WSA & ADAPT Models

Space Weather Forecasting Bootcamp

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Outline

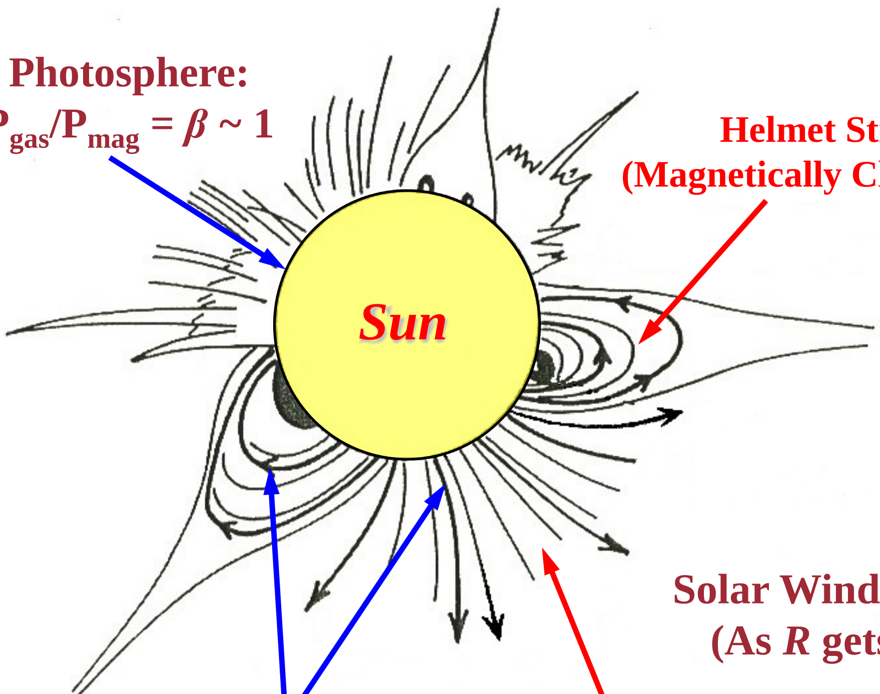
- The corona and solar wind
- Predicting the solar wind using magnetic flux tube expansion factor
- The Wang-Sheeley-Arge (WSA) coronal and solar wind model
- Photospheric magnetic field observations - primary driver to coronal & solar wind models
- Air Force Data Assimilative Photospheric Flux Transport (ADAPT) model

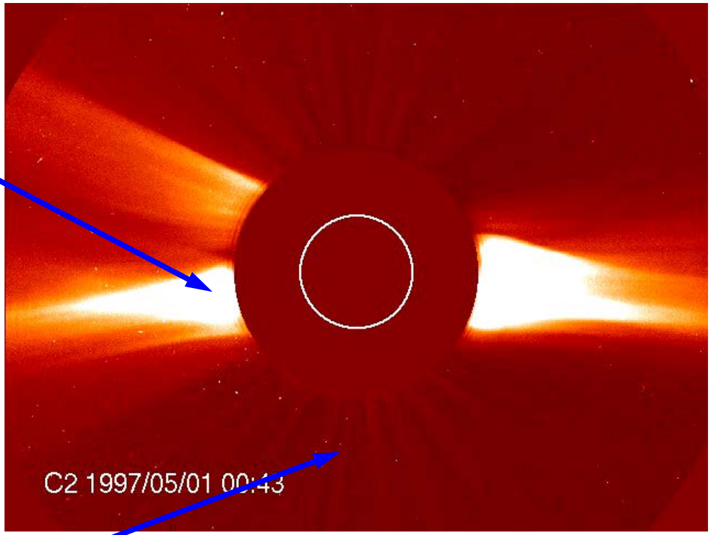
The Solar Magnetic Field

Photosphere:
$P_{gas}/P_{mag} = \beta \sim 1$

Helmet Streamer
(Magnetically Closed Region)

SOHO/LASCO





Solar Wind: $\beta \rightarrow \sim 1$
(As R gets large)

Corona: $\beta << 1$

Coronal Hole
(Magnetically "Open" Region)

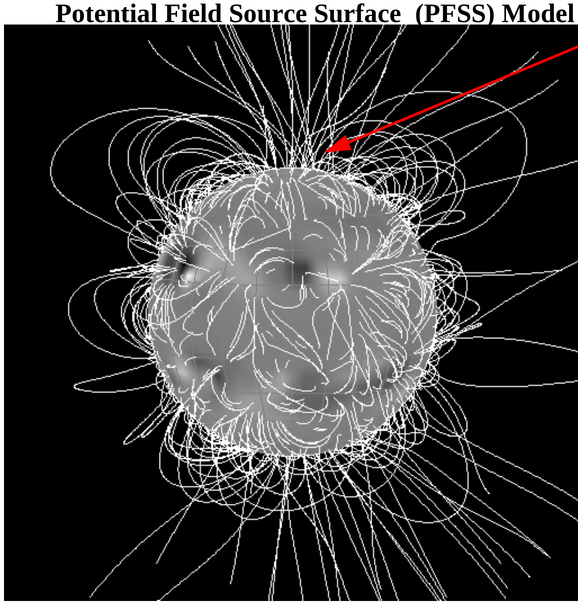
Coronal Holes

Theoretical/Modeling Definition: Regions with magnetic fields "open" to heliosphere.

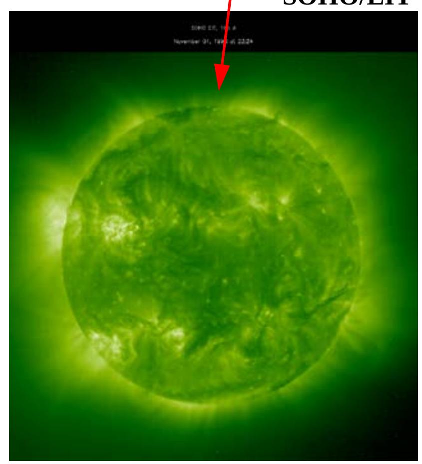
Observation Definition: Regions of low emission in the solar corona.

Coronal Hole

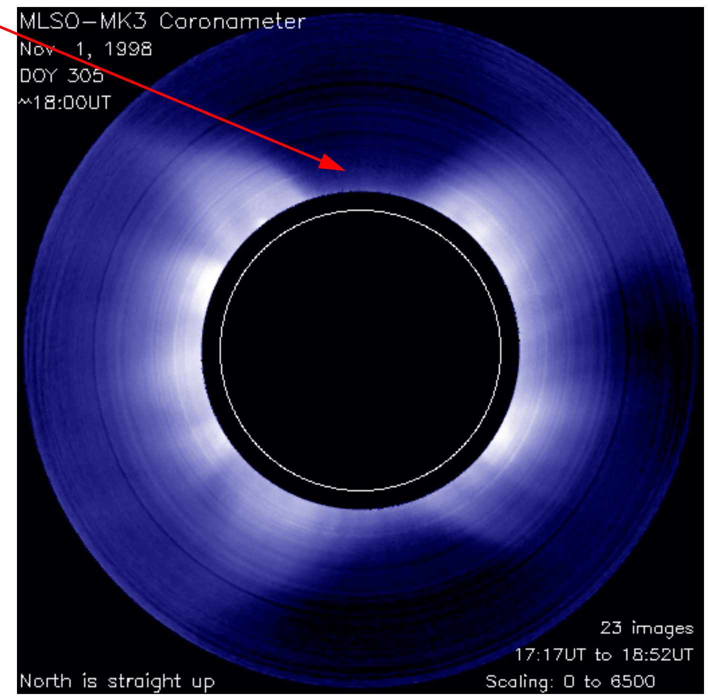
Potential Field Source Surface (PFSS) Model



SOHO/EIT



MLSO-MK3



Coronal holes are important because they are a major source of the solar wind and thus help <u>link</u> the Sun-Heliosphere system

What is the Ambient Solar Wind?

The ambient, or slowly varying, solar wind is hot magnetized plasma that streams from magnetically open (and possibly intermittently open) regions on the Sun such as coronal holes.

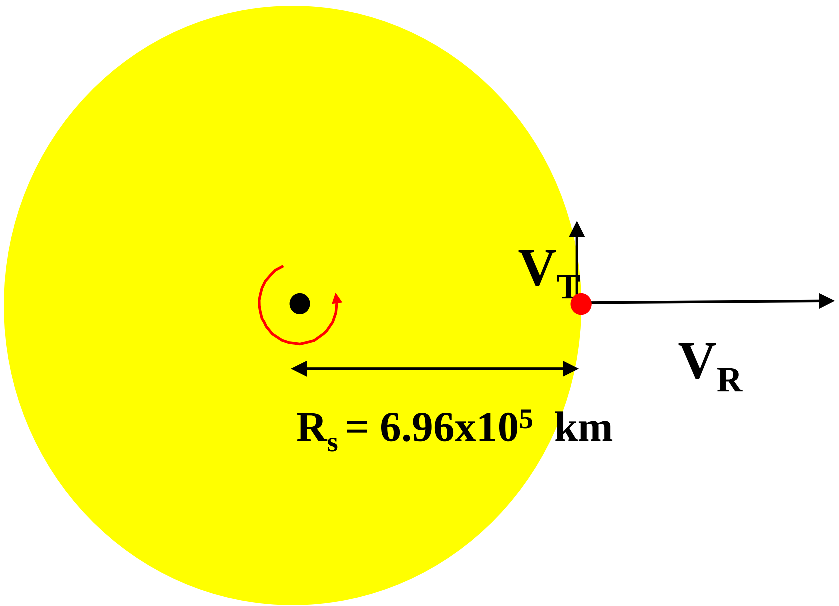
Two Types:

Fast or *high-speed* wind comes primarily from large polar coronal holes.

Slow wind comes from coronal holes boundaries, from smaller mid- to low latitude coronal holes, and from the vicinity of active regions.

(For more details see Holzer [2005], Neugebauer et al. [2002 & 1998], and Liewer et al. [2003])

Radial Flow of the Solar Wind



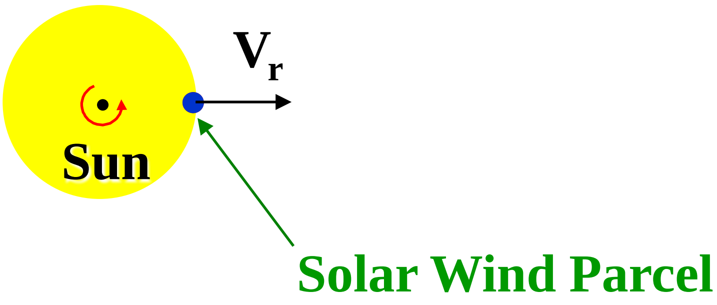
$T_{Sun} = 25.38$ days $= 2.192832\text{x}10^6$ sec

$V_T = 2\pi R_s/T_{Sun} \approx 2.0$ km/s

$V_R \approx 400$ km/s (typical solar wind speed)

$V_R >> V_T \Rightarrow$ **Solar wind flow from the Sun is primarily radial.**

The Solar Wind and the Interplanetary Magnetic Field (Formation of the Parker Spiral)



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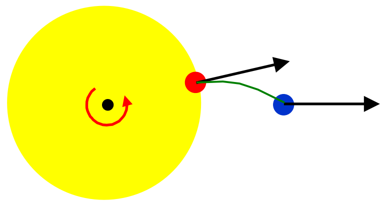

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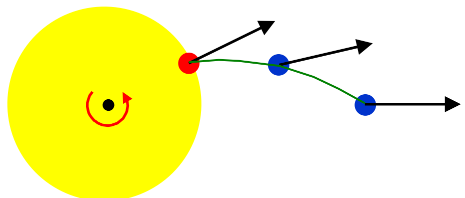

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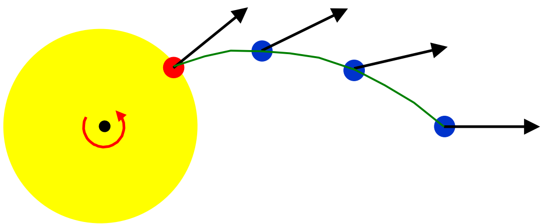

The Solar Wind and the Interplanetary Magnetic Field
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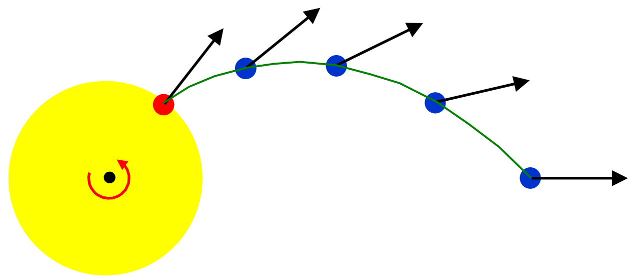
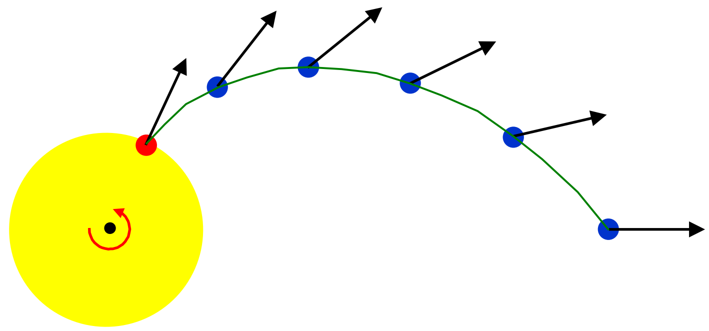


The Solar Wind and the Interplanetary Magnetic Field (Formation of the Parker Spiral)



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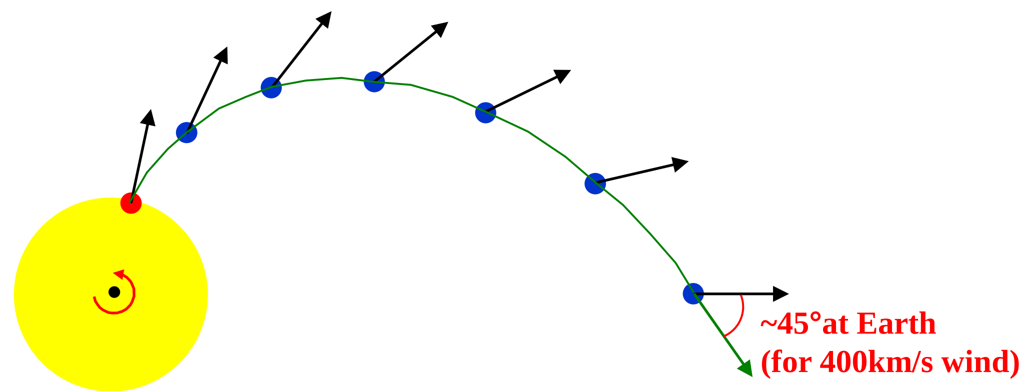


Magnetic Field Line

Because (1) the solar wind flows away from the Sun radially AND (2) the magnetic field and solar wind plasma flow together (i.e., frozen in flux condition), (some) magnetic field lines attached to the Sun are dragged out into space forming a spiral pattern called the Parker Spiral.

