

Comparing the PFSS coronal magnetic field prediction with the observed heliospheric magnetic field at 1 AU over several solar cycles



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1. Introduction

- Corona is the outermost part of the solar atmosphere and the layer between the Sun and the heliosphere. It consists of very low density plasma. Because it has a weaker intensity than the photosphere it is visible only when the photosphere is covered by a coronagraph or by the Moon during a solar eclipse (**Figure 1**).
- The coronal magnetic field determines the structure of the solar wind, which determines the structure of the heliospheric magnetic field (HMF) frozen in the solar wind plasma. Thus, in order to understand the connection between the Sun and the heliosphere, it is important to study the coronal field.
- The coronal magnetic field is difficult or impossible to measure, but the Potential Field Source Surface (PFSS) model (Altschuler and Newkirk, 1969; Schatten et al., 1969), has long been used to estimate the coronal field from the measured photospheric field.
- We use the PFSS model and photospheric measurements from WSO, MDI, HMI and SOLIS to calculate the magnetic field in the corona and compare it to the HMF at Earth's orbit. The data at 1 AU is obtained from NASA/NSSDC OMNI 2 dataset.

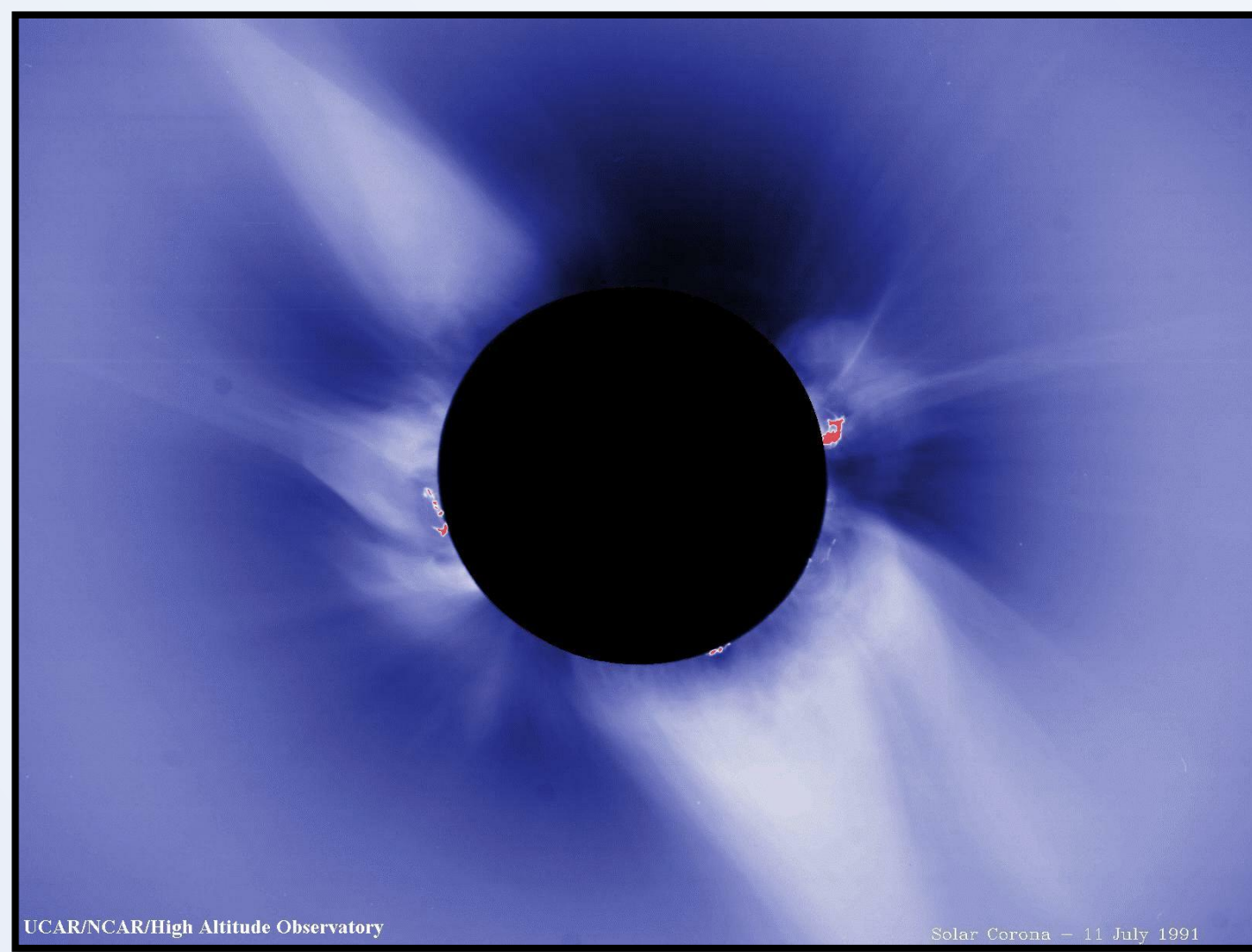


Figure 1: The Solar corona during the total solar eclipse in July 1991. (NASA)

3. Polarity match

- **Figure 3** shows a synoptic map of the coronal magnetic field and the projected polarity of the magnetic field at the Earth's orbit for Carrington rotation 2033, in the year 2005 during the declining phase of cycle 23. We can see that the polarities of these fields correspond very well with each other.

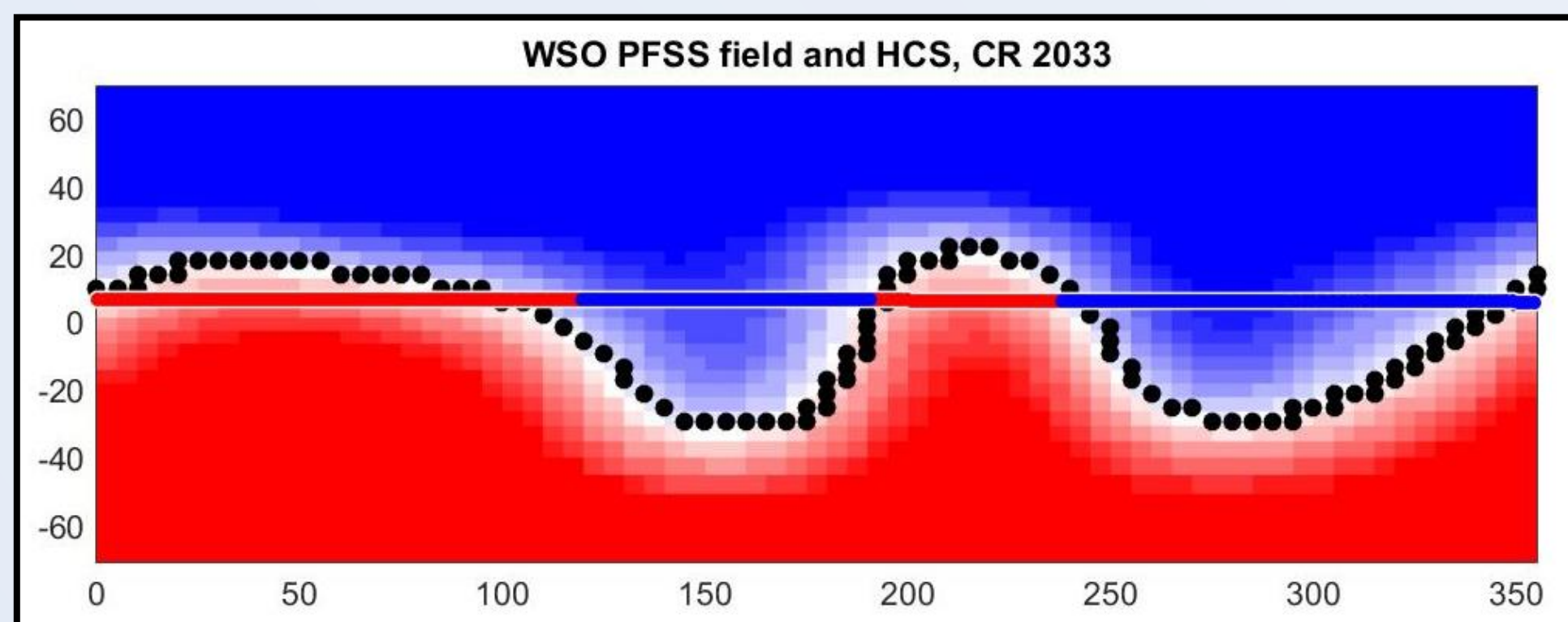


Figure 3: Map of the coronal magnetic field calculated at the source surface distance of $2.5 R_S$. Red denotes positive polarity and blue negative, and the saturation of the colours indicate field strength. The horizontal line is the projection of Earth's latitude and colour (red or blue) denotes the polarity of the HMF measured at 1 AU. The black dotted line is the neutral line.

