A Comparative Study of Different Approaches and Potential Improvement to Modeling the Solar Wind

Sun, X. and Hoeksema, J. T.

W.W. Hansen Experimental Physics Laboratory (HEPL), Stanford University

Abstract:

The Wang-Sheeley-Arge (WSA) model is regularly used to predict the background solar wind speed and the interplanetary magnetic field (IMF) polarity from photospheric observation. The predictions near the sun are made from an empirical function which has two parameters: (1) the magnetic expansion factor and (2) the minimum angular distance from a field line foot point to the edge of the coronal hole. A kinetic propagation model is then used to determine the values at 1AU. In this paper, we address two factors can affect the result to a significant extent: (1) treatment of input data and (2) the algorithm used to compute the two parameters. We discuss the effect of synoptic chart resolution and polar field correction, and then analyze the results using three different models (potential field source surface (PFSS) model, Schatten current sheet (SCS) model integrated with PFSS, and horizontal-current current-sheet source surface (HCCSSS) model). We compare the results with observational data, and evaluate them statistically, so as to find a more physically significant scheme that works as well or better.

Introduction

The solar wind speed is closely connected with the coronal fields. WSA uses two parameters from the modeled coronal field to predict the solar wind speed.

1. Flux tube expansion factor (f_s): for a flux tube connecting a certain height R and the photosphere:

$$f_s = \frac{B_{photo}}{B} \frac{R_{photo}^2}{R^2} .$$

Wang (1990) shows that there's an inverse relation between the observed solar wind speed and the expansion factor (fig1).
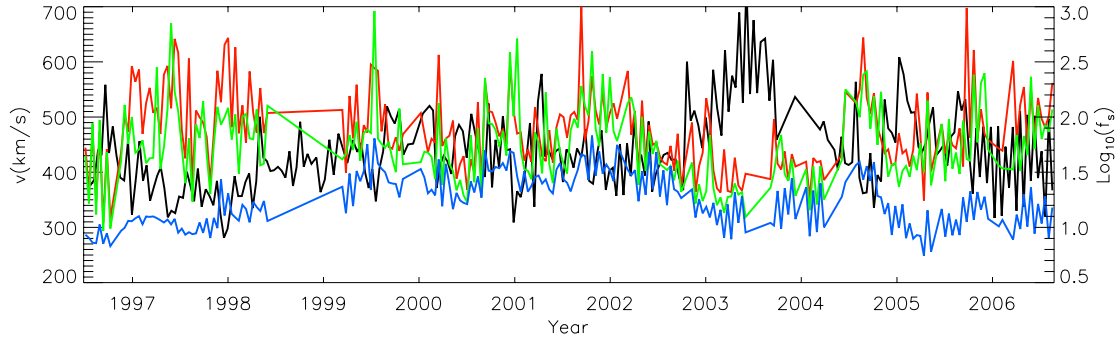
Fig1   WIND proton speed and flux tube expansion factor of sub-earth points, based on MDI data.

Black: WIND; Red: PFSS; Green: CSC; Blue: HCCSSS.

2.   Angular distance from the foot points to the nearest coronal hole boundary θ_b. It distinguishes the high speed solar winds from the low speed ones. High speed wind that comes from the center of a coronal hole has large θ_b; low speed wind that comes from the hole boundary has a small θ_b. The introduction of this new parameter greatly improves the accuracy of prediction.

   An empirical function, with various free parameters in the following form (Arge, 2003), is used to predict the solar wind speed near the sun (fig2).

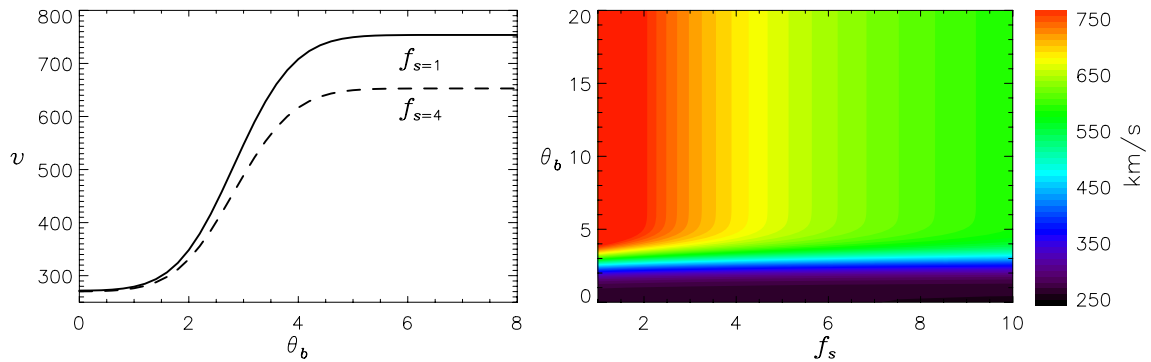$$v = 265 + \frac{1.5}{(1+f_s)^{0.4}}[5.8 - 1.5\exp(1-(\frac{\theta_b}{2.5})^{2.0})]^{3.5}.$$

Fig2   Left: Solar wind speed as a function of θ_b, for fixed f_s

Right: Contour of speed in the (f_s, θ_b) space given by the empirical function.

