Comparing the heliospheric magnetic field at the coronal base and Earth's orbit

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Introduction

- Coronal magnetic field determines the structure of the solar wind
- SW determines the heliospheric magnetic field because HMF is frozen-in the SW plasma
- Coronal field is difficult/impossible to measure → modelling is needed
- Coronal field can be calculated from photospheric measurements with the Potential Field Source Surface (PFSS) model
- We calculate the coronal field and use it to predict the value of the magnetic field at 1 AU, then compare with measurements
- The goal is to gain a better understanding of the connection between the Sun and the heliospheric environment

PFSS model

- Altschuler and Newkirk (1969) and Schatten et al. (1969)
- No electric currents between photosphere and corona: $\nabla \times \boldsymbol{B} = 0$

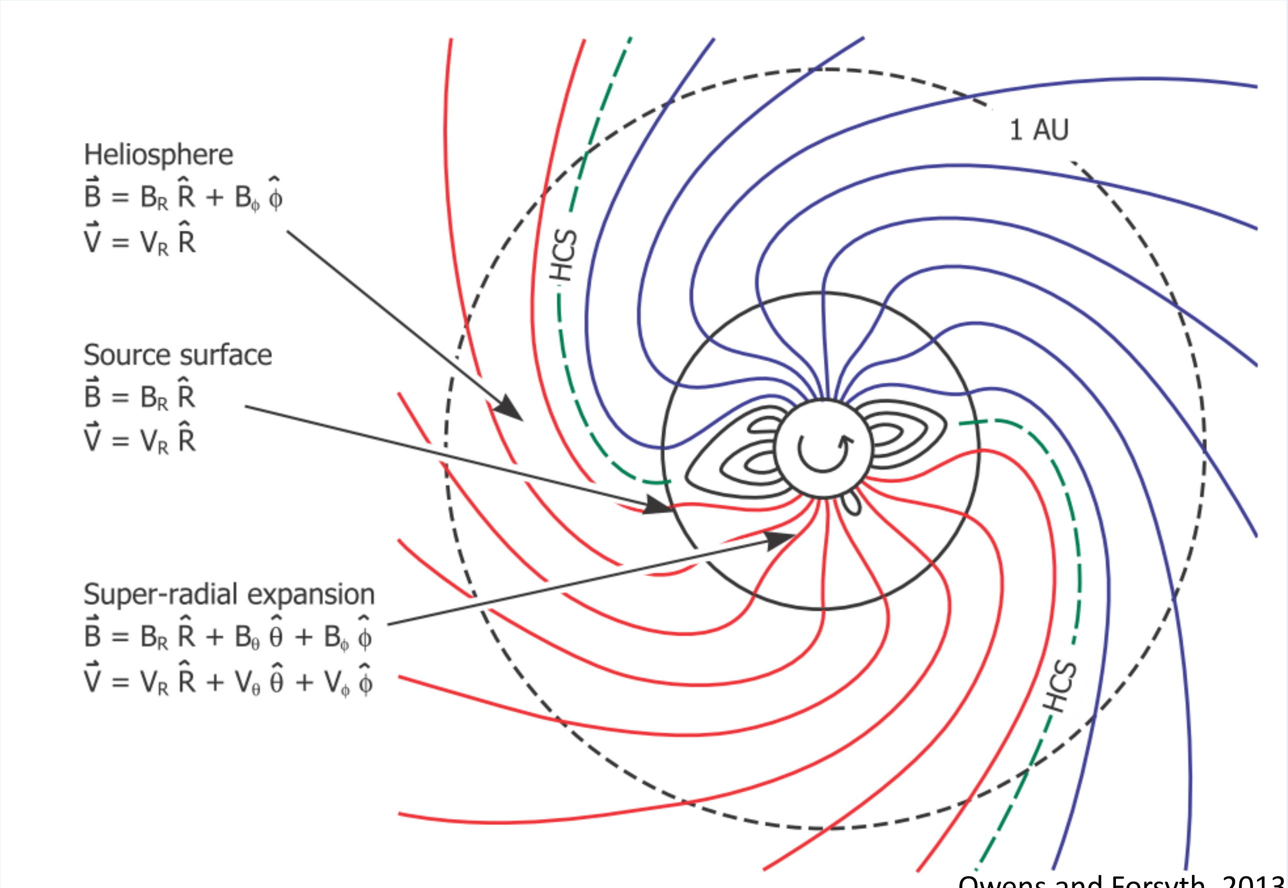
  $\Rightarrow \boldsymbol{B} = -\nabla\Psi$
- Gauss' law: $\nabla \cdot \boldsymbol{B} = 0$