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times (\mathbf{V} \times \mathbf{B}) = 0$$ (Frozen in flux condition)

$$\Rightarrow \quad \mathbf{B}_r = \mathbf{B}_o \left(\frac{\mathbf{r}_o}{\mathbf{r}}\right)^2 \sim r^{-2}$$

$$\mathbf{B}_\varphi = \frac{-\mathbf{B}_o \Omega \mathbf{r}_o{}^2}{\mathbf{v}_r \mathbf{r}} \sim r^{-1}$$

Why the Ambient Solar Wind is Important?

Scientific Understanding:

- The source regions of the slow solar wind are still a matter of debate.
- The solar wind acceleration mechanism is not well understood.

Provides Global Context:

- Solar transients such as Coronal Mass Ejections (CMEs) propagate through the ambient solar wind.
- Solar energetic particles (SEPs) flow along ambient wind magnetic fields.
- It is important in models seeking to simulate and explain real events to have a sufficiently accurate description of the ambient corona and solar wind.

Space Weather:

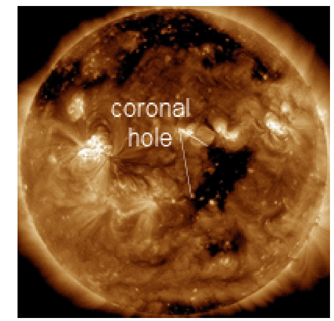
High-speed solar wind streams are associated:

- Recurrent geomagnetic disturbances/storms.
- Increased high-energy electron fluences near Earth.

Geomagnetic Storms: Disturb the Earth's upper atmosphere and this can affect satellites, astronauts, and aircraft. They can disrupt communications (e.g., short wave radio) and navigational systems. On the ground they can affect power grids, pipelines, geological exploration, migratory animals, etc.

Magnetic Flux Tube Expansion & the Solar Wind (Brief Historical Background)

1. Large near-equatorial coronal holes associated with high-speed solar wind streams (*Nolte et al.*, 1976).



   $\Rightarrow$ Coronal hole = Open field region on Sun.

2. *Levine*, *Altshuler*, & *Harvey* (1977) interpret correlation in terms of *flux tube expansion* (f_s).

   $f_s = (R_\odot/R_{ss})^2[B^P(R_\odot)/B^P(R_{ss})]$ = rate at which a flux tube expands between the *photosphere* and a spherical "*source surface*" located (2-3 $R_\odot$) in the corona.

   Central regions of large coronal holes $\longrightarrow$ Small f_s

Brief Historical Background Cont'd

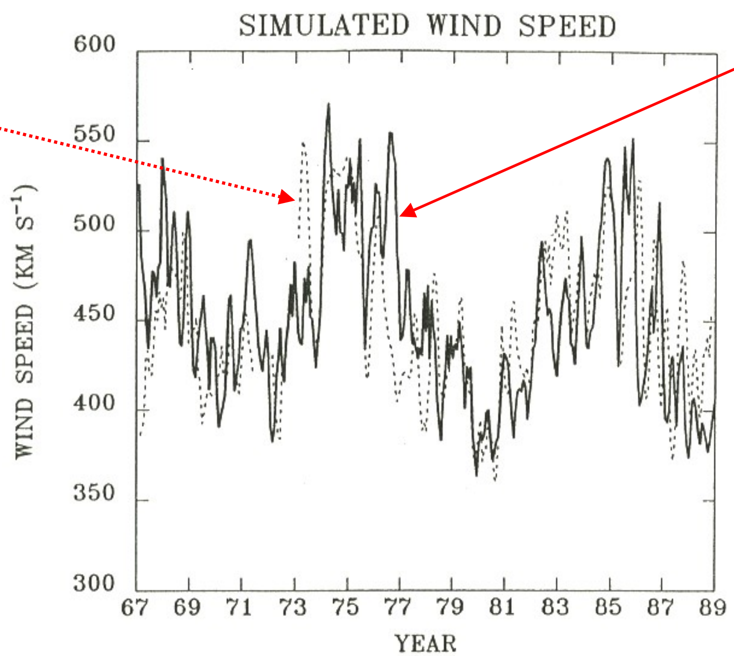
3. *Wang & Sheeley* (1990) simulate the solar wind speed at Earth for ~20 year period (1967-1988).

   i) Test hypothesis that V_{sw} and f_s are inversely correlated.

   ii) Correlation between observed & simulated wind speed found.

Observed Speed ....

Simulated speed ————



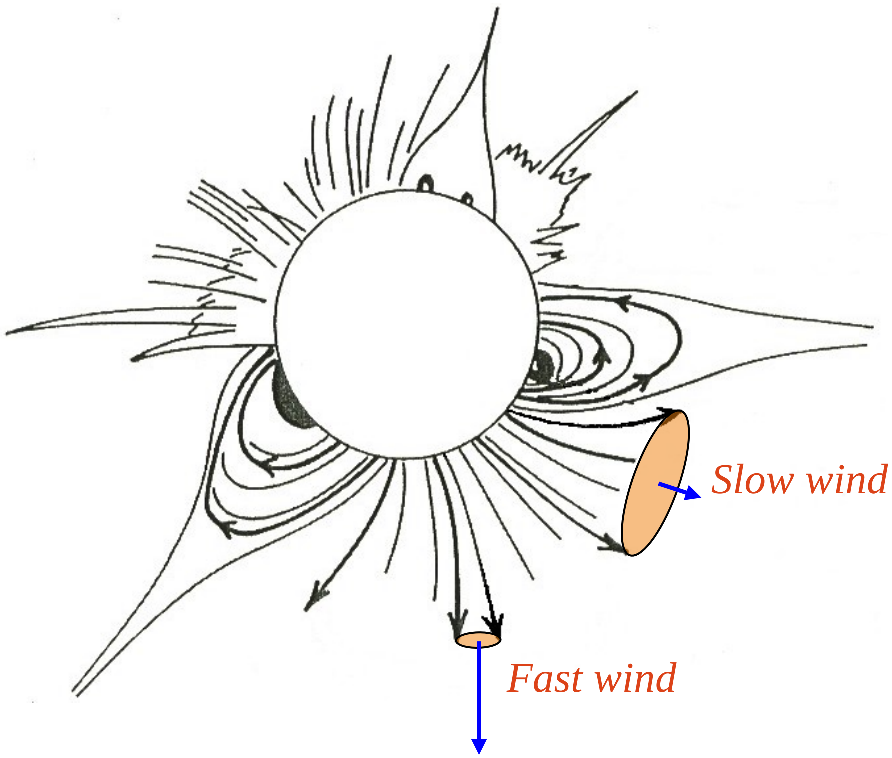
Wang & Sheeley, *ApJ*, ***355***, 726, 1990.

Brief Historical Background Cont'd

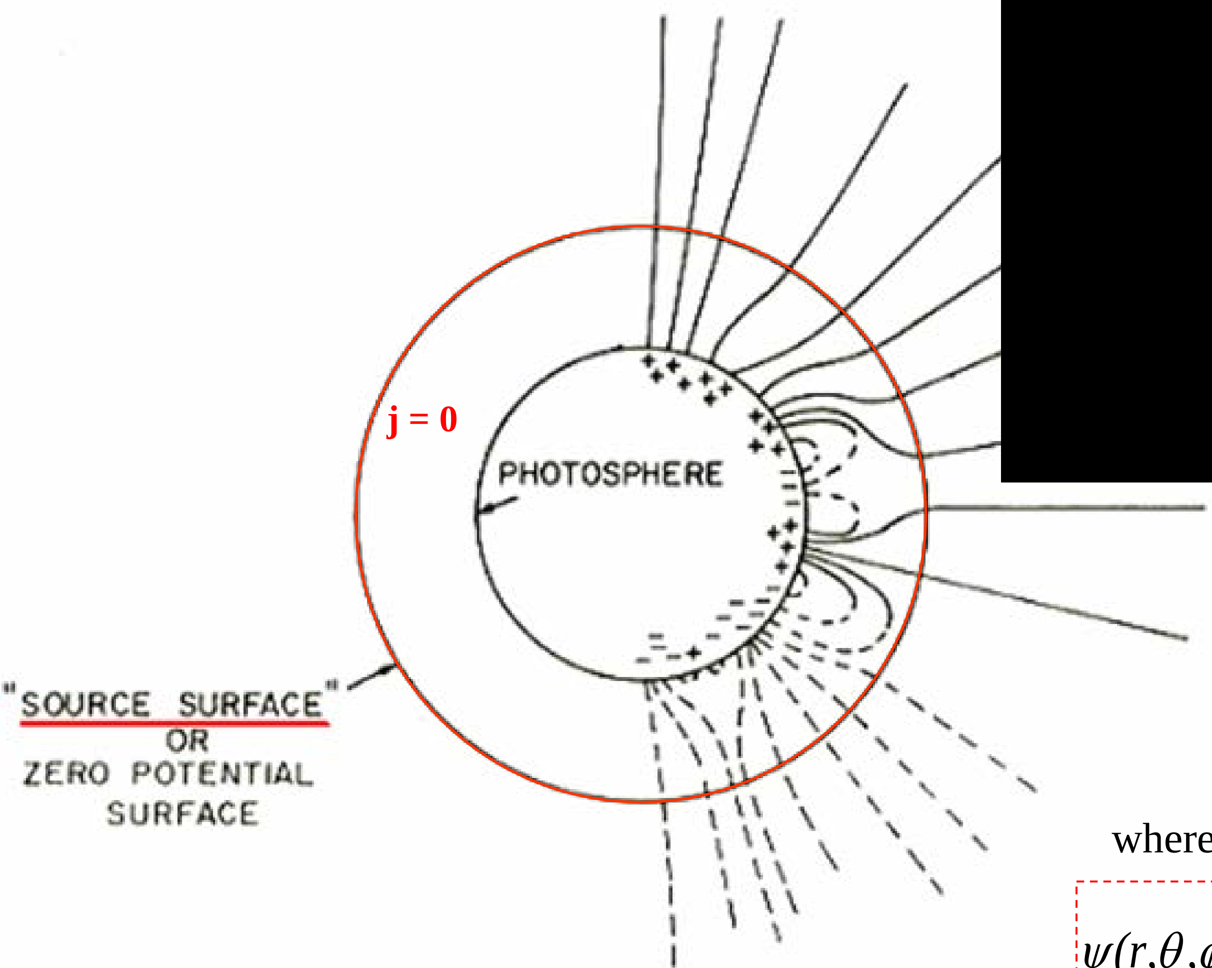
iii) Conclude: fast & slow solar wind originate from coronal holes.

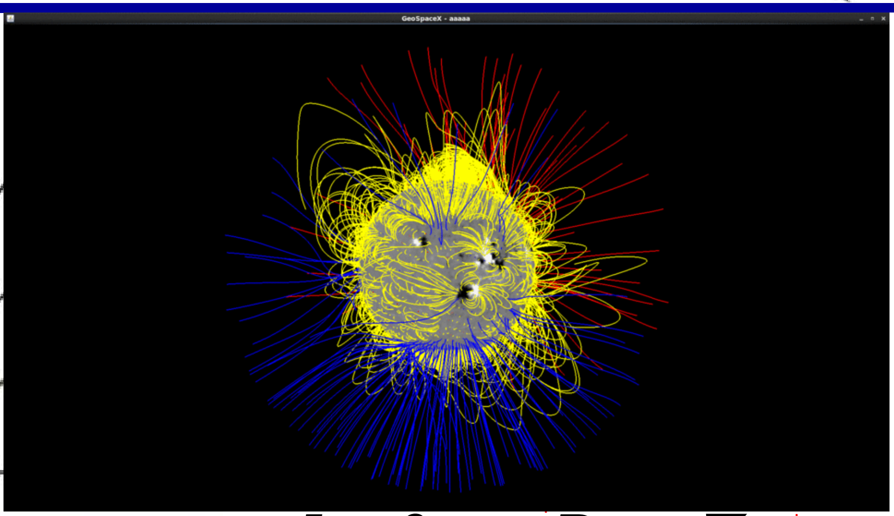
Fast wind ⟶ *central regions of coronal holes* (**Small** f_s)

Slow wind ⟶ *coronal hole boundaries* (**Large** f_s)



Potential Field Source Surface (PFSS) Model of the Corona





$$J = 0 \Rightarrow \boxed{B = -\nabla\psi}$$

$$\nabla \cdot B = 0$$

$$\nabla^2 \psi = 0$$

where,

$$\boxed{\psi(r,\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \left[\underline{A_{lm}}\, r^{l} + \underline{B_{lm}}\, r^{-(l+1)} \right] Y_{lm}(\theta,\phi)}$$

Coefficients $\boldsymbol{A_{lm}}$ and $\boldsymbol{B_{lm}}$ are determined from the *boundary conditions*.