   In order to get these two parameters, one needs to know the modeled coronal field. Potential field approximation has been used for years to infer the magnetic structure of the solar corona:

$$\nabla \cdot \vec{B} = 0.$$

It assumes that there exist no large scale currents. Based on this assumption, people have developed

several models and use them as an easy tool to understand the coronal field. In this study, we explore three existing models: PFSS, SCS and HCCSSS (fig3).
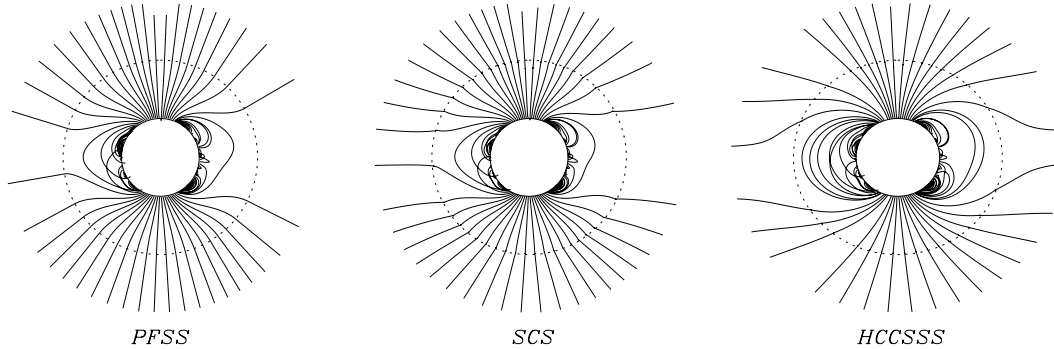

Fig3   Derived field configuration from three models (CR1922, MDI data).
The dashed circle implies a 2.5R$_\odot$ sphere.

1. PFSS: Potential Field Source Surface Model
   - Potential field everywhere
   - Fields become open and purely radial from a certain height (source surface)
2. SCS: Schatten Current Sheet Model
   - Potential field below the source surface where fields become open and radial
   - Current sheet exists above the source surface, so field is realigned
   - No radial field confinement
3. HCCSSS: Horizontal-Current Current-Sheet Source-Surface Model
   - Source surface placed near the Alfvén critical point, where all the fields become radial
   - Introduces cusp surface, where field becomes open but not necessarily radial, to include effects of streamer current sheets.
   - Horizontal electric current in the lower corona is included as a free parameter.

The PFSS model requires the field to be radial at source surface, which does not match observation very well. The SCS model requires the field to be radial at the source surface, but the current sheet then alters the field lines, causing discontinuities in the horizontal field at the source surface. The HCCSSS model introduces a horizontal current, relaxes the radial field requirement at 2.5R$_\odot$, so the field becomes continuous everywhere and fits observation best among the three (Zhao and Hoeksema, 1995).

While extensive work has been done to incorporate the PFSS and SCS model into the WSA model, little has been explored for the HCCSSS model. The coronal model dependence of the prediction is

unknown either. In this study, we try to follow the existing procedures and explore various possible improvements, in   order to come up with a more robust scheme.

Data Processing and Computation Scheme:

  Observed photospheric field is used as the only input of the model. For a high resolution MDI line of sight (LOS) synoptic chart (3600x1080 in sine latitude), several procedures are essential:

1. Correct for the effect of the solar b angle and convert LOS map into a radial field map.
2. Convert the map to a lower resolution of 2.5º (144x72), from sine latitude to latitude, with flux conserved both locally and globally.
3. Use well observed polar field data and a temporal interpolation (Liu, 2007) to fill in the polar regions.
4. Remove the monopole.

  Using one of the three models, we trace the field line downward from a certain height (2.5$R_\odot$ for PFSS, 5$R_\odot$ for SCS; 15$R_\odot$ for HCCSSS) to the photosphere. If we assume the solar wind materials are transported along the flux tube from a lower height, then those field lines can specify the source of the solar winds.

  The two parameters are then computed near the sun. We use a simple 1D kinetic model to propagate the solar wind from the sub-earth points to 1AU. Materials travel radially. When faster solar winds catch up with the slower ones, they interact and obtain a new speed. This way, we get the time series of solar wind speed 1AU with a 4 hour resolution.

  As a validation of this method, 4-hour averaged WIND data is used. We crosscheck the WIND proton speed data with OMNI proton temperature, remove the points with extra low proton temperature, which is an indicator of CMEs (Richardson, 1995). Mean square error (MSE) is used to evaluate the predictions and to optimize the empirical function.

Foot Point Location and Neutral Line over the Solar Cycle:

  For all three models, over one solar cycle, inferred neutral lines based on MDI data are generally consistent with those from WSO data and PFSS model (fig4). The difference mainly results from the polar field correction, where a north-south asymmetry is sometimes introduced. Except for solar maximum, the derived foot points locations are generally consistent with Kitt Peak and EIT data. Because of the introduced currents, neutral lines at 5$R_\odot$ (SCS) and 15$R_\odot$ (HCCSSS) are usually

flatter than the PFSS model, and open field regions are smaller than those of PFSS model. For SCS and HCCSSS model, neutral lines at different heights are nearly identical. This indicates that fields are nearly radial near the current sheet, between these two heights, though they are not required to be so.