  $\Longrightarrow$Laplacian equation: $\nabla^2\Psi = 0$
- Solutions to $\Psi(r,\theta,\phi)$ in spherical harmonics is (Sun, 2009)

$$\Psi(r,\theta,\phi) = R_S \sum_{n=1}^{n_{max}} \sum_{m=0}^{n} P_n^m(\cos\theta)(g_{nm}\cos m\phi + h_{nm}\sin m\phi) \times \left(\frac{R_S}{r}\right)^{n+1} \frac{1-\left(\frac{r}{r_{ss}}\right)^{2n+1}}{n+1+n\left(\frac{R_S}{r_{ss}}\right)^{2n+1}}$$

- Two free parameters: r_{ss} is the source surface distance from the centre of the Sun, and n_{max} is the number of multipoles in the spherical harmonic expansion
- After source surface the solar wind plasma starts to dominate the magnetic field → the field cannot be potential anymore

Source surface



Owens and Forsyth, 2013

- The field is assumed to be radial at photosphere and source surface
- Beyond source surface the magnetic field is dominated by solar wind plasma flow. This together with solar rotation leads to the Parker spiral structure of the HMF.

Data

- Magnetogram measurements
  - Wilcox Solar Observatory (**WSO**) in Stanford, California. Synoptic measurements of the photospheric magnetic field since 1976.
  - Mount Wilson Solar Observatory (MWO) in California, measurements since 1974 using various instruments.
  - Kitt Peak in Arizona, measurements since early 70s, problems with data calibration. Succeeded by **SOLIS**.
  - Satellite magnetographs SOHO/**MDI**, SDO/**HMI**.

- Satellite measurements of the HMF and solar wind speed at 1 AU compiled to OMNI 2 dataset by NASA