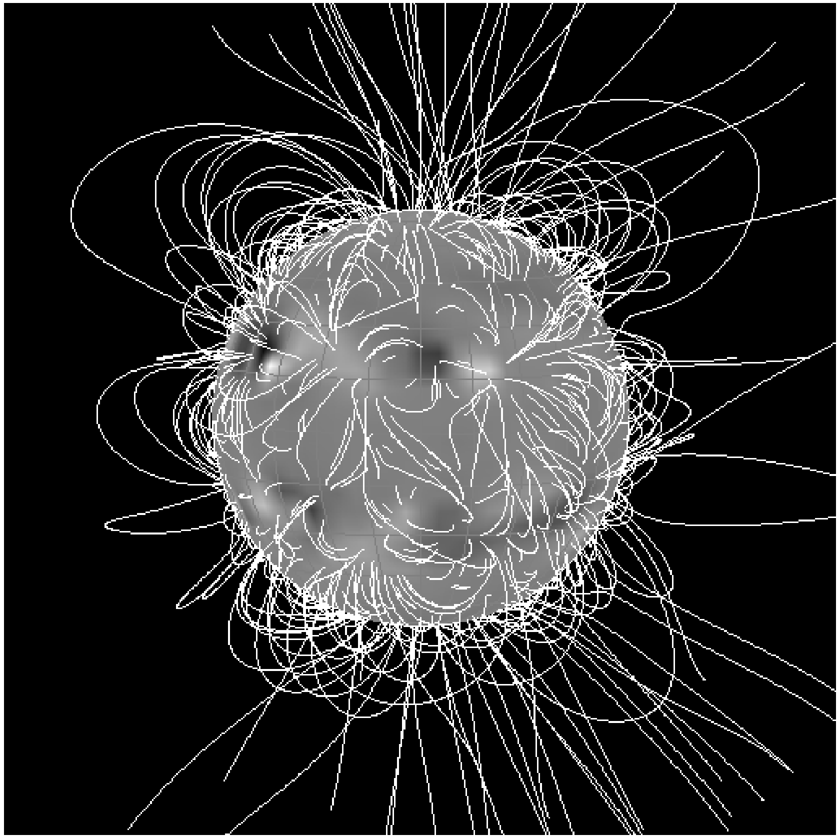
——— Outward Directed Field

- - - - - - Inward Directed Field

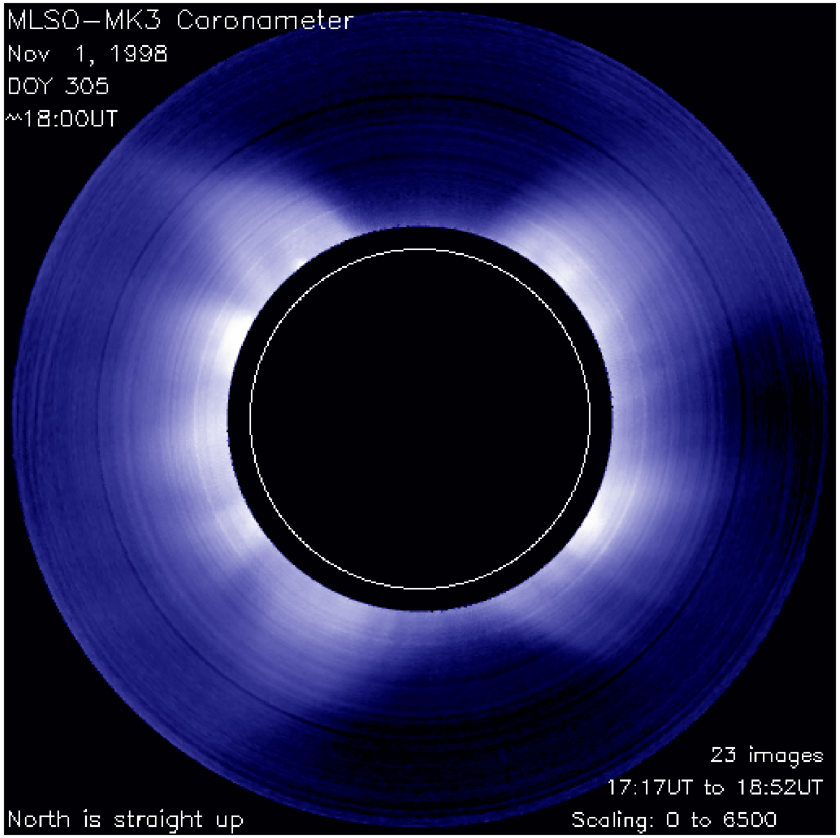
Schatten, Cosmic Electrodynamics, 2, 232, 1971.

Global Coronal Field: Observations & Extrapolations

Photospheric field extrapolation (MWO)

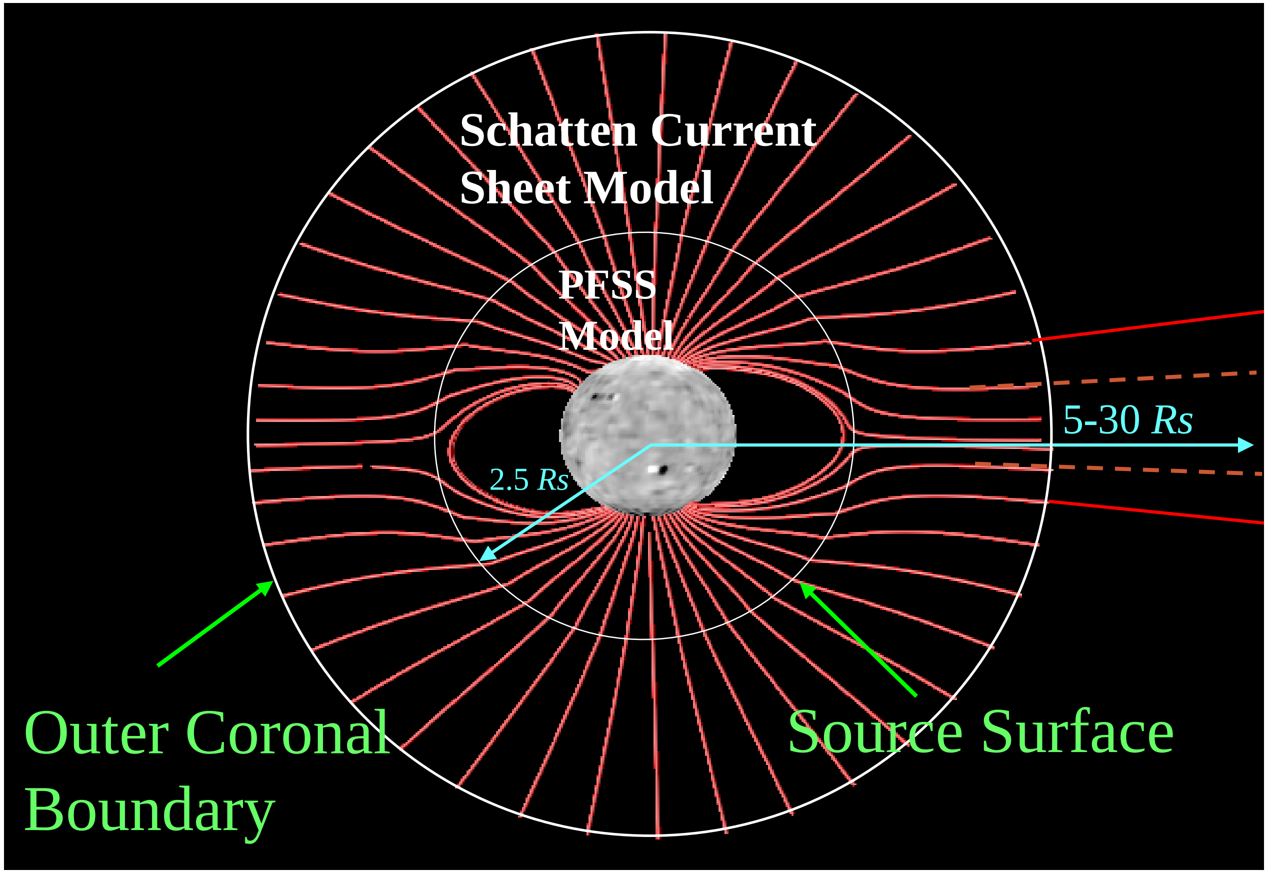


White light (pB) data HAO/MLSO/Mk3



Comparison of photospheric field extrapolations (left) to white light (pB) image (right) indicate a degree of **qualitative** correlation between closed field lines and streamers

Wang-Sheeley-Arge (WSA)* Coronal & Solar Wind Model



*(Origin of the Wang–Sheeley–Arge solar wind model, Neil Sheeley, Geo- and Space Science, 2017)

Solar Wind Models such as:

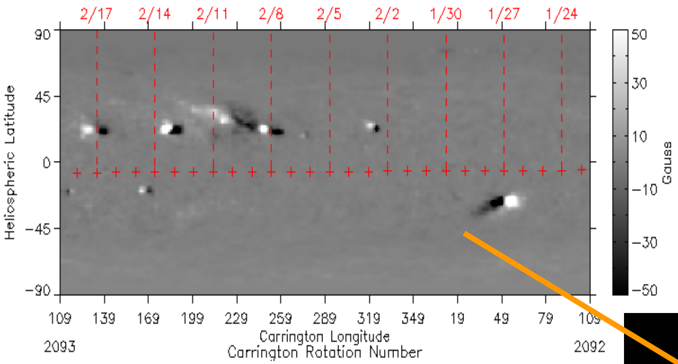
1) WSA 1D Kinematic
2) ENLIL
3) LFM-Helio
4) MS-FLUKSS
5) HAF

(5-30*Rs* to 1AU)

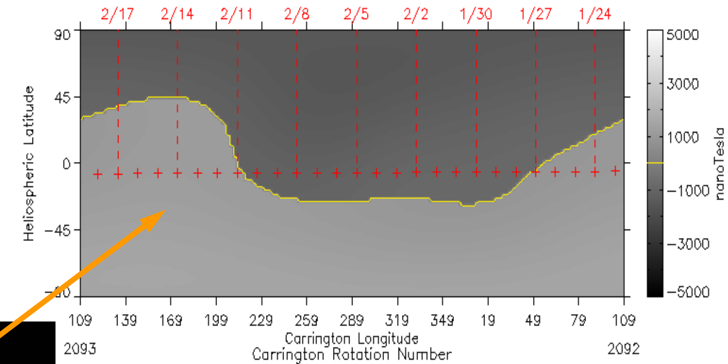
- **Wang-Sheeley-Arge (WSA) model - combined empirical and physics based model of the corona and solar wind.**
- **Improved version of the original Wang & Sheeley model developed at NRL.**

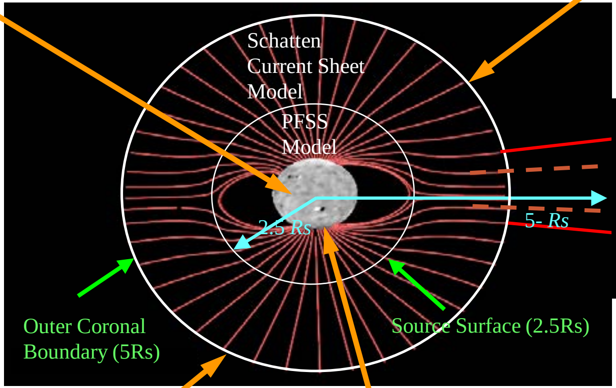
WSA Coronal Solution

MODEL INPUT: Observed Photospheric Field



MODEL OUTPUT
Field at Outer Coronal Boundary (5.0 R_s)

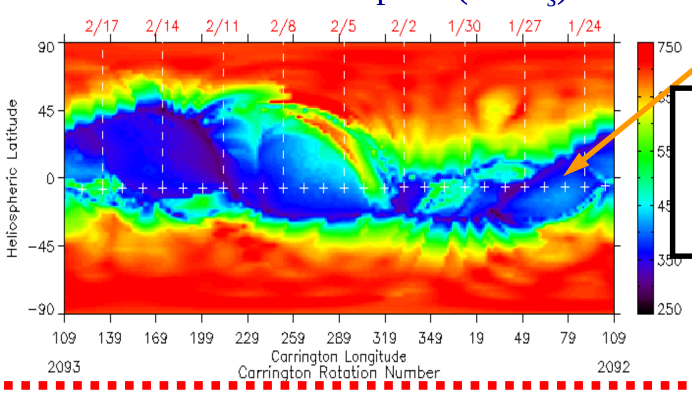




Solar Wind Model
(e.g., WSA 1D Kinematic model, Enlil, & LFM-Helio, MS-FLUKSS, & HAF)
(5-30*Rs* to 1AU)