Solar wind speed are low near the current sheet. During the solar minimum, the sub-earth line is constantly near the current sheet, where expansion factors are huge. This leads to the relatively uniform and low speed solar wind we observe. In this period, the speed becomes sensitive to the free parameters in our model, thus are hard to predict. During the solar maximum, however, neutral line has great curvature and can possibly extend to the pole. This gives a more variable expansion factor and solar wind speed at 1AU. If we exclude the effect of transient events, we should be able to get better prediction.

A major advantage of SCS and HCCSSS model is that their current sheet "attracts" open field lines so the expansion factor drops significantly for SCS and HCCSSS model. This gives a higher predicted speed that PFSS model has trouble to obtain (fig1). They also predict the magnetic field strength at 1AU.

Preliminary Comparison of Three Models:

The expansion factors of HCCSSS are generally smaller and more uniform than those of SCS and PFSS. This is because we start field line tracing from a much higher point (15R$_\odot$), but compute f_s between the cusp surface (2.5R$_\odot$) and photosphere. Field line foot points at 2.5R$_\odot$, where we take the field magnitude, now moves further to the poles. Hence we have a stronger field in the corona, then a smaller expansion factor. It gives a clearer inverse relationship between the expansion factor and the speed at certain time period, for example June 2003 to June 2005, but not so much during the others (fig1). High speed are constantly predicted without enough variations. This shows that the same scheme used for PFSS model may not be applied directly to HCCSSS model, and a lower height to start tracing needed to be found.

Prediction of solar wind speed at 1AU mainly depends on the parameter of expansion factor f_s, since most solar winds come from small coronal holes near the equator, and thus have small θ_b. However, it improves a lot from the older version of WSA, which includes only the expansion factor (fig5).

The WSA model works well when the current sheet is not constantly near the sub-earth line (solar minimum). For CR2029 (April/May 2005) when all three models work well, the square root of MSE for SCS and HCCSSS shows an average 75 km/s error, while PFSS model has a mean MSE 33% larger. All three models predict the first three spikes, while missing the last one. The performance of three models varies with time, with SCS and HCCSSS working generally better.
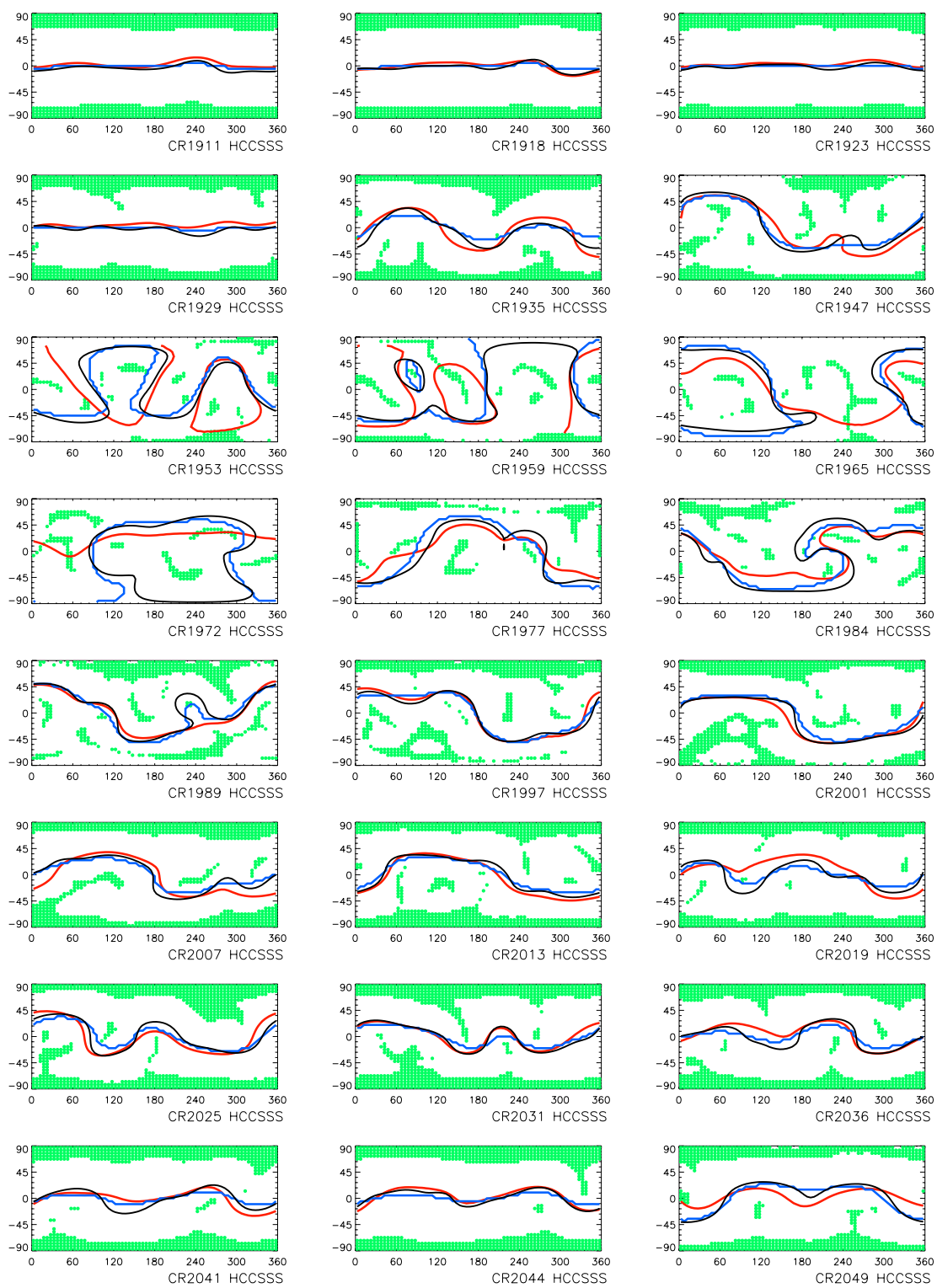
Fig4 Foot points and neutral line map from HCCSSS. (MDI, order 9)