- **Figure 4** shows the polarity match percentage, i.e. the percentage of how frequently the 25-hour running means of hourly values of the PFSS model field and the measured field at 1 AU have the same polarity.
- We compare the effect of changing the source surface distance, the number of multipoles, and the data source for the photospheric synoptic maps, on the polarity match.

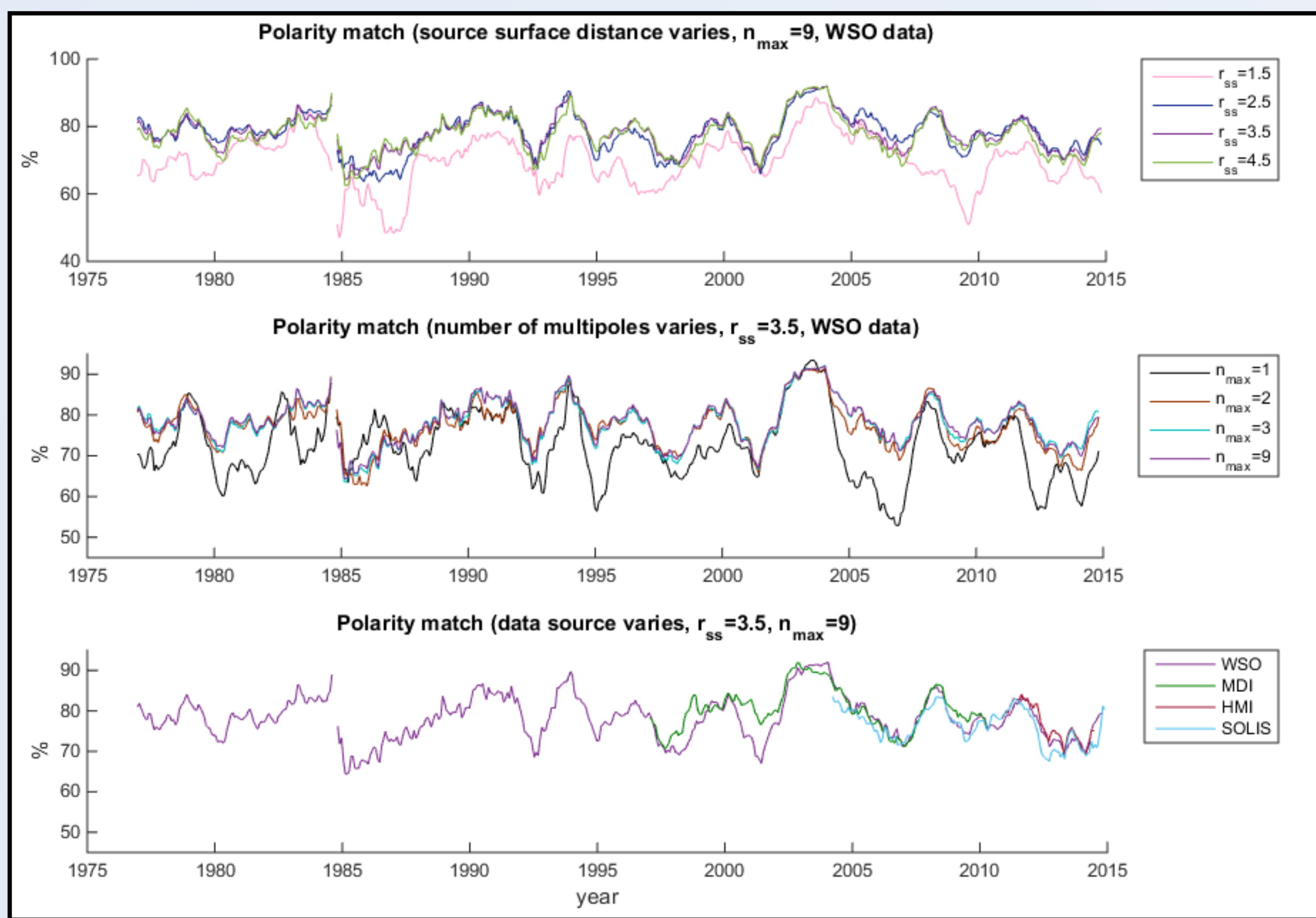


Figure 4: Top panel: WSO polarity match ($n_{max} = 9$) for four source surface distances: $1.5 R_S$ (pink), $2.5 R_S$ (dark blue), $3.5 R_S$ (purple) and $4.5 R_S$ (green). Middle panel: WSO polarity match ($r_{ss} = 3.5 R_S$) for a variable number of multipoles: 1 (black), 2 (red), 3 (turquoise) and 9 (purple). Bottom panel: Polarity match ($r_{ss} = 3.5 R_S$, $n_{max} = 9$) for four datasets: WSO (purple), MDI (green), HMI (red) and SOLIS (light blue). All curves are 13-rotation running means of the rotational polarity match. The purple curve is the same in all panels.

- Source surface distance $r_{ss} = 3.5 R_S$ gives a slightly better polarity match than $2.5 R_S$ or $4.5 R_S$. The source surface distance of $1.5 R_S$ gives clearly a worse match than the others.
- Using 9 multipoles gives the best match on average, but the difference to 2 or more multipoles is very small. This shows that the exact number of multipoles does not have much effect beyond 2.
- All four datasets yield quite similar match percentages. MDI gives slightly better percentages than the other datasets.
- Polarity match is highest during the declining phase, especially in 1984, 1994 and 2003-2004. All these years are characterised by high speed streams. During the declining phase the HCS is fairly flat and has a significant tilt angle so the sector structure in the heliosphere is well defined.
- During solar minima (1986, 1997 and 2009) there is a local minimum in the match percentage. HCS is flat during minimum times but the tilt is small, so the Earth is long periods of time within the HCS where the sector structure is less well defined.