MODEL OUTPUT

Predicted Solar Wind Speed (5.0 R_s)

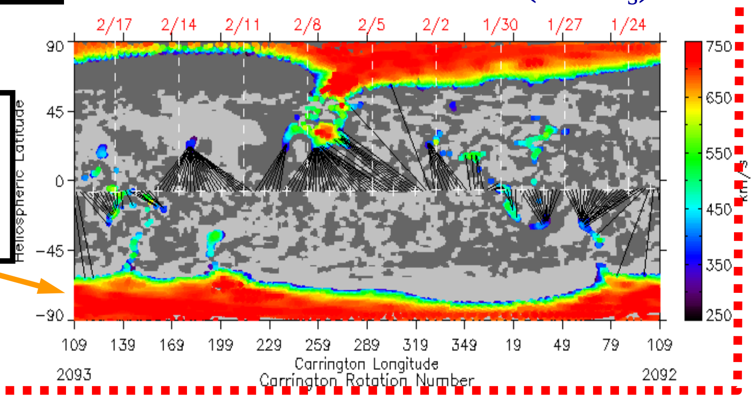


$$V_{\text{solar wind}} \sim f(f_s, \theta_b)$$

(Arge et al., *JSTP*, 2004)

MODEL OUTPUT

Derived Coronal Holes (1.0 R_s)



Empirical Relationships

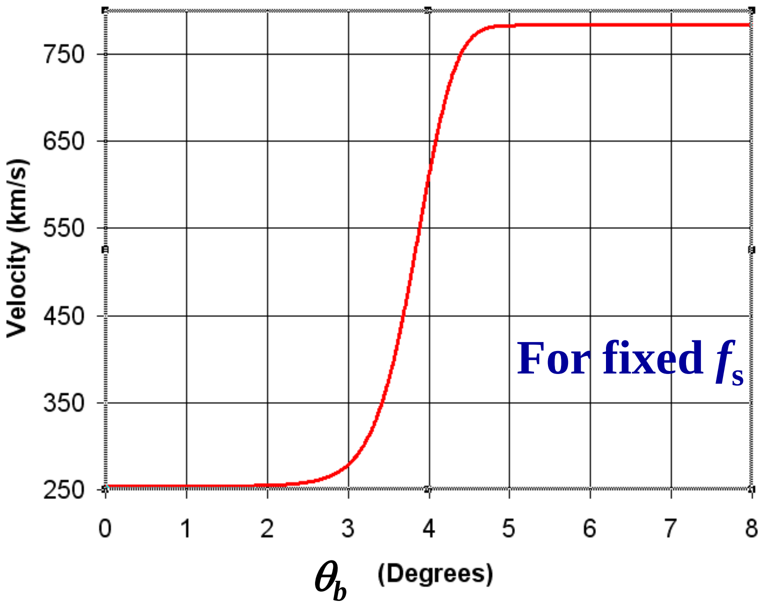
Old: $V(f_s) = 285 + 650/(f_s)^{5/9}$ km s^{-1}

New: $$V(f_s,\theta_b) = 250 + \frac{650}{(1+f_s)^{2/7}}\left\{1.0 - 0.8e^{-\left(\theta_b/3\right)^{7/4}}\right\}^3 \quad \text{km s}^{-1}$$

Where:

f_s = Magnetic field expansion factor.

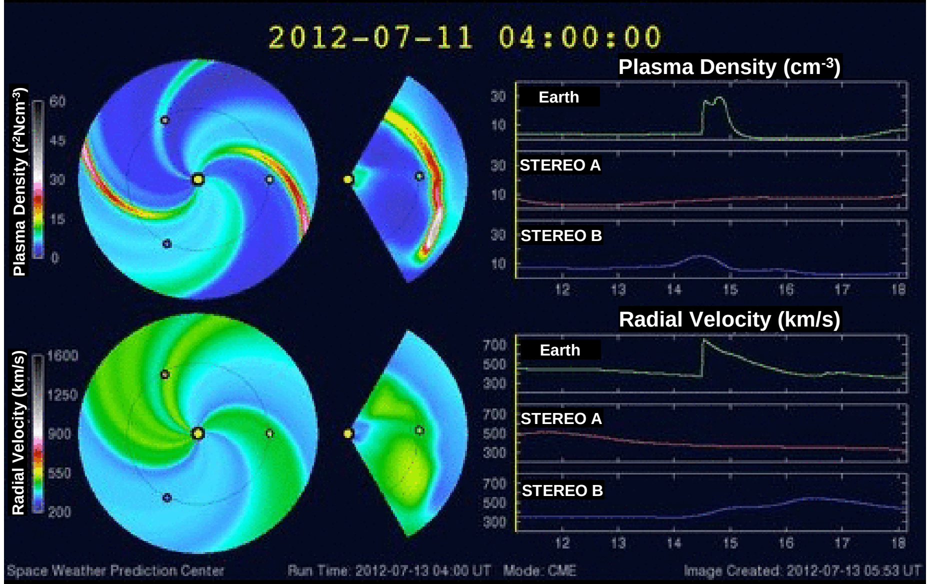
θ_b = Minimum angular distance that an open field footpoint lies from nearest coronal hole boundary.



Nation's Operational Solar Wind/CME Forecast Model (Wang-Sheeley-Arge (WSA)-Enlil Model)

- **The WSA+Enlil+Cone model: Advanced coronal and solar wind model used to forecast 3D solar wind out past Earth.**
- **Operational (Sep. 2011) at NOAA/NCEP & being evaluated by the AF 557th.**
- **Community effort requiring coordinated, long-term effort by AFRL, NOAA, & CISM.**

WSA-Enlil



Solar Wind Model

- **Uncertainty in CME arrival time forecasts *reduced by half*!**
- **Available for runs on demand at NASA/CCMC.**

First large-scale physics-based operational space weather model at NOAA!

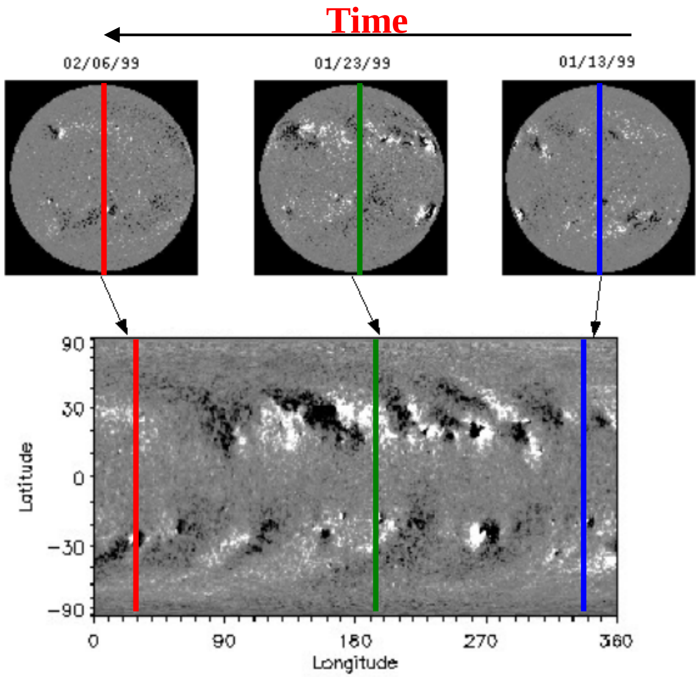
Pizzo et al., Space Weather, 2011

Diachronic (Traditional Carrington) Photosphere Magnetic Field Maps

The global solar photospheric magnetic field distribution serves as primary input to all coronal and solar wind models!

"Traditional" Carrington maps typically:

- **Remap line-of-sight full-disk magnetograms into heliographic coordinates with the assumption that the magnetic field is radial.**
- **Employ a "solid body" rotation rate of 27.2753d. This blurs feature position & time as additional images are included in the synoptic map.**
- **Weight the merged data to minimize the spatial blurring. For example, $\cos^4$, to give more weight to the central meridian.**

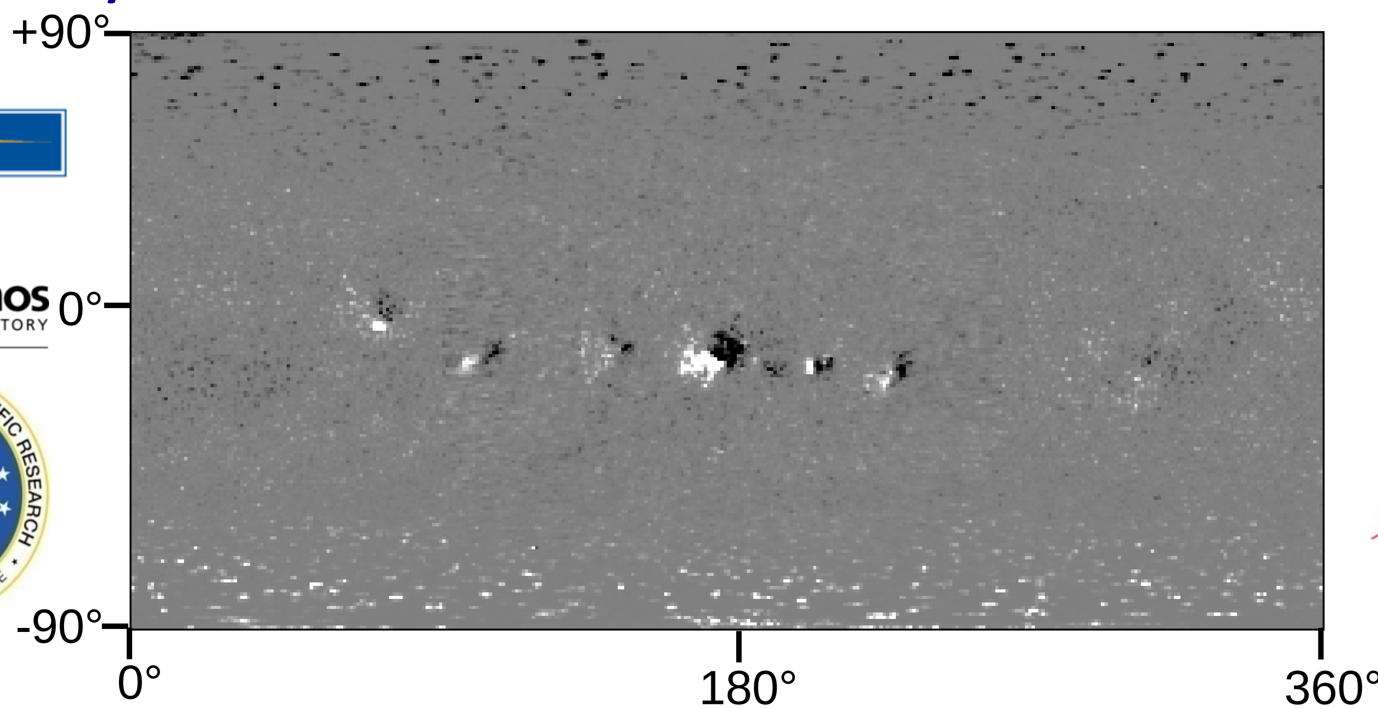


Carrington rotation 1 starts from November 9, 1853.

- **Traditional Carrington Map**
- **Time History of Central Meridian**
- **Diachronic – 27 day rotation period**
- **Most recent data on left**

Air Force Data Assimilative Photospheric Flux Transport (ADAPT) Model

1. Evolves solar magnetic flux using well understood transport processes where measurements are not available.
2. Updates modeled flux with new observations using ***data assimilation methods***
   - Rigorously takes into account model & observational uncertainties.



Sun's surface magnetic field (*movie length ~60 days*)

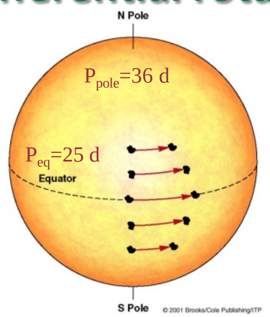
Provides more realistic estimates of the instantaneous global photospheric magnetic field distribution than those provided by traditional synoptic maps.