Green areas: open field foot points; Black line: derived cusp surface (2.5R$_\odot$) neutral line;

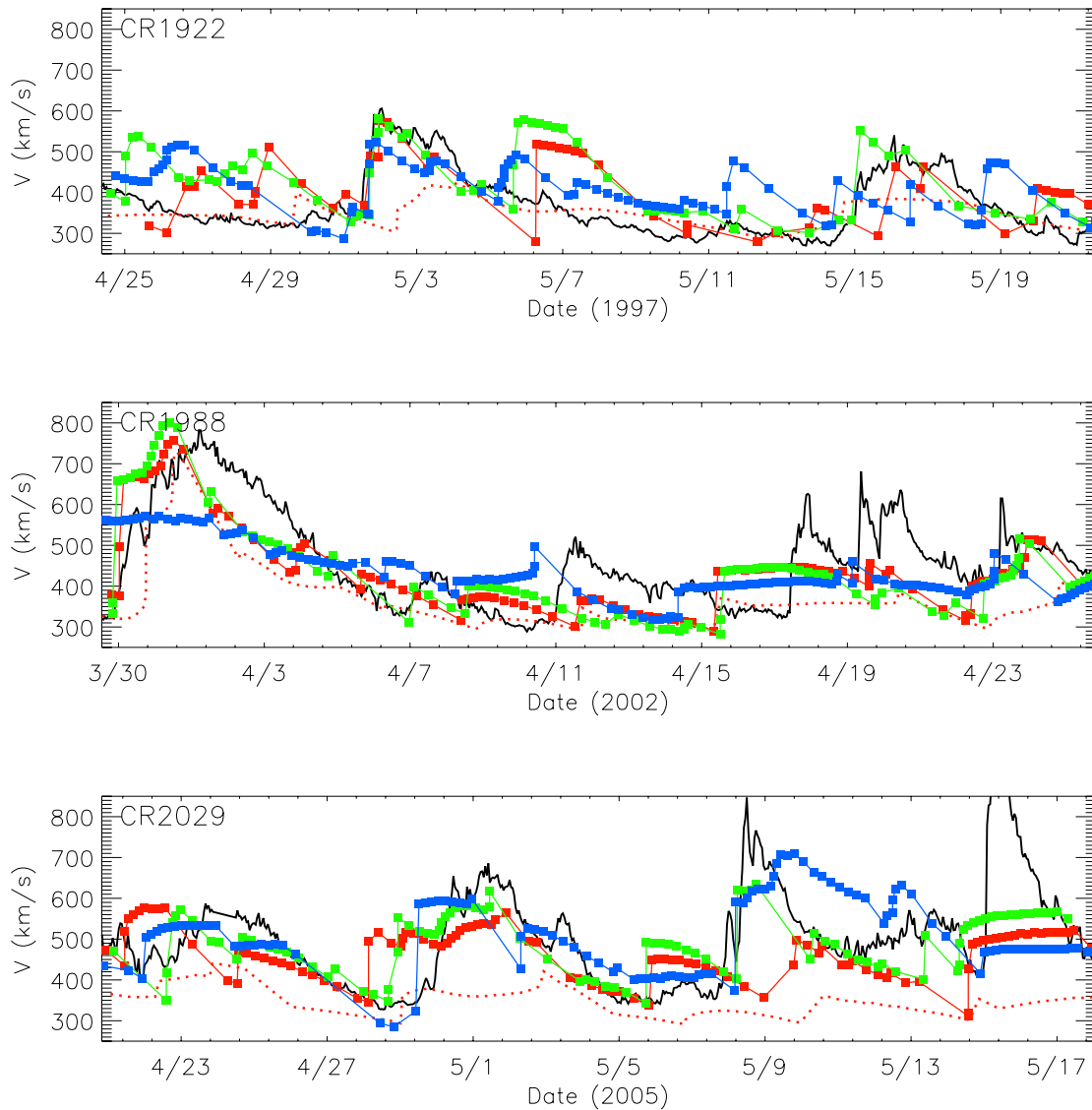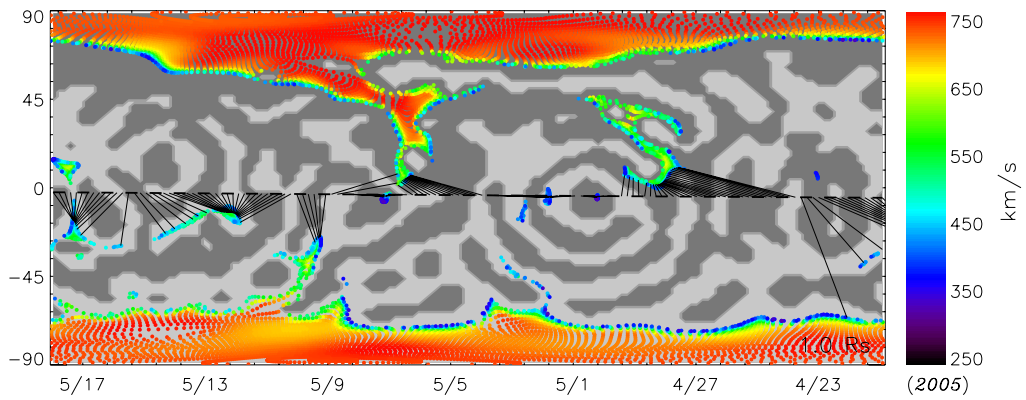Blue line: source surface (15R$_\odot$) neutral