Sun's polar magnetic field during minimum activity

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1. Abstract

Does flux emergence reshape anisotropically the polar cap field?

During the solar minimum of activity, the large scale solar magnetic field is close to a dipole field. The deviations from the axisymmetric dipole may impact on a number of processes, from the dynamo mechanism below the photosphere to the acceleration of the fast solar wind above the solar surface.

In this work, we measure the deviation of the polar coronal field from the dipole by analyzing the orientation of plumes in coronal polar EUV images. We then identify two parameters:
(1) the magnetic pole location,
(2) the magnetic opening.
Finally, we consider a Sun's open magnetic flux model to compare with the observations.

2. Model: Sun's Open Magnetic Flux model

The model combines the Sun's open magnetic flux and the heliospheric current sheet model. **Input:** Location, time and area of sunspots. **Output:** Synoptic map showing the magnetic field $\vec{B}(r,\theta,\phi)$ on the surface at 1.15 $R_\odot$ (*R. Cameron et al ; J. Jiang et al, 2010*). To test how the magnetic pole location is sensitive to the emergence of sunspots, we artificially introduce 2 sunspot groups at 2064 Carrington rotation with different strengths and with same location.

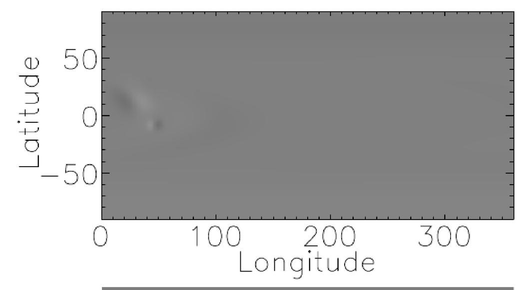


Fig.1: Original synoptic magnetogram with the radial field B_r.

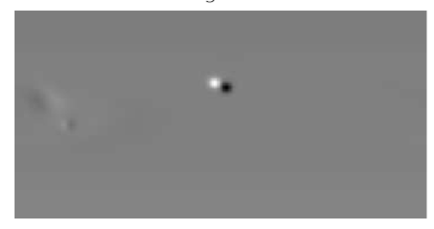


Fig.2: Synoptic magnetograms with an artificial sunspot.

3. Method: Plume Identification

Plumes are identified with the Hough-wavelet transform of an image, $I(r,\phi)$, of the solar polar region in cylindrical coord.,

$$H_M(\rho,\theta) = \max_a \left[\int_{\phi_1=-35^\circ}^{\phi_2=35^\circ} \int_{r_1=1.01\ R_\odot}^{r_2=1.39\ R_\odot} I(r,\phi)\ \psi_{\rho,a,\theta}(r,\phi)\ \mathrm{d}r\ \mathrm{d}\phi \right],$$

where $\psi_{\rho,a,\theta}(r,\phi)$ is a 1D Mexican-Hat wavelet rotated by θ, scaled by a factor a, and shifted by ρ. We determine the optimum scale, and calculate the Hough-space, $H_M(\rho,\theta)$. (*de Patoul, et al, SoPh. 2013*)

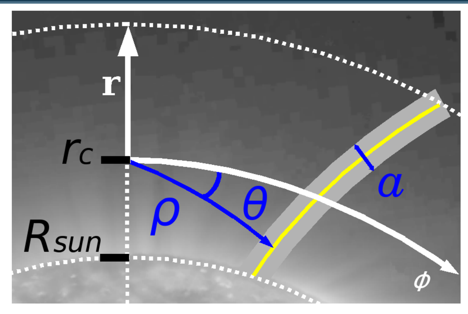


Fig.3: Image Space with cylindrical coordinates (r,ϕ).

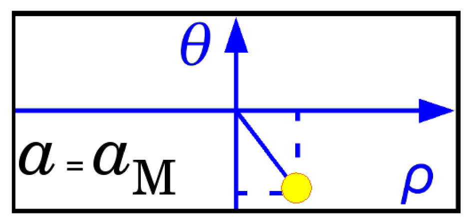


Fig.4: Hough Space (ρ,θ).