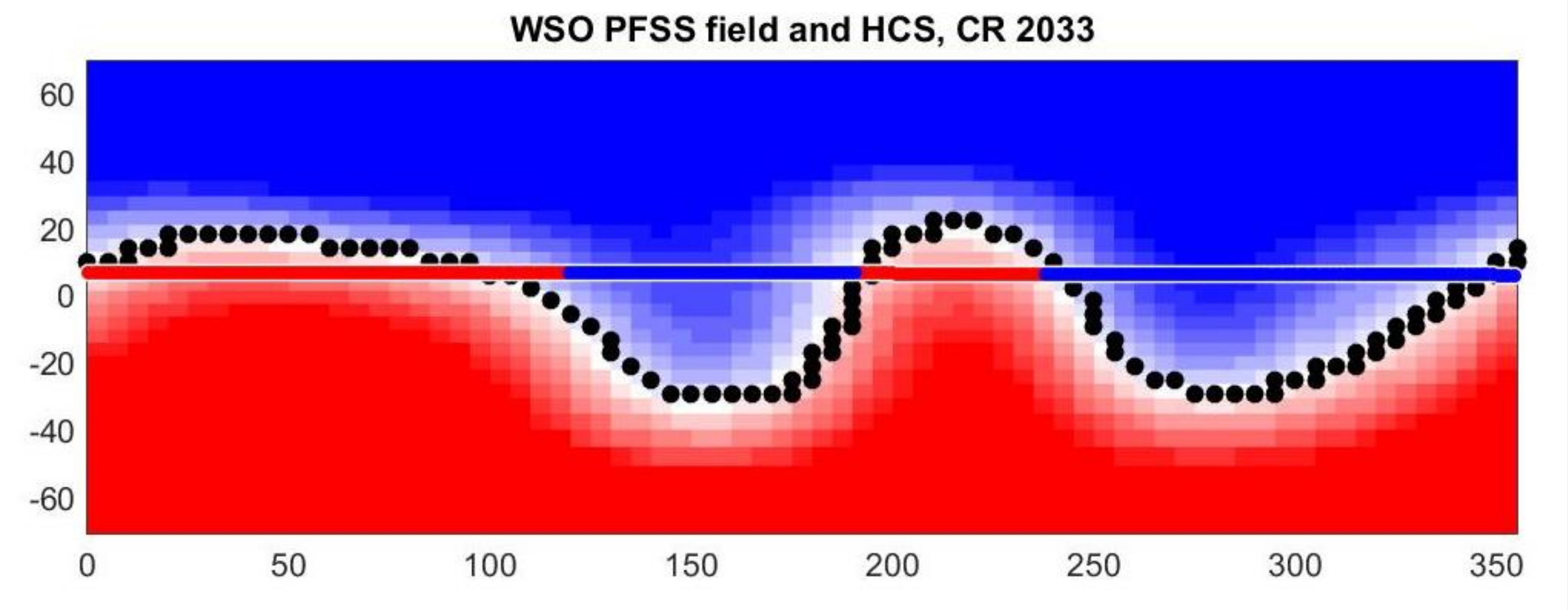
Evaluating the PFSS model

- We calculate the magnetic field in the solar corona using various source surface radii (1.5 R_s, 2.5 R_s, 3.5 R_s and 4.5 R_s), various number of multipoles (1, 2, 3 and 9), and with different datasets (WSO, MDI, HMI and SOLIS)
- We backtrace measured field at 1 AU to the solar corona and compare with model results for
  - Polarity
  - Magnitude
- Polarity is compared by calculating how often the sign of the model field and measured field match
- Magnitude was compared by calculating *n* from

$$B_r(1AU) = B_r(r_{ss})(\frac{r_{ss}}{1AU})^n$$

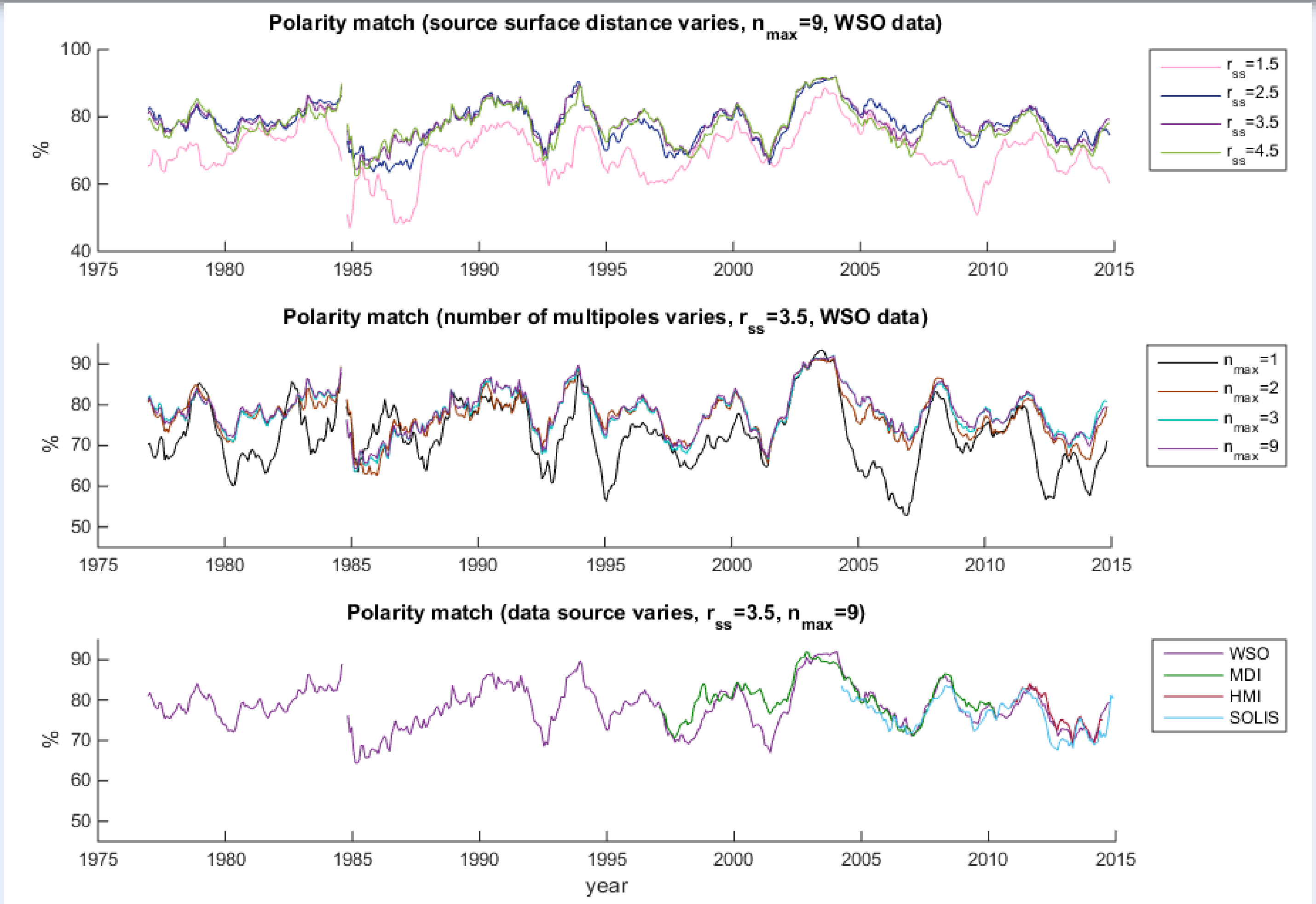
  - *n* should be 2 according to Maxwell's equations (in case of no other effects like super-expansion)