line; Red line: neutral line from WSO website, based on PFSS model.
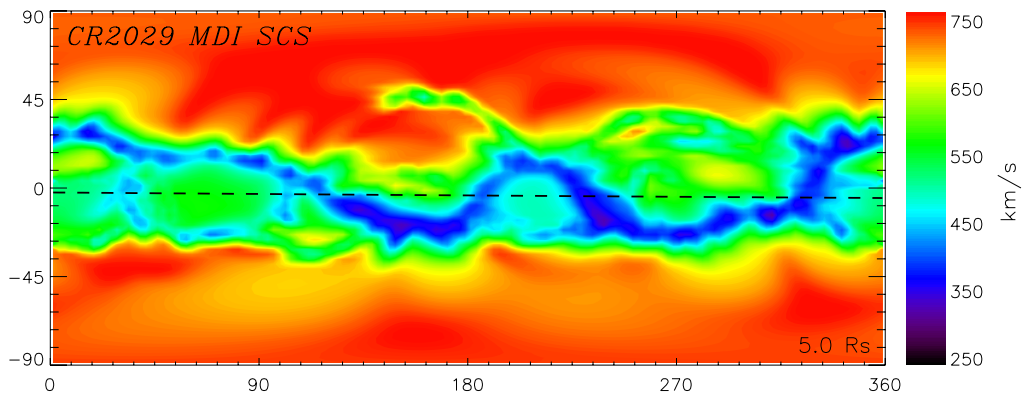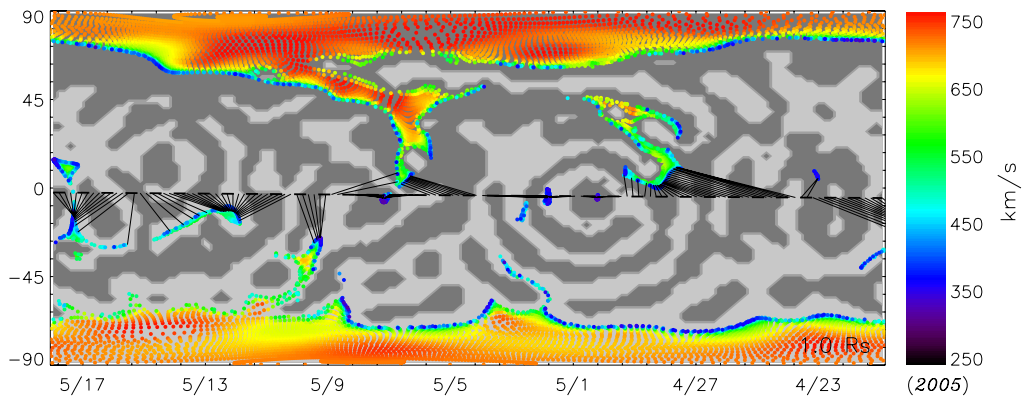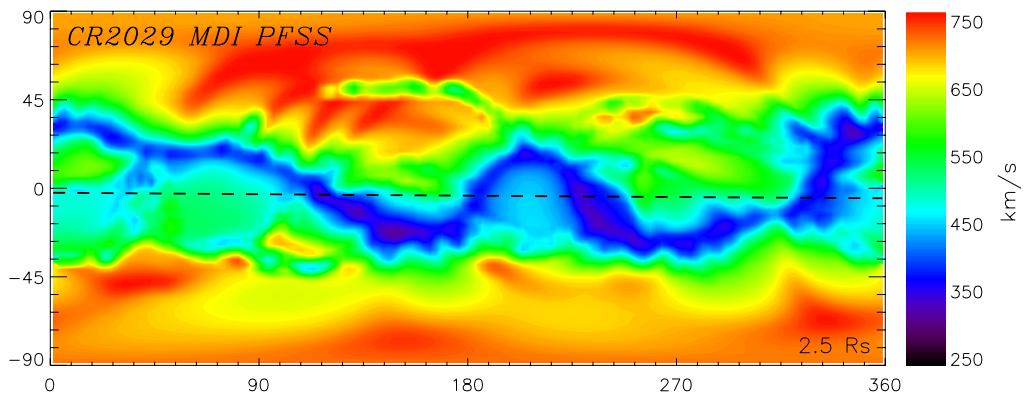
Fig5　Speed prediction at 1AU (MDI, order22)