ADAPT Flux Transport Model

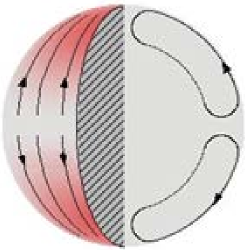
Overview: **The ADAPT flux transport model (Arge et al. 2010, 2011, 2013; Henney et al. 2012 & 2014; Hickman 2015, Lee et al. 2013; Linker et al. 2013) is based on Worden & Harvey (2000), which *accounts for known flows in the solar photosphere.***

The modified Worden & Harvey (WH) model used in ADAPT includes:

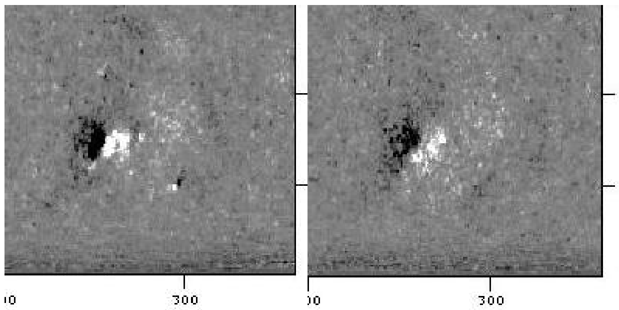
(1) Differential rotation



(2) Meridional flow



(3) Supergranular diffusion

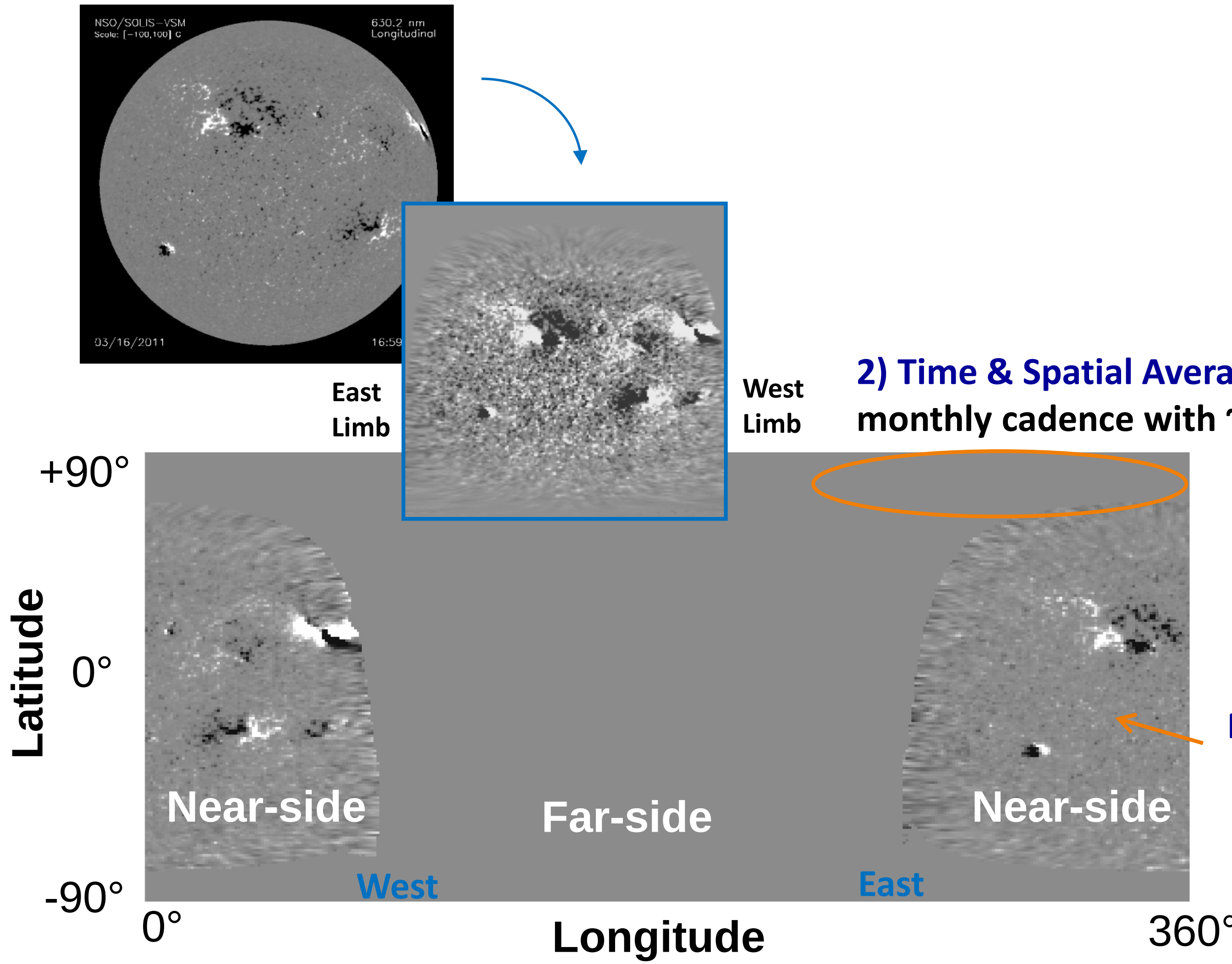


(4) Random flux emergence

(5) Data assimilation of new observations (LANL)

(6) An *ENSEMBLE* of solutions representing the model parameter uncertainties

Global Maps: Data Sources



2) Time & Spatial Averaged Polar:
monthly cadence with ~6 month gap

1) Remapped Magnetograph Data:
~10 min to 1-day cadence

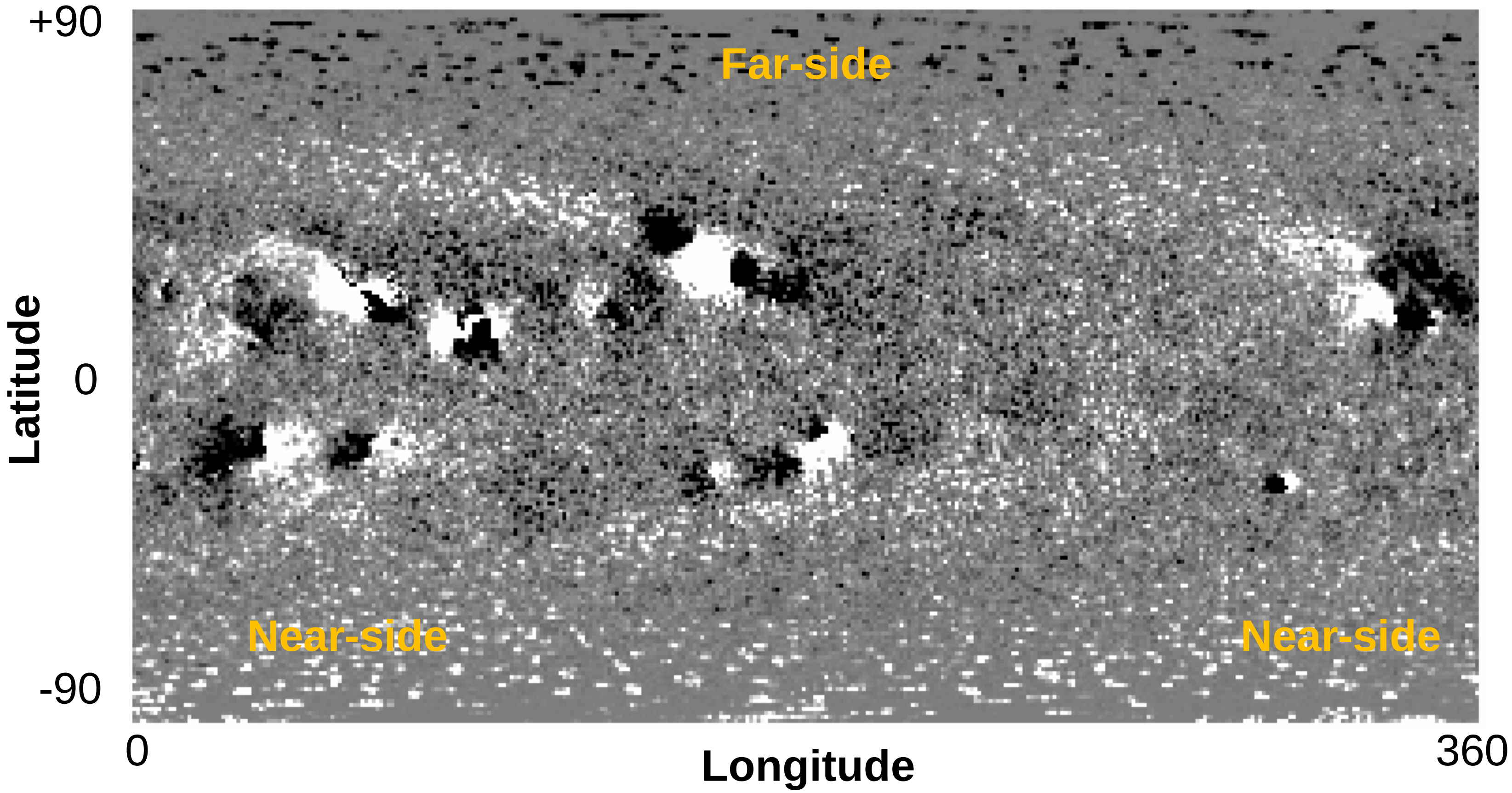
New observation *at time t_{obs}*

Data Assimilation: Analysis

Analysis = $X_a = X_f + \omega\,(y - H(X_f))$

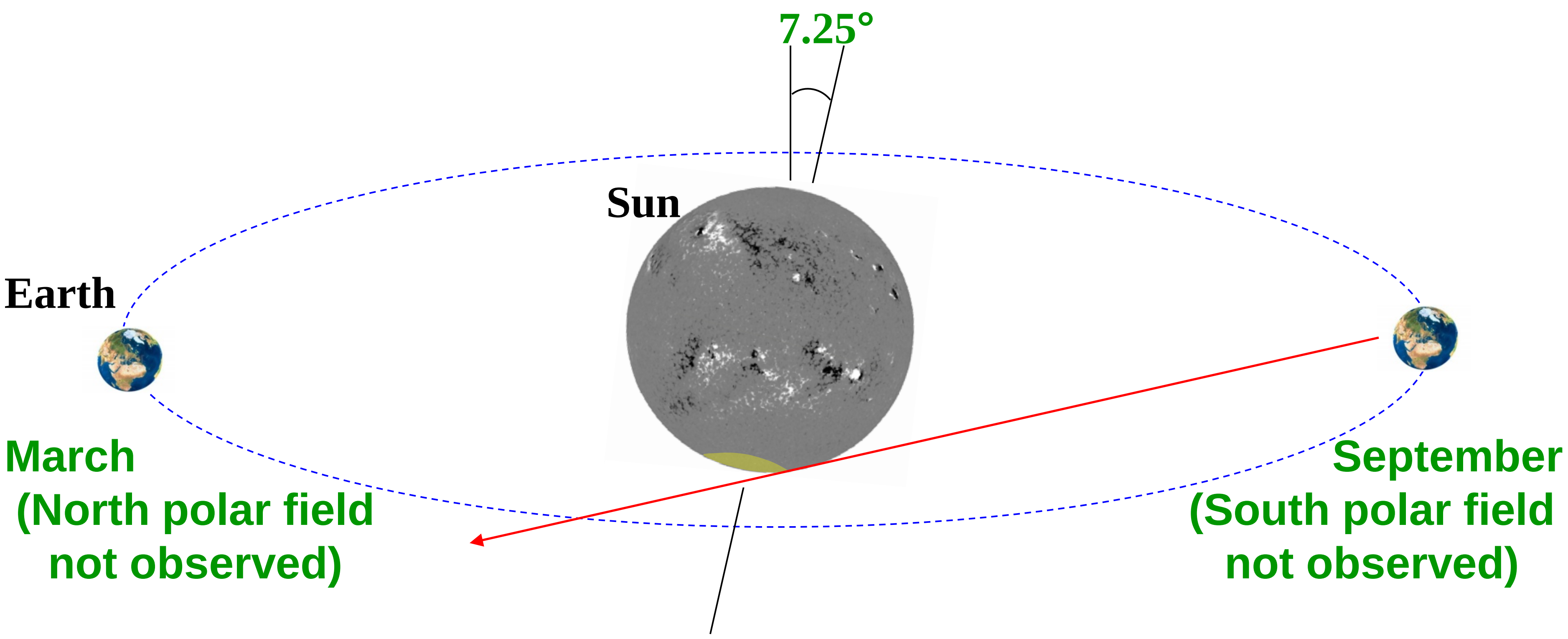
Weight = $\omega = \sigma_f^2 / (\sigma_f^2 + \sigma_y^2)$

Example with 16 realizations (*at time t_{obs}*)



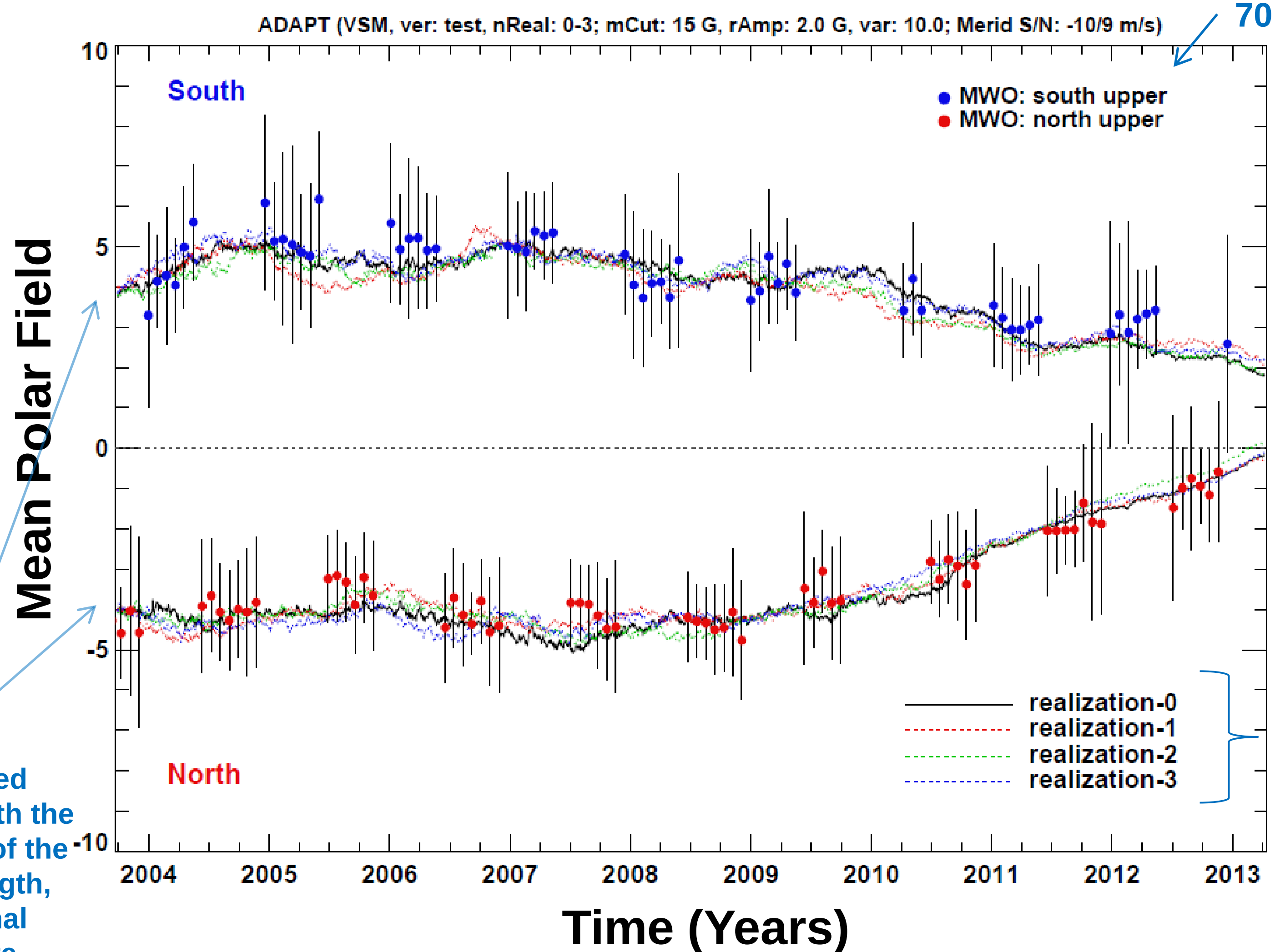
The Inclination of the Sun's Axis to the Ecliptic Impacts Measurements of the Photospheric Field

The Sun's rotational axis is inclined 7.25° to the ecliptic.