References

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2. PFSS model

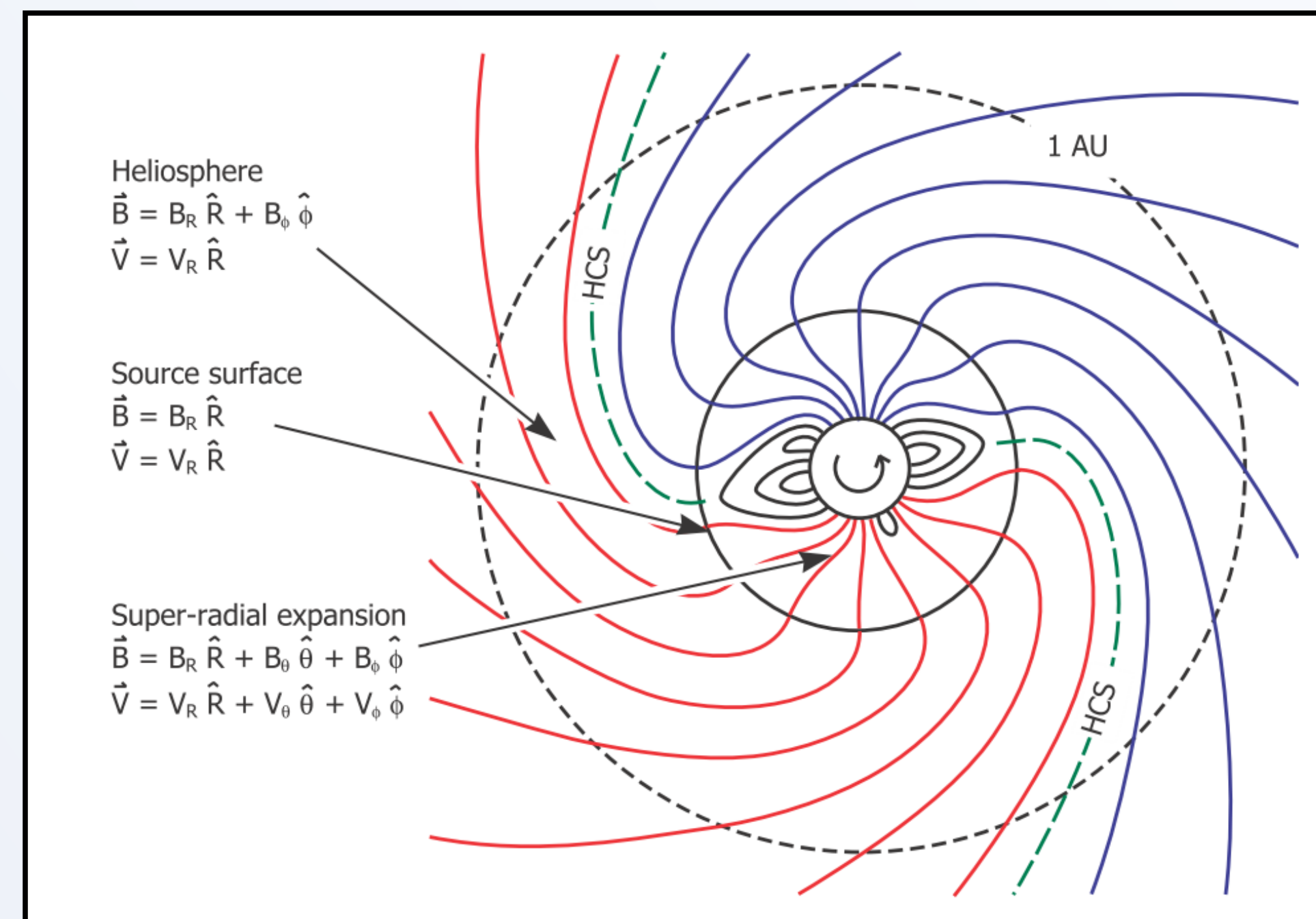


Figure 2: A schematic of the PFSS model. Inner circle is the photosphere, middle circle is the source surface, and the outer dotted circle is Earth's orbit. Red (blue) lines show the outwards (inwards) pointing magnetic field lines. Black lines are closed magnetic loops. The green dotted line shows where the heliospheric current sheet (HCS) cuts through the ecliptic plane. Image from Owens and Forsyth (2013).

- **Figure 2** shows the behaviour of the magnetic field in the PFSS model. The field is assumed to be radial at the photosphere and on the source surface.
- The PFSS model also assumes that there are no currents between the photosphere and the source surface. This leads to the Laplacian equation $\nabla^2 \Psi = 0$, which can be solved with spherical harmonics.
- Any field lines that pass the source surface are defined as open field lines and they contribute to the strength of the HMF. The amount of magnetic flux going into the heliosphere is thus defined by the source surface distance. Beyond source surface the magnetic field is dominated by the solar wind plasma flow, forming the Parker spiral (Parker, 1958).
- The model gives a latitude dependent solution to the magnetic field – The field goes to zero at the neutral line, i.e. the projection of the HCS on the source surface.
- The free parameters of the model are the source surface distance and the number of multipoles included in the spherical harmonic solution of the Laplacian equation.

4. Magnitude comparison

- We use the value of n , defined according to the expression $B_r(r) = B_r(r_{ss}) \left(\frac{r_{ss}}{r}\right)^n$, to quantify the radial field decay from corona to 1 AU. This allows us to determine how well the field magnitude calculated with the PFSS model corresponds to the field magnitude at 1 AU. Unless other factors contribute, Maxwell equations would require n to be 2. The value of n is plotted in **Figure 5**.