4.1. Orientation and Location of Plumes

■ Plumes appear as elongated straight faint columns in solar coronal image (Fig.5). Synthetic plumes can be constructed by considering the field line from the Sun's Open Magnetic Flux model (Fig.6).

Fig.5: STEREO/EUVI-A at 171Å Nov, 1st 2007.

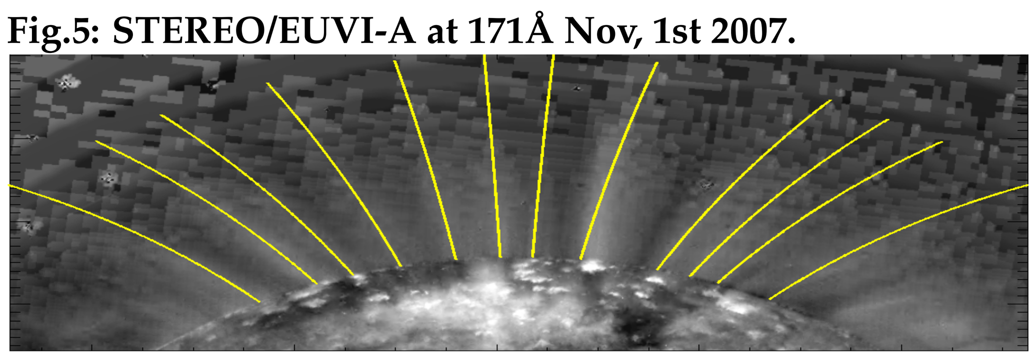
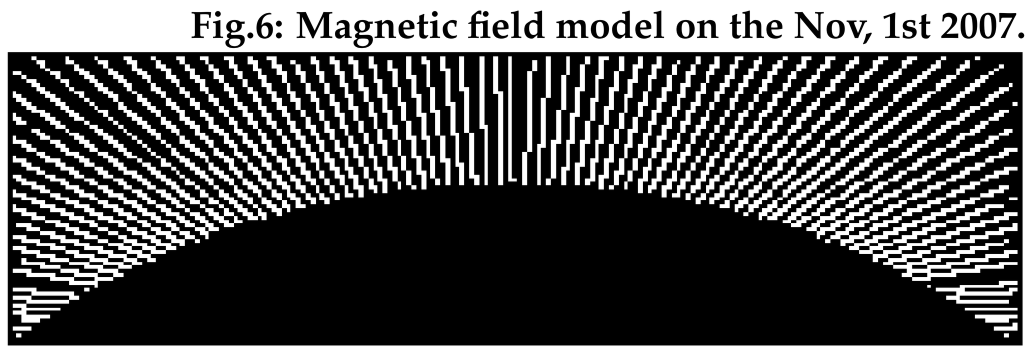


Fig.6: Magnetic field model on the Nov, 1st 2007.



■ We calculate the Hough-space of Fig.5-6 and identify the plumes. In Fig.7, the yellow circles show the plume peaks, which correspond to maximum intensity over different scales of the Hough-wavelet coefficients. The backward transformation of the plume peaks are shown on Fig.5 as yellow lines.

Fig.7: Hough space $H_M(\rho,\theta) = \max_a H(\rho,a,\theta)$ **for** $a = 1.1..10$.