The Polar Magnetic Fields are NOT observed for extend periods of time.
Coronal models are very sensitive to the values of the polar fields!
(First *non-zero* term in multipole expansion of field is the Dipole.)

Observed vs ADAPT Predicted Polar Fields



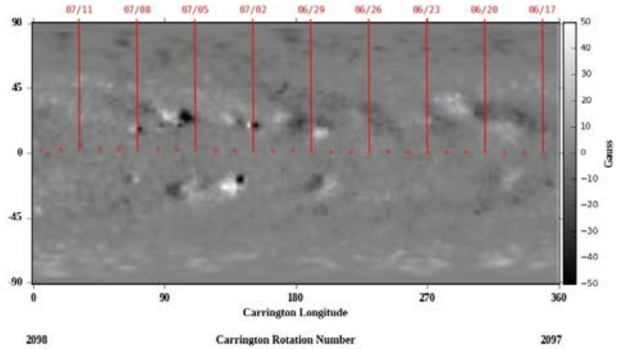
70 to 90 degrees

Identical model parameters

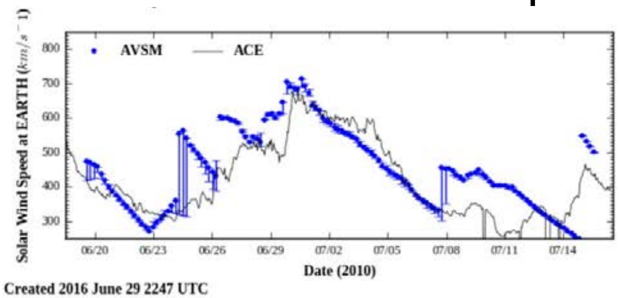
Note: initial "seed map" begins with the best estimates of the polar field strength, with no additional data for all future time steps.

ADAPT-VSM (Realizations 1-12)
(July 8, 2010)

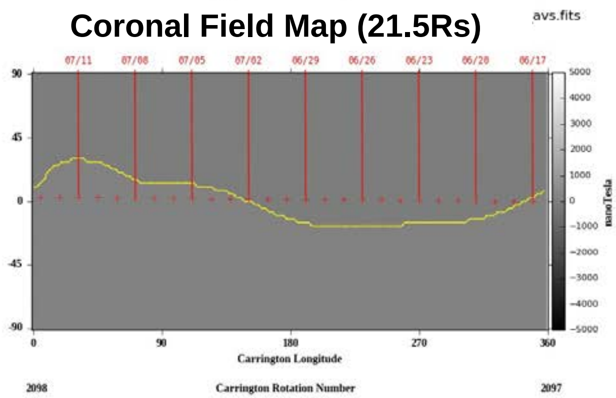
Photospheric Field Map



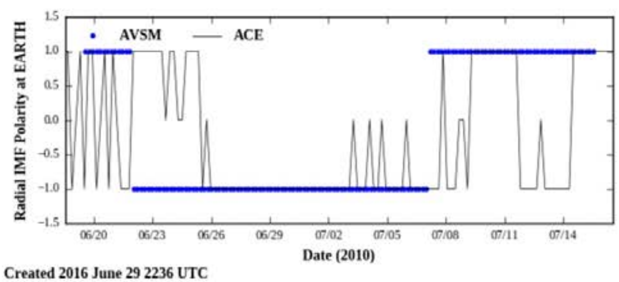
Predicted vs Obs. Solar Wind Speed



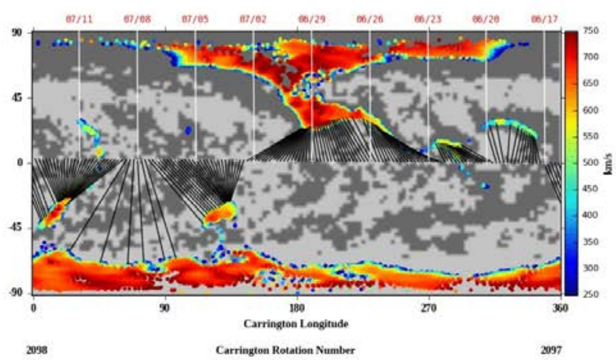
Coronal Field Map (21.5Rs)



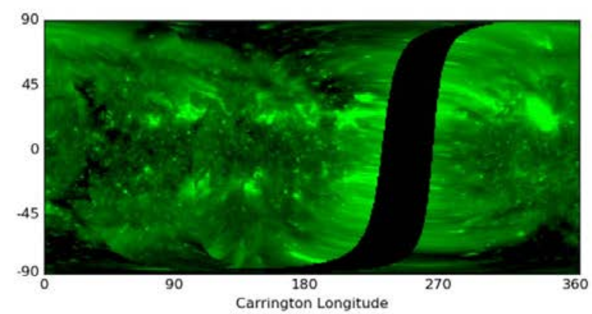
Predicted vs Obs. IMF Polarity



Derived Coronal Holes

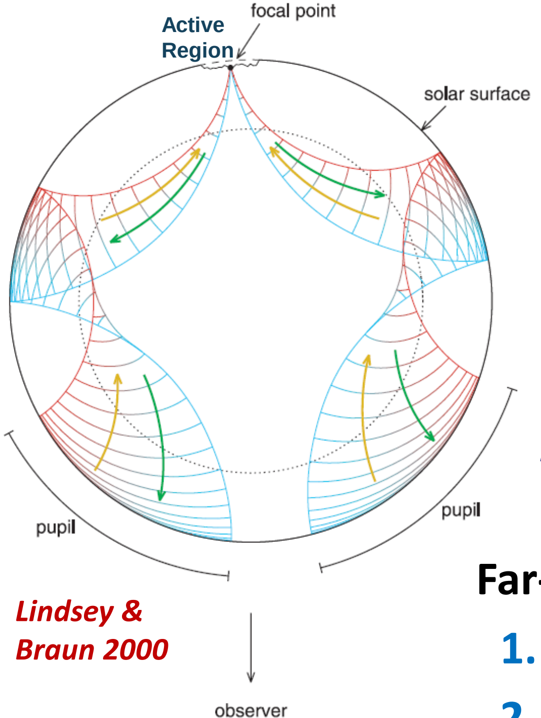


STEREO A&B – SDO/AIA (EUV)



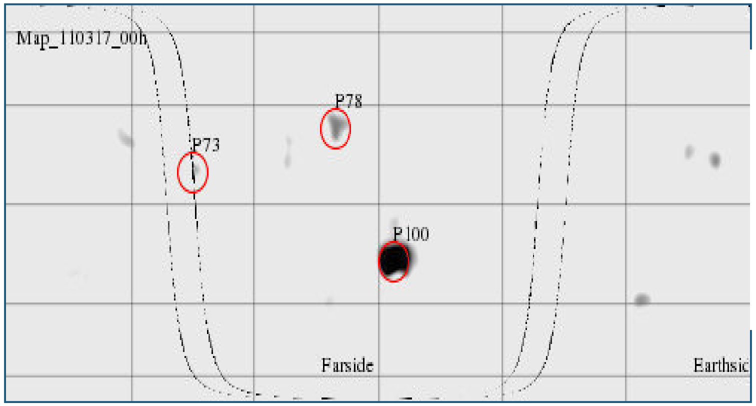
Incorporating Far-side Maps

Far-side detections are derived from helioseismic holography



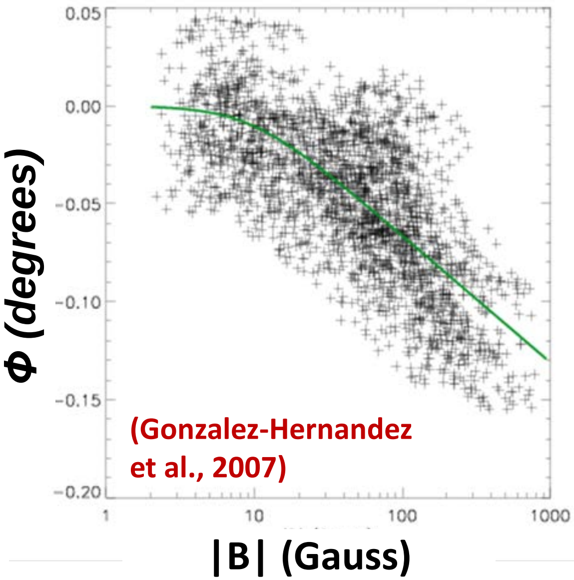
Lindsey & Braun 2000

NSO Far-Side Map



NSO/GONG March 17, 2011

|B| vs Far-Side Phase Shift



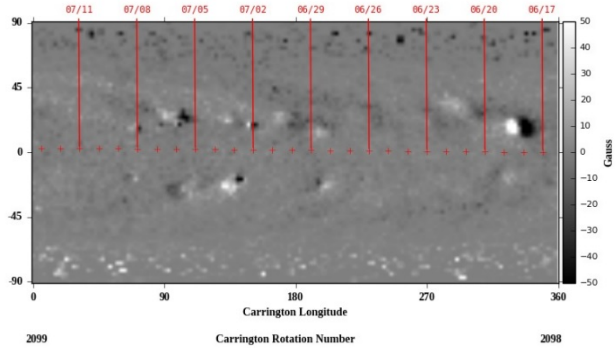
Far-side data assimilation requires a realistic estimation of the:

1. **magnetic field strength & uncertainty**
2. **position & uncertainty**
3. **simple polarity & tilt estimations (i.e., Hale's law & Joy's Law, other approaches)**

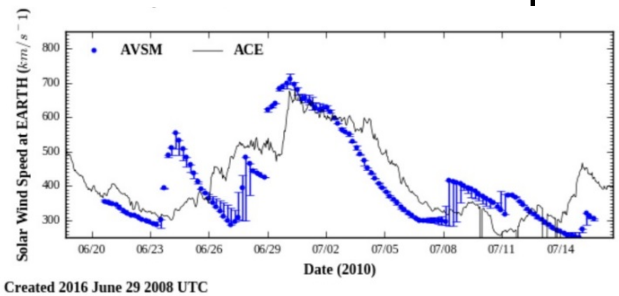
A "far-side ensemble" can be generated from these 3 factors.