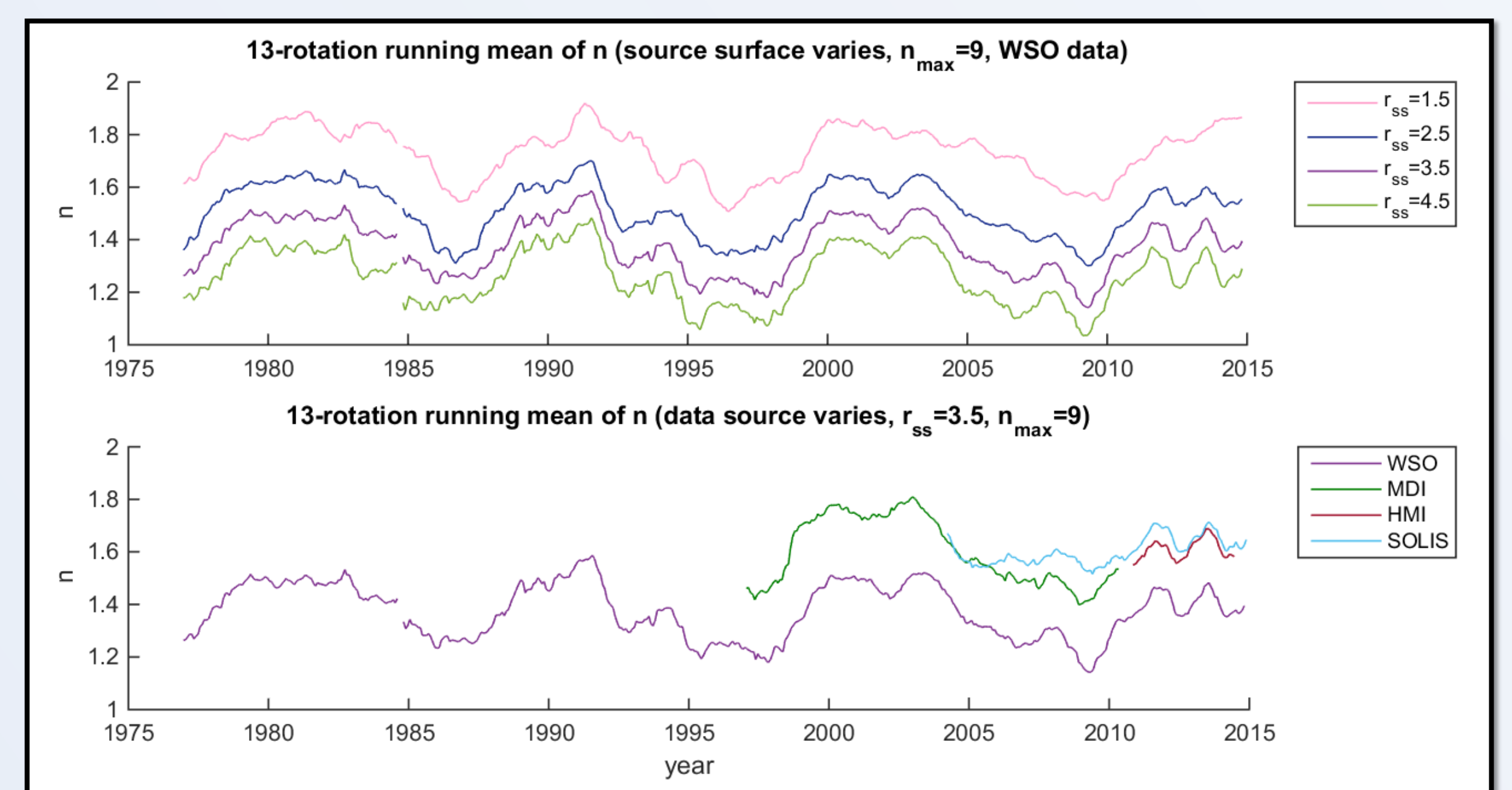


Figure 5: Upper panel: 13-rotation running means of the rotational average of n for WSO for four source surface distances. Lower panel: 13-rotation running means of the rotational average of n for WSO (purple), MDI (yellow), HMI (red) and SOLIS (green) data.

- The power n increases when the source surface distance is decreased. For a lower source surface distance less flux is confined within magnetic loops and there is more open flux going into the heliosphere.
- There is a cyclic variation: n is highest soon after sunspot maxima and smallest during sunspot minima. This is partly due to the solar cycle variation of the heliospheric magnetic field, partly due to the varying proximity to the heliospheric current sheet. During sunspot minimum the HCS is flat and thus the source of the solar wind is close to the neutral line, making n small. (PFSS model gives low values close to the neutral line; see white areas around the HCS in **Figure 3**).
- WSO gives a lower value for n (and thus a lower magnetic field strength) than the other datasets. A scaling factor is needed when comparing synoptic maps from different observatories (Riley et al., 2014). This implies that determining the value for n is dependent on both the data source and the source surface distance.

5. Summary

- The PFSS coronal model field and the observed heliospheric magnetic field have in general a fairly good polarity correspondence for source surface values between $2.5 R_S$ and $4.5 R_S$.
- A very small number of harmonic components of 3 or more is sufficient for a good polarity match.
- Polarity match is best in the declining phase of solar cycle because HCS is flat and tilted. Polarity match has local minimum during each solar minimum.
- Polarity matches for data from different observatories are mostly very similar.
- The PFSS model gives too low radial field strength, especially during the minimum phase when Earth is close to the HCS.