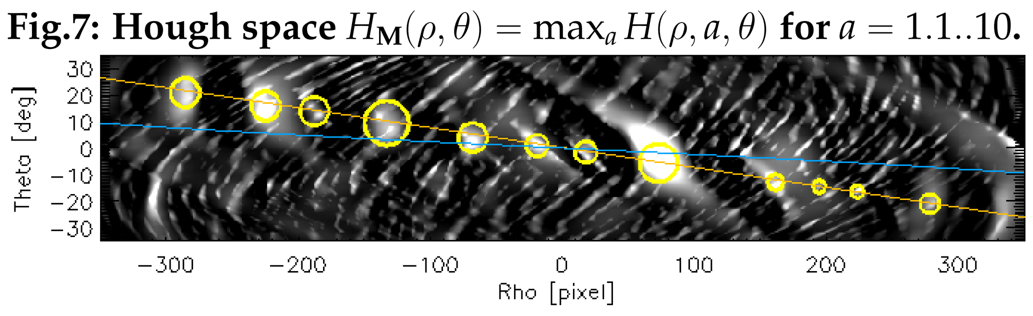
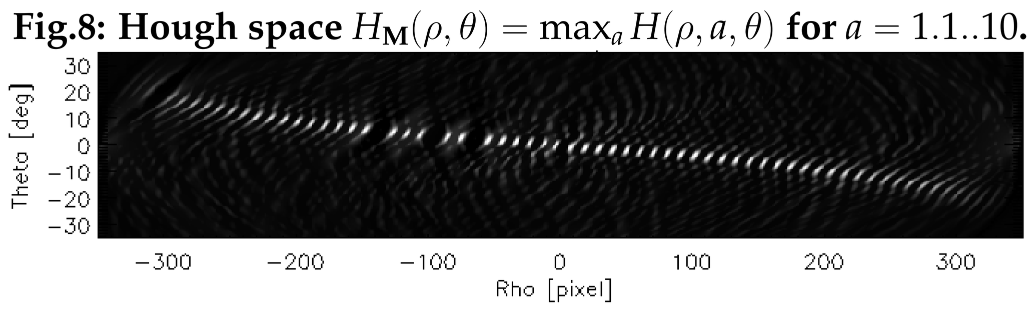


Fig.8: Hough space $H_M(\rho,\theta) = \max_a H(\rho,a,\theta)$ **for** $a = 1.1..10$.



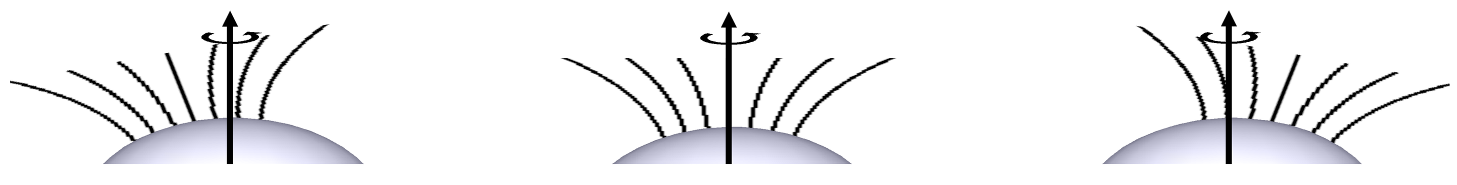
■ Plume peaks are aligned along an inclined line (*de Patoul, et al, SoPh. 2013*):

$$\theta = u\ \rho + v\ ,$$

where u and $-v/u$ measure the magnetic opening and the magnetic pole location.

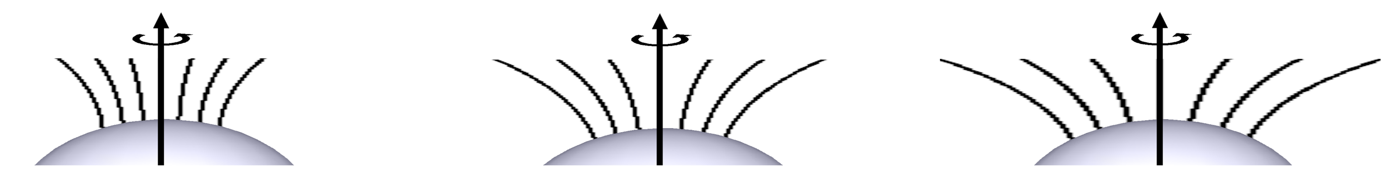
4.2. Magnetic Pole & Magnetic Opening

■ **Magnetic pole location ($-v/u$)** is the point where the large scale field is perpendicular to the surface. The ρ-intercept, $-v/u$, is proportional to the heliographic co-latitude of the magnetic pole seen in projection. A zero ρ-intercept value means that the dipole magnetic axis is aligned with the rotation axis of the Sun on the projected images. During the solar rotation, we expect the ρ-intercept varying with a period of a full rotation:



$-v/u < 0$ | $-v/u = 0$ **after** 90° | $-v/u > 0$ **after** 180°

■ **Magnetic opening (u)** is the rate at which the polar coronal flux widens. The slope parameter, u, measures the projection of the magnetic opening. A dipole field gives $u = 0.025$ (blue line in Fig. 6). We obtaine $u > 0.025$ (yellow line in Fig. 6) due to superradial inclination of plumes. During the solar rotation, we expect the slope varying with a period of half a rotation:



$|u| \sim 0.025$ | $|u| > 0.025$ **after** 45° | $|u| >> 0.025$ **after** 90°

4.3. Time series: from April, 3rd 2007 to May, 8th 2008 (North pole)

■ Time series of u and $-v/u$ for STEREO/EUVI-A, EUVI-B and SOHO/EIT at 171Å, and for the model (in black) and with the 2 extra sunspot groups (in red and blue):

Fig. 9: Observation – Intercept, $-v/u$.

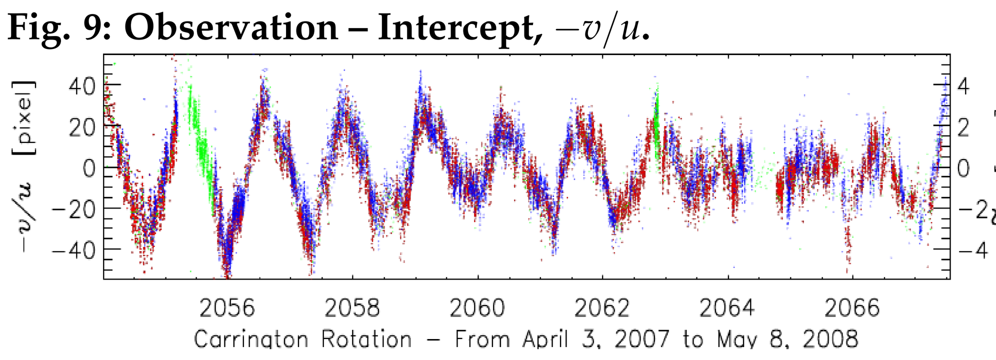


Fig. 10: Observation – Slope, u.

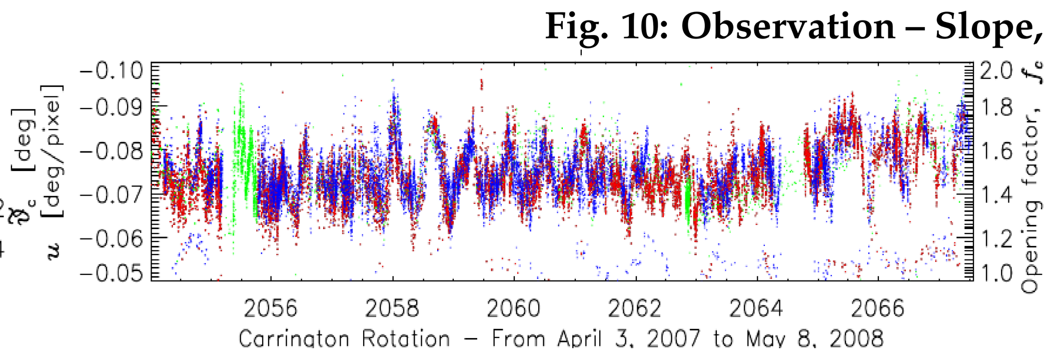


Fig. 11: Model –Intercept, $-v/u$.

