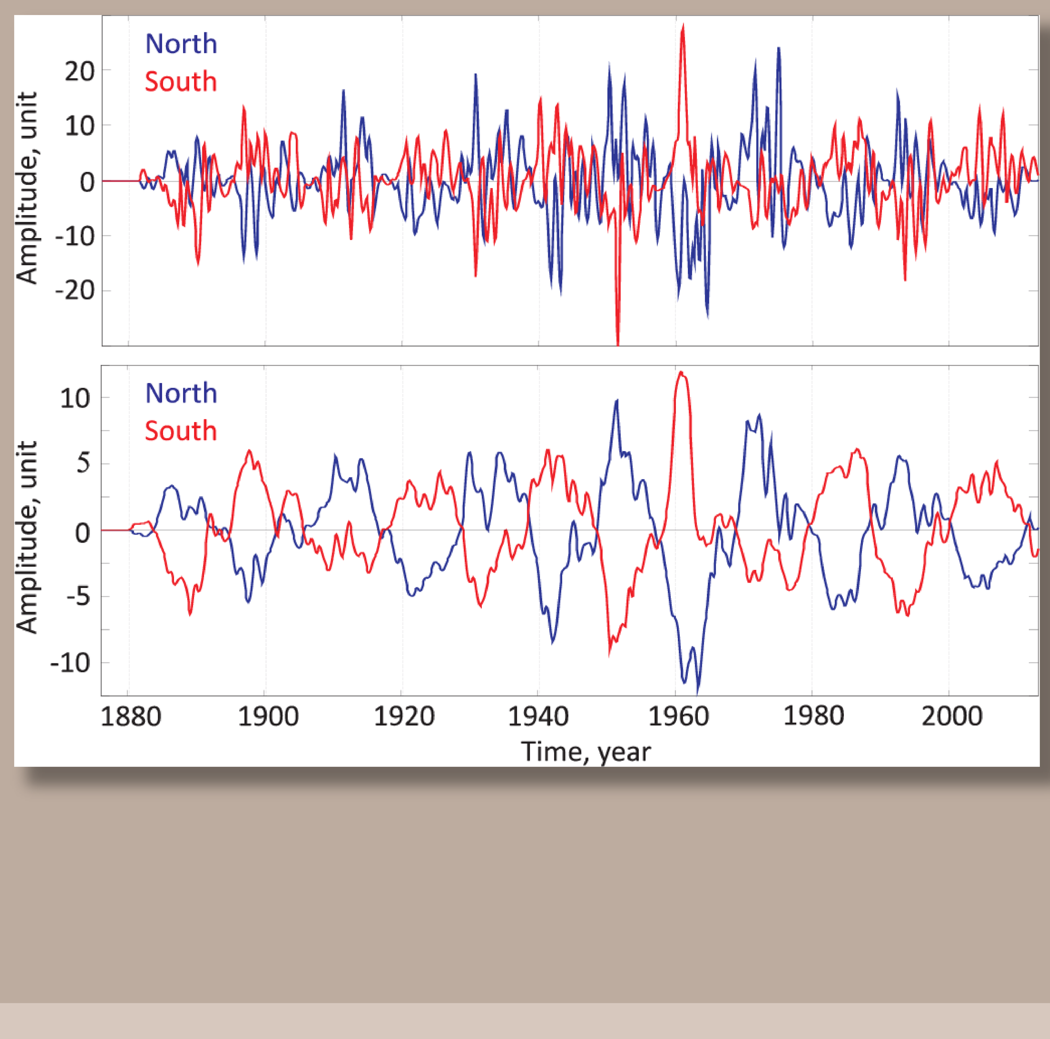
-- Normalized sunspot impulses from 1875 to 2012. The cycle 19 has strongest impulses. Size and shape of impulses depends on smoothing window: we use $dl \times dt$ = 0.6×1 and iteration step i = 20.

--- Reconstructed magnetic poleward surges in dimensionless units $S_{\text{Result}}(l, t)$. In absence of background field and diffusivity, each surge reaches polar latitudes. Flux surplus of leading polarity is evident at low latitudes, like real photospheric pattern. Due to gaps between impulses, the pattern has intermittent behaviour.

--- Unsmoothed strength of surges at latitudes 80° and −80° has strong fluctuations, when the new polarity surges are succeeded by old polarity surges, though we perform modeling without time variations of speed of meridional flow. Gleisberg cycle is evident.



--- Strength of surges from model, smoothed over 10 Carrington rotations from 1875 to 2012, in comparison with KPNO, SOLIS, SOHO data at latitudes 80° and −80° from 1975 to 2012. Polar field gradually decreases.



--- To avoid underestimating the contribution of large spots with an area of more than 3000 msh, we define the magnetic flux from individual sunspot equal to spot area. The peak in the southern hemisphere in 1946 corresponds to biggest spot with area more then 6000 msh.

--- The same, smoothed over 10 Carrington rotations. In spite of biggest spots during the cycle 18, the cycle 19 has strongest polar field due to numerous (~25%) spots with weak magnetic field (< 500 G). The cycles 12, 19 and 20 generate markedly asymmetric polar fields, that is consequence of asymmetrical sunspot activity in hemispheres.