Polarity comparison



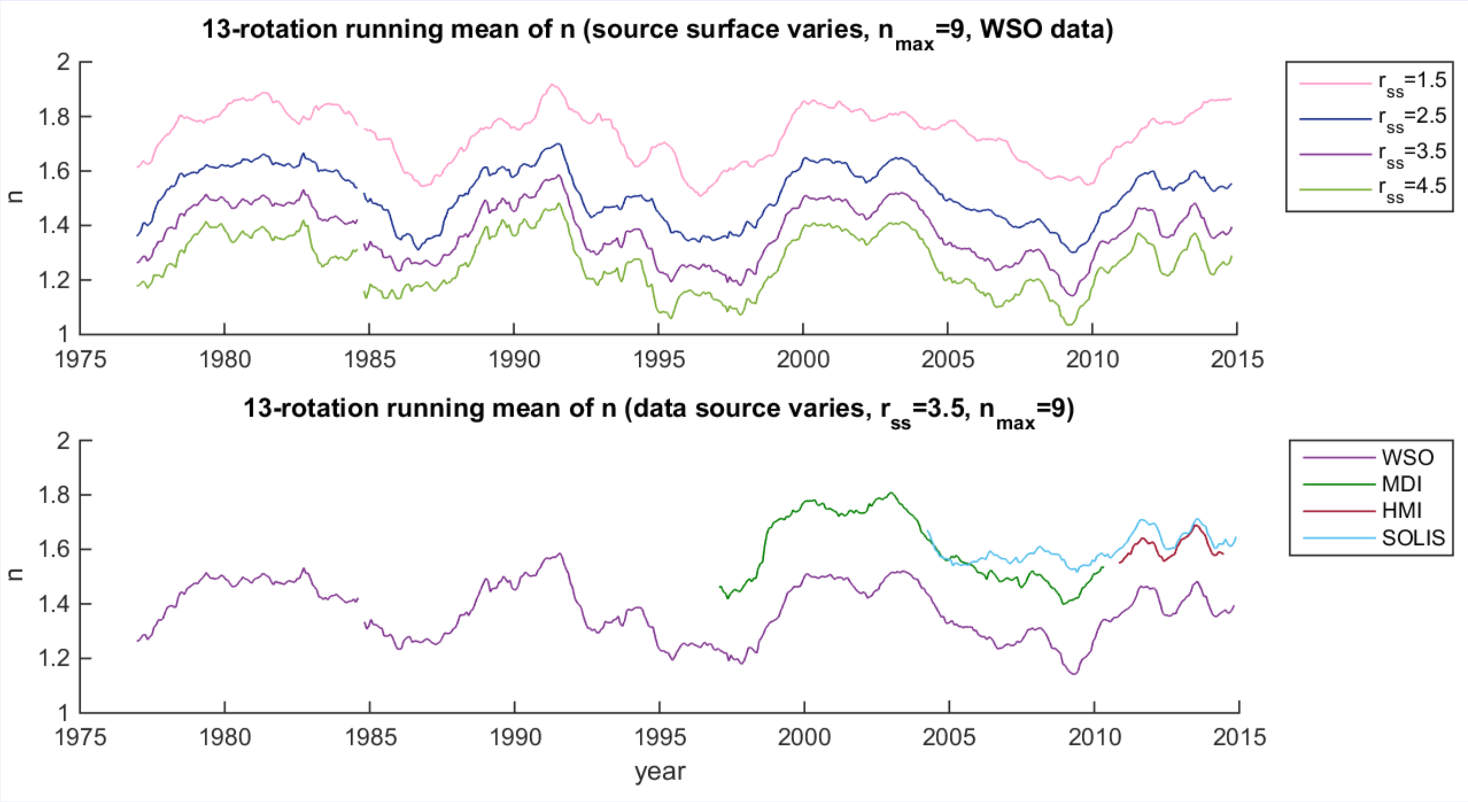
- Synoptic map of the corona ($r_{ss} = 2.5\ R_s$)
- Horizontal line is the projection of the HMF polarity at 1 AU
- Black line is the neutral line, i.e. projection of the HCS
- red: positive field, blue: negative field