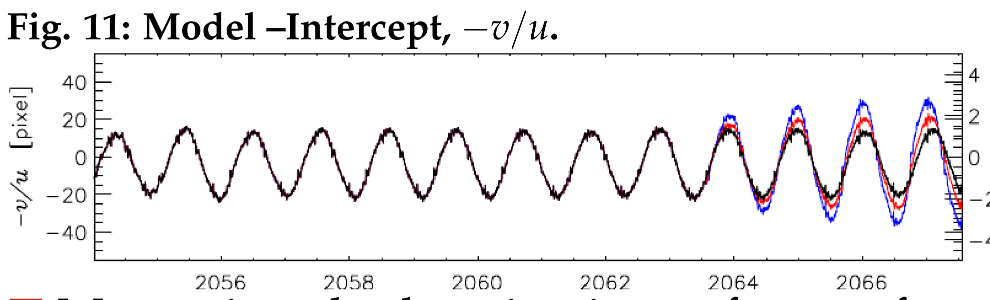
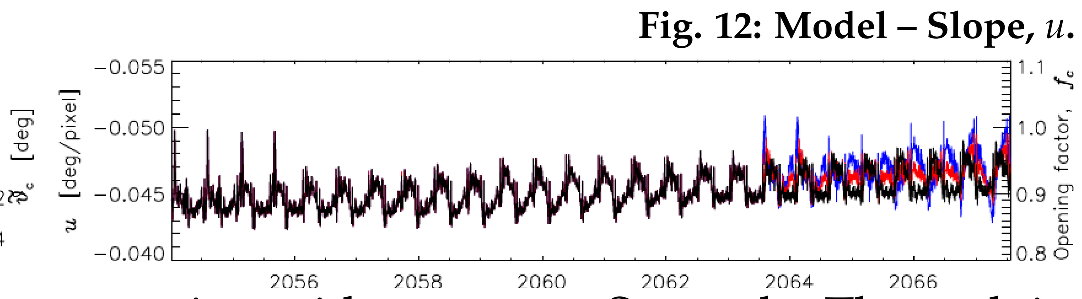
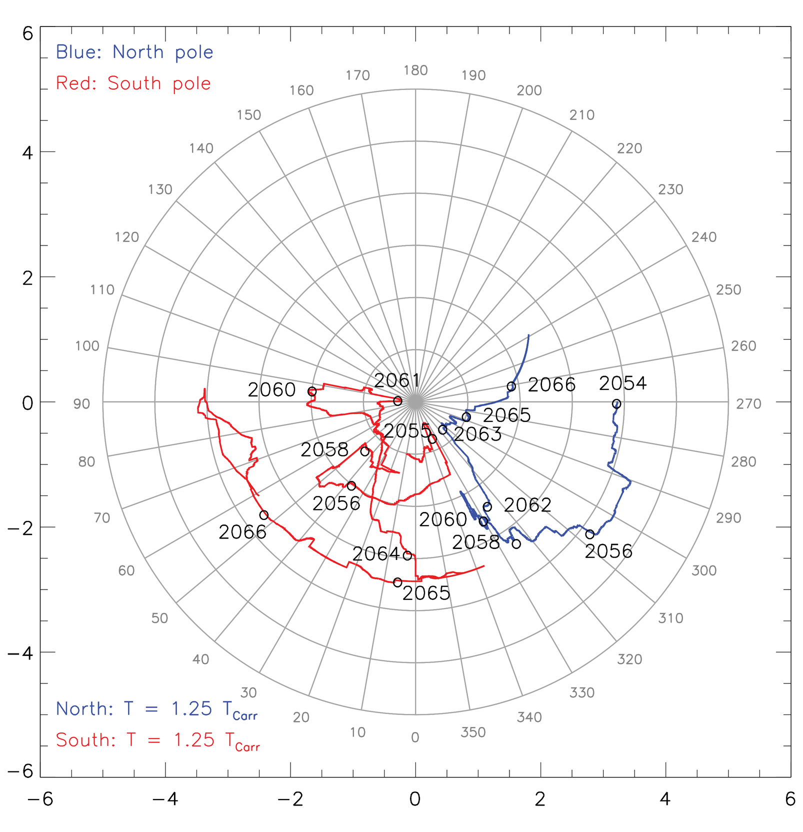


Fig. 12: Model – Slope, u.