Black: WIND data; Red: PFSS; Green: SCS; Blue: HCCSSS; Dashed line: old version of WSA

For the global prediction, the HCCSSS model predicts lower polar winds, but more uniform high speed winds in the low latitude (fig6). SCS and PFSS model give constant high speed (>700 km/s) in the pole regions. The most significant difference is the location of foot points. For HCCSSS, the effect of the horizontal current and a high starting point smooth out the low latitude small open field regions, so more field lines go back to the polar regions.

CR2029 MDI PFSS

2.5 Rs

km/s

5/17   5/13   5/9   5/5   5/1   4/27   4/23

(2005)

CR2029 MDI SCS

5.0 Rs

km/s
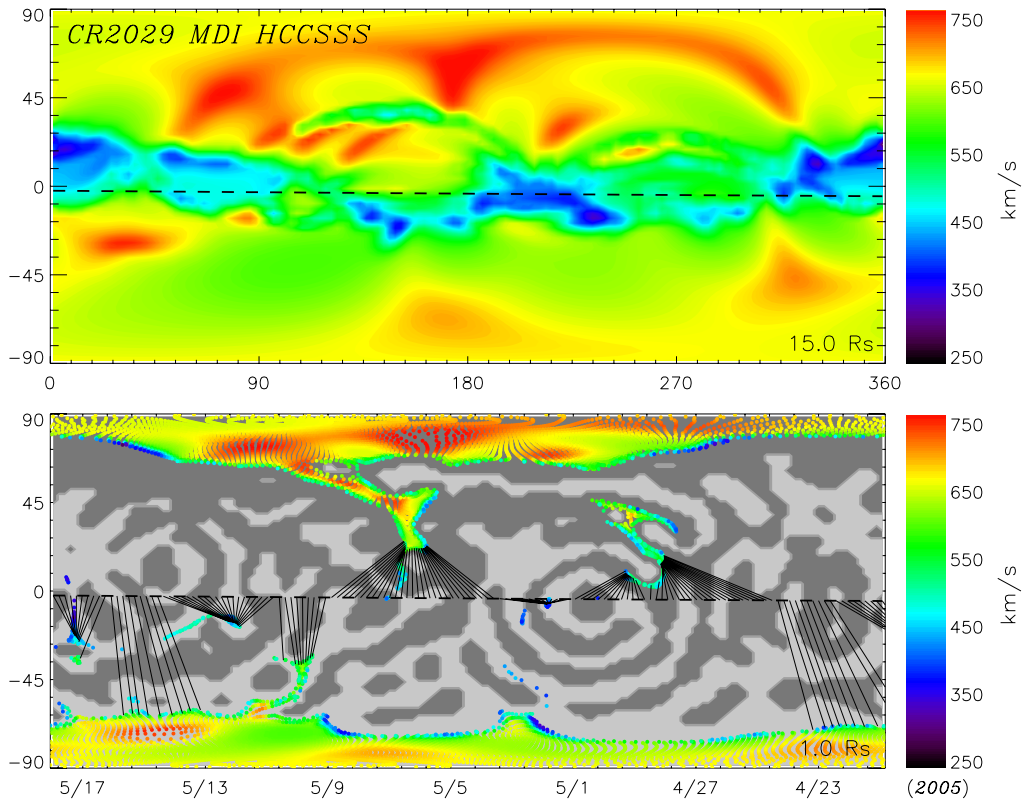
5/17   5/13   5/9   5/5   5/1   4/27   4/23

(2005)

Fig6 (CR2029, MDI, order22) Upper: global speed prediction;

Lower: foot points with speed specified, reconstructed photospheric field polarity (light for positive, dark for negative), and sub-earth point connectivity to the photosphere.

Discussion of Miscellaneous Issues:

1. Polar Field Corrections

Polar field corrections are essential to obtaining a reasonable coronal field structure. Unreasonable polar field will lead to misplaced foot point locations, and eventually inaccurate predictions (fig7).

We take those well observed MDI polar data (September for north pole and March for south pole). For each specific point in the polar region, we get a time series of field values over ten years. A cubic-spline fit is used to determine the value at each specific time (Liu, 2007). This method proves to be the best among the common polar corrections (fig8).