ADAPT-VSM-Far-Side (Realization-7)
(July 8, 2010)

Photospheric Field Map

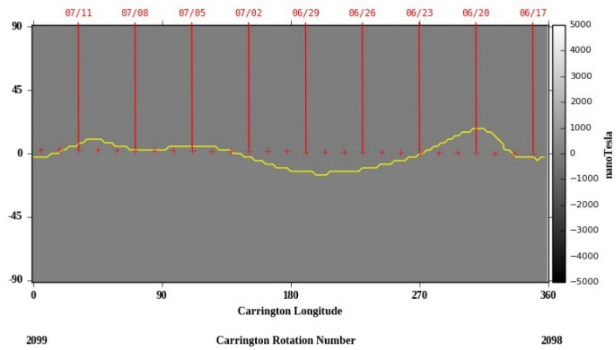


Predicted vs Obs. Solar Wind Speed

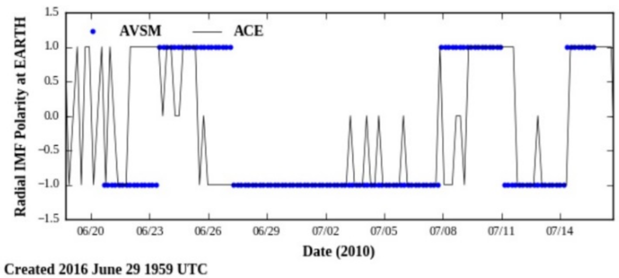


Coronal Field Map (21.5Rs)

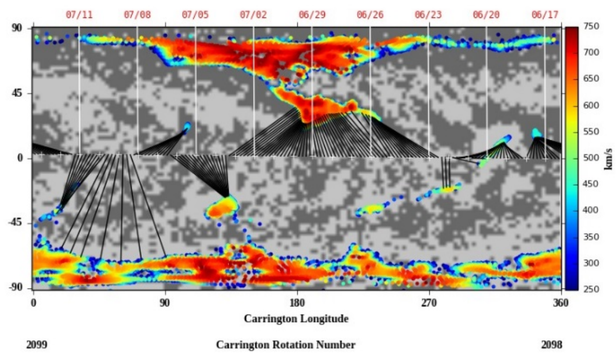
_avs.fits



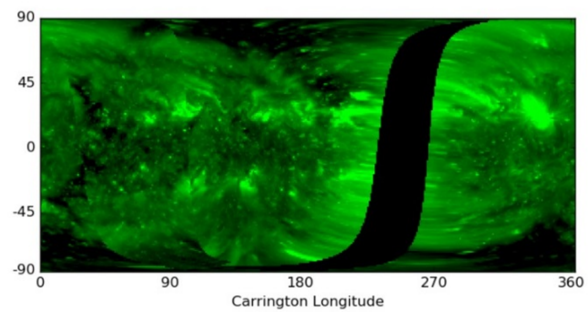
Predicted vs Obs. IMF Polarity



Derived Coronal Holes



STEREO A&B – SDO/AIA (EUV)

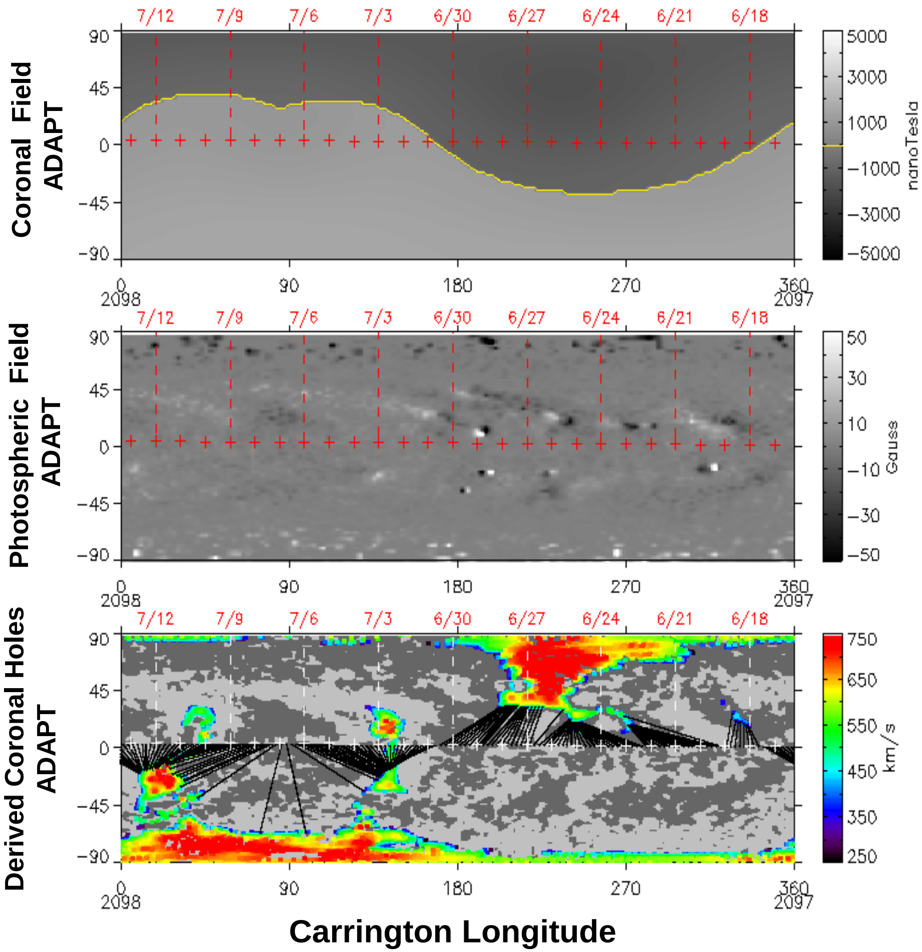


Summary

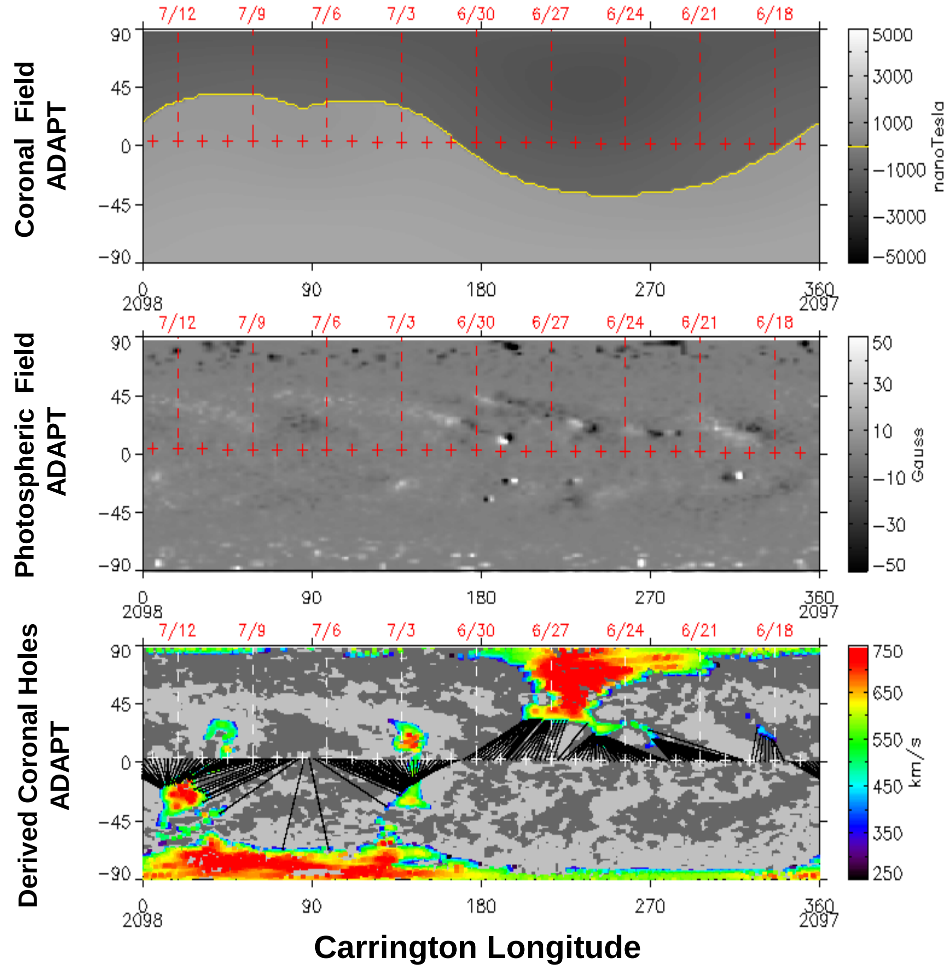
- **Wang-Sheeley-Arge (WSA) model - combined empirical and physics based model of the corona and solar wind.**
  - **Improved version of the original Wang & Sheeley model originally developed at NRL.**
  - **Operational at NOAA/NCEP & available for runs on demand at NASA/CCMC.**
- **ADAPT: data assimilative, photospheric magnetic field flux transport model.**
  - **Provides synchronic (“i.e., instantaneous snapshots”) of the Sun’s global magnetic field as input for coronal, solar wind, F10.7, and EUV models.**

Time Evolution of the Photosphere & Coronal (With & Without Far-Side Active Region Inserted)

Without Far-Side Active Region Inserted

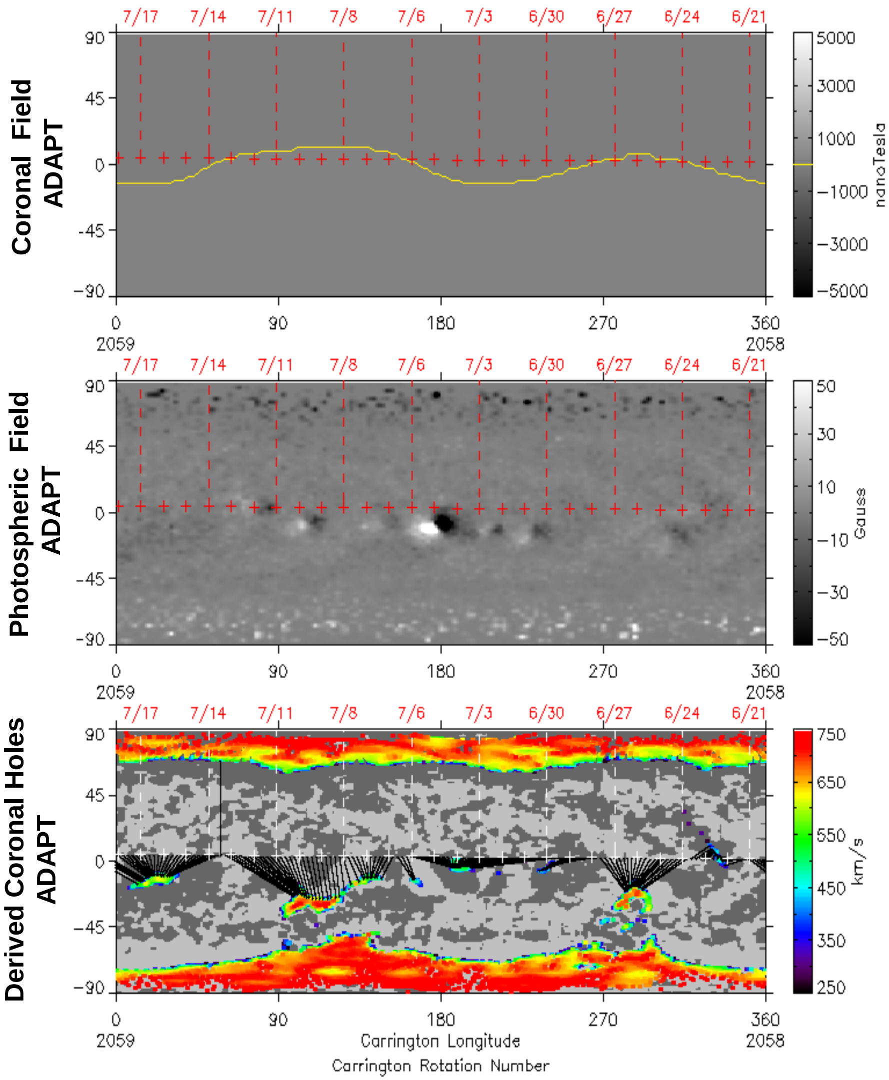


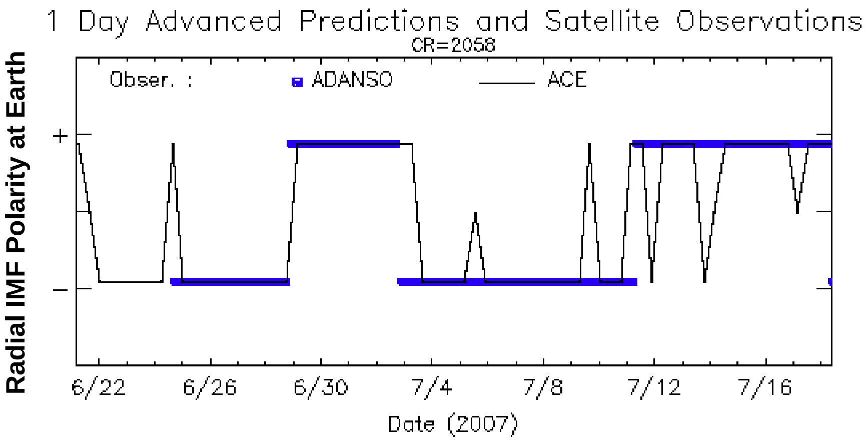
With Far-Side Active Region Inserted

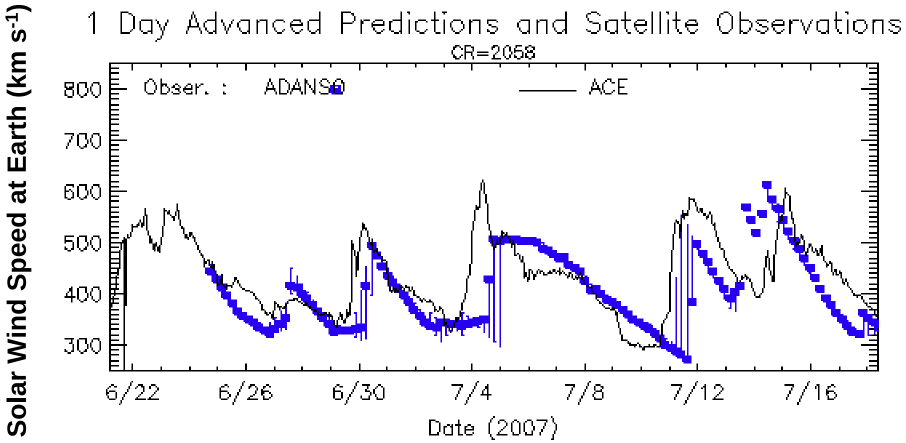


Realization #1

WSA Coronal & Solar Wind Solutions using the 12 ADAPT Realizations for June 21, 2007 (Start of CR2058)