Polarity comparison



- Polarity match calculated with data from four observatories with different sets of variables
- There is some cyclic variation in the polarity match

Results – magnitude comparison



- n is smaller than 2 → PFSS model gives too small field magnitude
- n depicts a solar cycle variation: small n during minima is due to HCS proximity
- with a smaller source surface n is larger because there are less closed loops and more open magnetic field lines
- variation of n is similar with all magnetograms – WSO gives lowest value

Summary

- The PFSS coronal model field and the observed heliospheric field have in general a fairly good correspondence.
- The number of multipoles does not have a significant effect to polarity prediction, as long as $n_{max} > 2$.
- Polarity prediction is best during the declining phase because of the flatness and the tilt of the HCS.
- The polarity match calculated with data from different observatories is most of the time equally good.
- The PFSS model predicts too weak a radial field, especially during the minimum phase when the Earth is close to the HCS

Extra slides

PFSS model

- Altschuler and Newkirk (1969) and Schatten et al. (1969)
- No electric currents between photosphere and corona: $\nabla \times \boldsymbol{B} = 0 \quad \Rightarrow \boldsymbol{B} = -\nabla\Psi$
- Gauss' law: $\nabla \cdot \boldsymbol{B} = 0$

  $\Longrightarrow$Laplacian equation: $\nabla^2\Psi = 0$
- Components of the magnetic field
  - $B_r(r, \theta, \phi) = -\frac{\partial\Psi}{\partial r}$
  - $B_\theta(r, \theta, \phi) = -\frac{1}{r}\frac{\partial\Psi}{\partial\theta}$
  - $B_\phi(r, \theta, \phi) = -\frac{1}{r\sin\theta}\frac{\partial\Psi}{\partial\phi}$

PFSS model

- Solutions to $\Psi(r,\theta,\phi)$ in spherical harmonics is (Sun, 2009)

  $$\Psi(r,\theta,\phi) = R_S \sum_{n=0}^{\infty} \sum_{m=0}^{n} P_n^m(\cos\theta)(g_{nm}\cos m\phi + h_{nm}\sin m\phi)$$

  $$\times \left(\frac{R_S}{r}\right)^{n+1} \frac{1-\left(\frac{r}{r_{ss}}\right)^{2n+1}}{n+1+n\left(\frac{R_S}{r_{ss}}\right)^{2n+1}}$$

- g_{nm} and h_{nm} are harmonic coefficients which can be calculated from photospheric synoptic maps
  - $g_{nm} = \frac{2n+1}{N_X N_Y} \sum_{i=1}^{N_X} \sum_{j=1}^{N_Y} B_r(R_S,\theta_i,\phi_j)\, P_n^m(\cos\theta_i)\cos m\phi_j$
  - $h_{nm} = \frac{2n+1}{N_X N_Y} \sum_{i=1}^{N_X} \sum_{j=1}^{N_Y} B_r(R_S,\theta_i,\phi_j)\, P_n^m(\cos\theta_i)\sin m\phi_j$
- r_{ss} is the source surface distance from the centre of the Sun