This method is largely successful at reproducing the foot points configurations, but the north-south polar fields are usually asymmetric (fig8). After taking out the monopole component, the global field magnitude zero-point might shift, causing the shift or deformation of the current

sheet. During the solar minimum, this shift of current sheet towards the sub-earth line could result in too uniform and huge expansion factors, thus too low speeds with little variation.
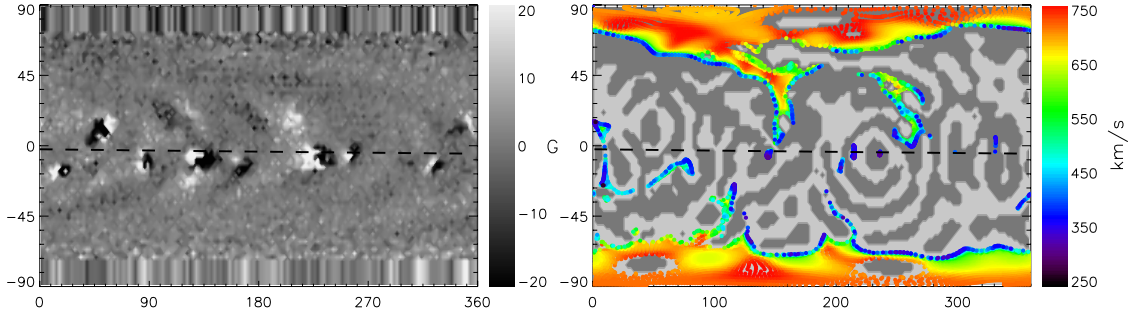

Fig7   Artificial polar field correction and its effect on foot point locations (CR2029, PFSS, MDI).
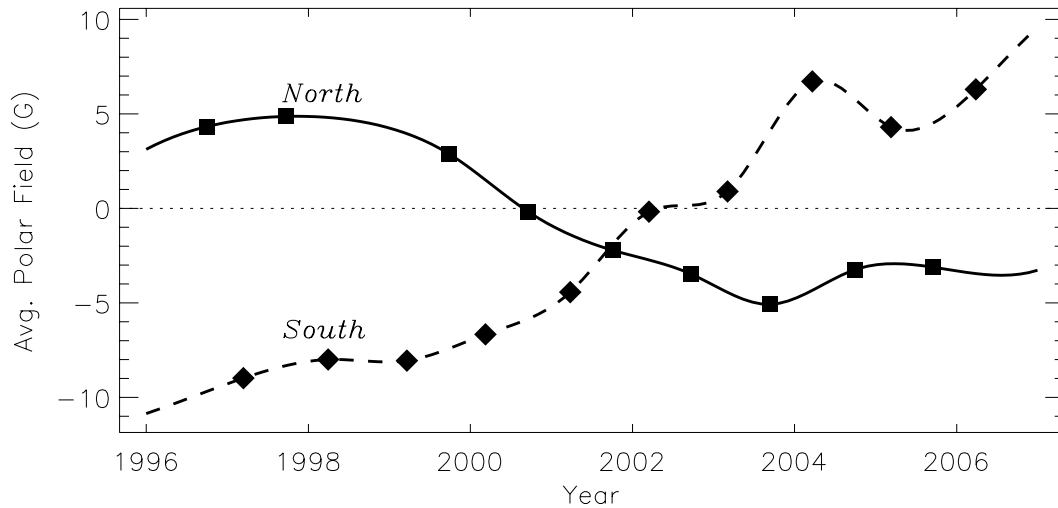

Fig8   Mean field of reconstructed MDI polar data, cubic-spline-fitted.

2. Input Data Format: sine latitude or latitude

In the sine latitude format synoptic chart, each grid cell has the same area, so the flux is proportional to the observed field value. However, fields above certain latitude are not resolved. (For example, the WSO data has a -14.5/15~14.5/15 sine latitude grid. The highest cell center is located at 75.2º, above which we have no data.)

As we compute the harmonic coefficient for the potential field, the numerical effect becomes serious. If we use sine latitude format, the numerical integral algorithm emphasizes too much on the polar fields. Furthermore, the eigenvectors in sine latitude format are not orthogonal with each other, causing unrealistic fluctuations in field magnitude (fig9).
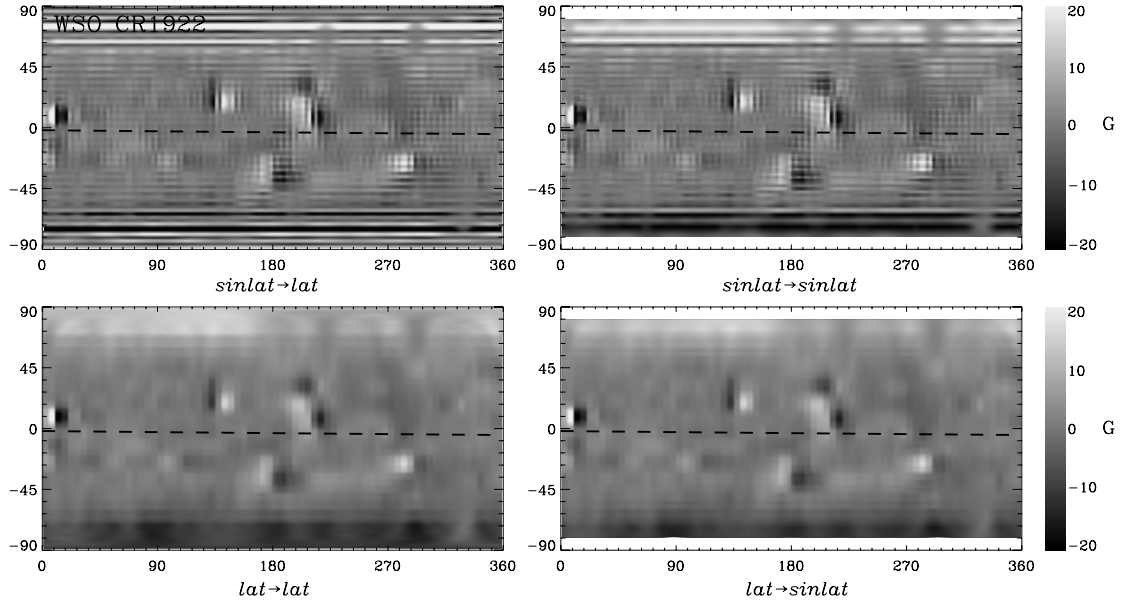
Fig9   Reconstructed synoptic chart with various input/output format (CR1922, WSO, PFSS, order 22)