■ Magnetic poles location in a reference frame corotating with respect to Sun pole. The path is derived from the parameters displayed in Fig. 9 & 11.



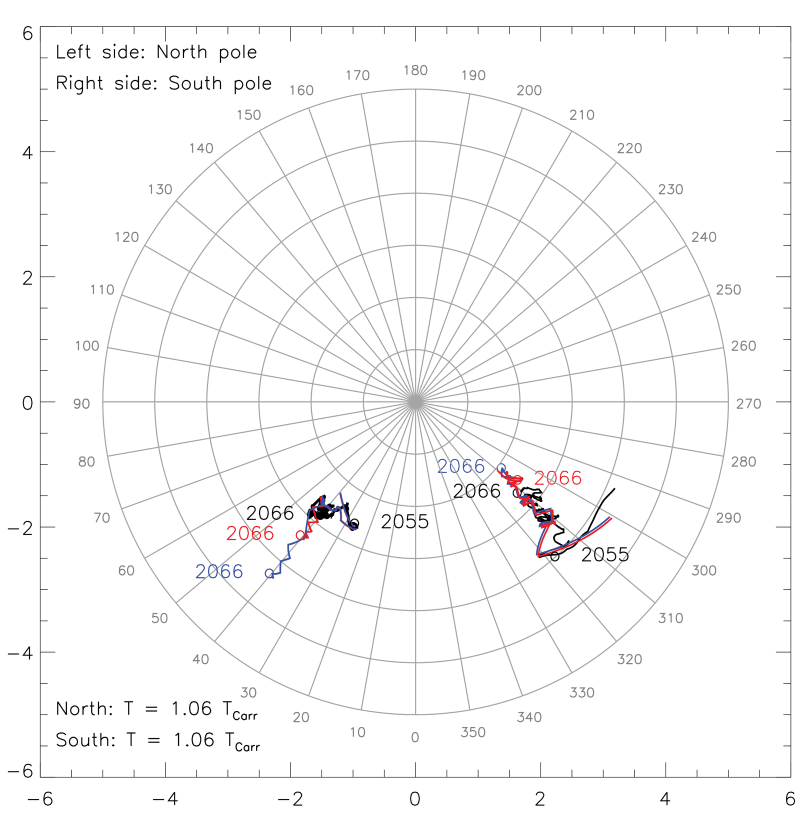


Fig. 13 (left): Plumes observations, north and south poles are drawn in blue and red.

Fig. 14 (rigth): Model, the red and blue lines are the model with artificial sunspots.

(*de Patoul, et al, A&A 2013*)

5. Conclusion

Yes, newly emerging flux produces a signature in the coronal magnetic field and in the orientation of the polar plumes.

(1) Magnetic poles location ($-u/v$ parameter):
■ In the simulation, it slowly drifts towards the pole (Fig.14). It reflects the decay of a previously existing non-axisymmetric field as it is dispersed over all longitudes by differential rotation.
■ When artificial sunspot groups are included in the simulation, the results show a clear change Fig.11&14, which demonstrates that the magnetic pole location is sensitive to the flux emergence anywhere on the solar surface.
■ In plume observations, there is a more erratic behavior (Fig.13). It reflects the changes in the coronal magnetic field resulting from small-scale flux emergences that modifies the global magnetic field of the entire corona within an Alfvén transit time scale. It demonstrates the sensitivity of the parameters derived here to the structure of the coronal field.
(2) Magnetic opening (u parameter):
■ It is ~50% larger in the observations than in the simulations (Fig.10 vs. 12): the observed polar fields expand more rapidly than the simulations predict. A possible explanation is a higher concentration of the photospheric field towards the poles suggesting that the meridional velocity is more efficient in convecting the magnetic field to the poles than assumed in the flux transport simulations. In this regard the observed average opening factor provides a sensitive constraint on the meridional flow near the poles where it is difficult to measure.