Upper-left: sin-lat input, lat output; Upper-right: sin-lat input, sin-lat output;

Lower-left: lat input, lat output; Lower-right: lat input, sin-lat output.

3. Effect of N_{max}

The maximum order of harmonic coefficient is important when computing the field. Past study (Bala and Zhao, 2004) shows that for PFSS model and WSO data, N_{max}=22 seems to be a reasonable choice. By mapping back from 1AU to $1R_\odot$, solar wind speed are connected with the single parameter f_s. Above order 22, the locations of certain foot points and the computed expansion factors become stable.

We make the global speed prediction with different orders of harmonic coefficient (fig10). Compare this with fig6, we see the foot point locations are similar for order 22 and 72, while order 9 oversimplifies the configurations. Also, we find the predicted speed is too low for order 9. For order 72, the prediction introduces some artificial fluctuation in speed, as well as lots of local mixed polarities, both of which are possibly due to numerical effects. According to the limited cases we have explored, order 22 gives a relatively smooth distribution of speed and photospheric field, and the predictions at 1AU are no worse then higher order computations. We argue that order 22 is the most reasonable choice amongst the three.
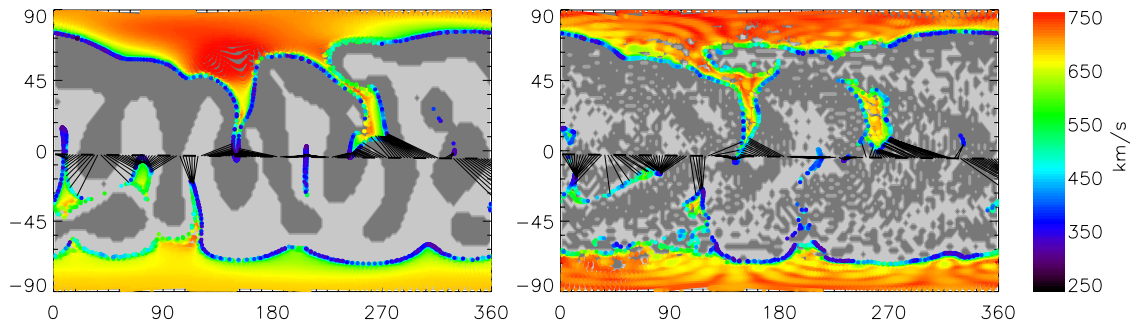
Fig10　Foot points location and photospheric field (CR2029, PFSS, MDI).

Left: order 9; Right: order 72.

Conclusion and Challenges:

  In the hope to improve the WSA model, we explore various possible approaches. For the input data, a temporal interpolation is used for polar correction, and latitude grid format is adopted. For the prediction algorithm, the parameter θ_b greatly improves the prediction. We also make a preliminary comparison between three models. The SCS model generally performs better than the PFSS model, while the current version of HCCSSS model predicts higher wind speed, with less variations.

  Several questions remain unsolved:

1. The temporal interpolation introduces a north-south asymmetry, whose effects are still unknown.

2. The HCCSSS model gives the best description of coronal field amongst the three. But the current scheme for determining the solar wind speed is not working so well. A more appropriate scheme is yet to be found.

3. An appropriate statistical evaluation that could guide this study is to be found.

4. The predictions are sensitive to the free parameters in the empirical function. Finding a more robust function will be our next step.

References:

Wang, Y.-M. & Sheeley Jr., N. R., 1990, ApJ, 355, 726.

Arge, C. N. et al., 2003, Solar Wind Ten, CP679.

Schatten, K. H., 1971, Cosmic Electrodynamics, 2, 232.

Zhao, X. & Hoeksema, T., 1994, Solar Physics, 151, 91.

Bala, P. & Zhao, X., 2004, J. Geo. Res., 109, A08102.

Richardson, I. G. & Cane, H. V., 1995, J. Geo. Res., 100, 23297.