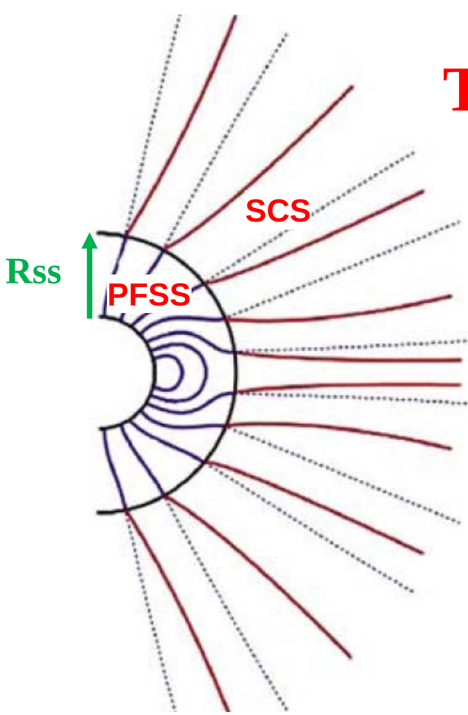


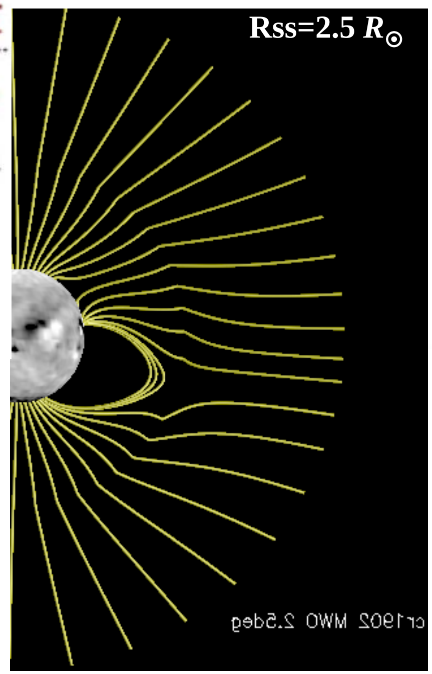




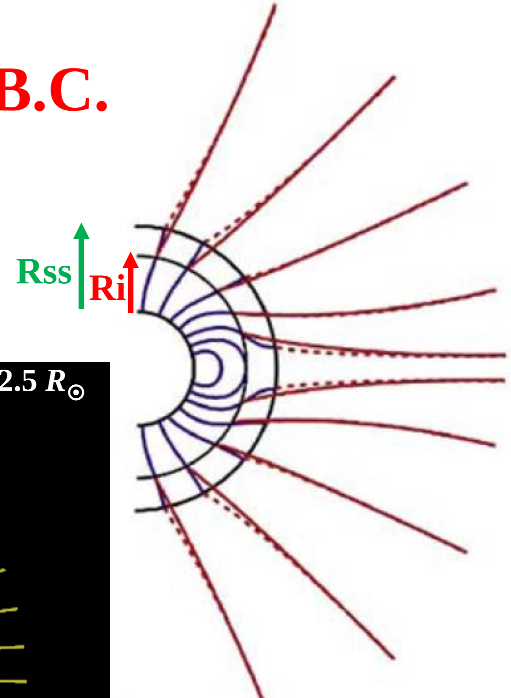
Improved Interface B.C. Between PFSS & SCS Models

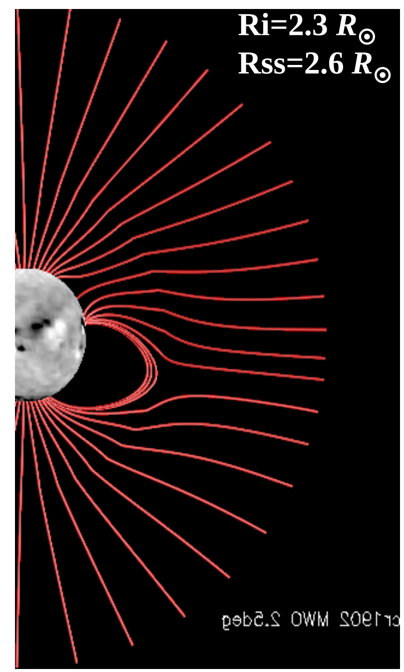
Traditional B.C.





Improved B.C.





WSA 4.0 allows user to choose between standard interface B.C. (left) and improved one (right)

McGregor et al., JGR, 2008

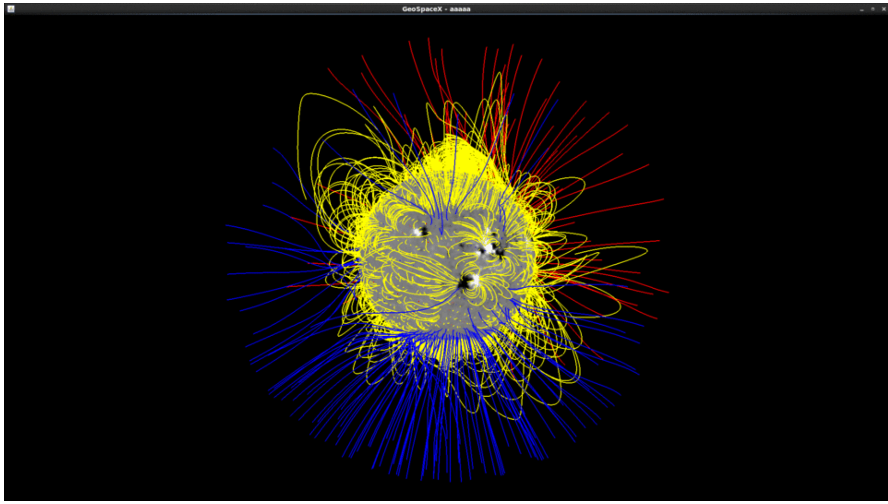
WSA 4.2

Key Features:

1. Field line tracing parallelized
2. Compatible with
   - NSO (VSM, GONG, KPVT), WSO & MWO
   - ADAPT (VSM, GONG, HMI)
     - Understands multi-realization input files
3. Can be run in the following modes:
   - PFSS
   - Coupled PFSS+Schatten Current Sheet (SCS)
   - Traditional or Improved interface between PFSS & SCS models.
     - Improved: minimizes “kinking” at interface.
4. IDL & Perl scripts replaced with Python
5. Forecasts solar wind speed and IMF polarity at
   - L1, STEREO A & B, Ulysses, & all inner planets
   - Easy to add other positions/satellites
6. Retuning empirical solar wind speed relationship
7. New field line tracing package

Wang-Sheeley-Arge (WSA)

(Coronal Model)



Input: Global maps of photospheric magnetic field (e.g., ADAPT)

Data Assimilation

The ADAPT data assimilation method used: ***Los Alamos National Laboratory (LANL) data assimilation framework.***

– Efficient and flexible data assimilation code.

– Uses either an Ensemble <u>Least Squares</u> or <u>Kalman</u> filter techniques.

1) **Ensemble Least Squares (ENLS) estimation method:**
   - Method currently used most often.
     – Takes into account both model and data errors.
     – Does ***not*** consider spatial correlations.
2) **Ensemble Transform Kalman filter (ETKF) method:**
   - Recursive algorithm that automatically takes into account ***past correlations between different regions of the photosphere***.
3) **Local Ensemble Transform Kalman Filter (LETKF) method:**
   - Localized version of the ETKF.
   - Handles ***unique*** properties of solar magnetic field observations better.
   - Recently incorporated.

Physical Basis for Correlation Between V_{sw} & f_s (WS's Argument)

Flux tube expansion rate regulates solar wind acceleration.

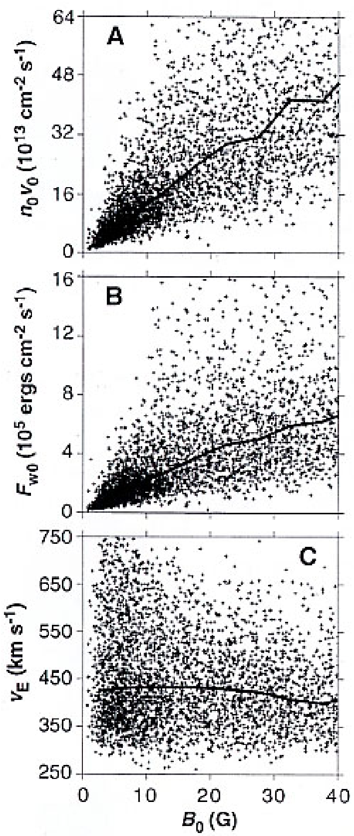


Fig. 5. Scatterplots of magnetic field strength B_0 at the sun versus (**A**) ion flux density $n_0 v_0$ at the sun, (**B**) total solar wind energy flux density F_{w0} at the sun, and (**C**) solar wind speed v_E at Earth. Each cross represents a daily average during 1976–1994. Solid lines indicate the median trends calculated over 5-G-wide intervals of B_0.

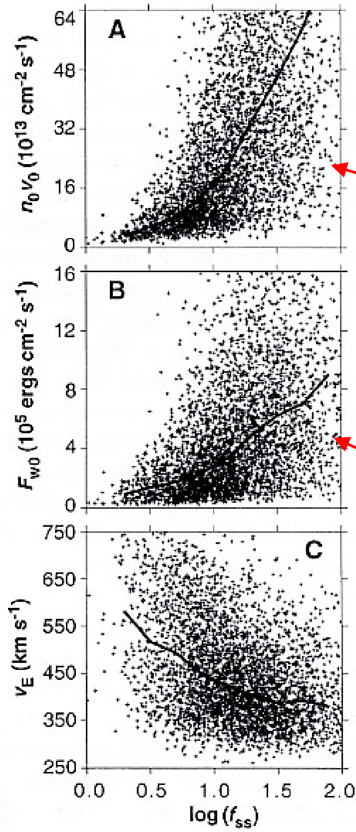


Fig. 6. Scatterplots of the logarithmic expansion factor log (f_{ss}) at the sun versus (**A**) ion flux density $n_0 v_0$ at the sun, (**B**) total solar wind energy flux density F_{w0} at the sun, and (**C**) solar wind speed v_E at Earth. Each cross represents a daily average during 1976–1994. Solid lines indicate the median trends calculated over intervals of 0.2 log units.

Ion Flux Density at Coronal Base.

$n_o v_o = (B_o/B_E) n_E v_E$

Total Energy Flux Density at Coronal Base.

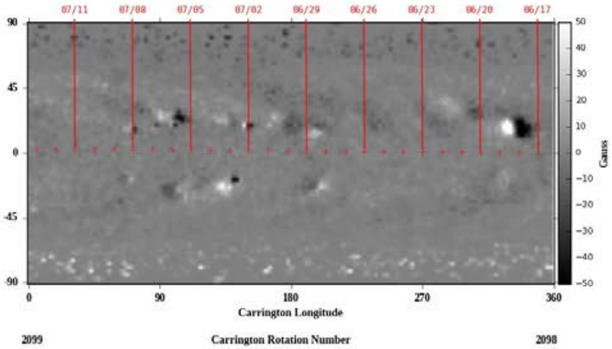
$F_{wo} = ½ (B_o/B_E) \rho_E v_E^3$

$$\boxed{v_E \approx (2F_{wo}/\rho_o v_o)^{1/2}}$$

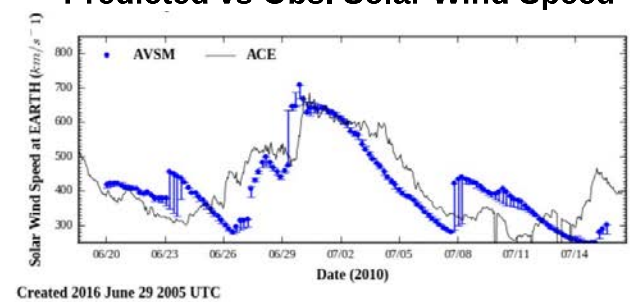
Wang et al., Science, 271, 417, 1996

ADAPT-VSM-Far-Side Included (Realizations 1-12)
(July 8, 2010)

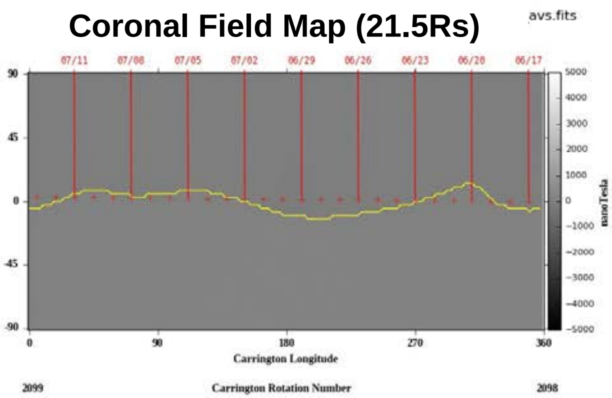
Photospheric Field Map



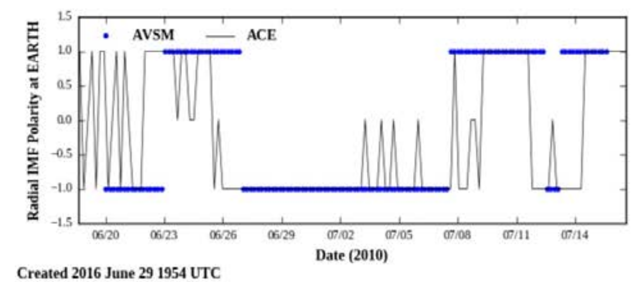
Predicted vs Obs. Solar Wind Speed



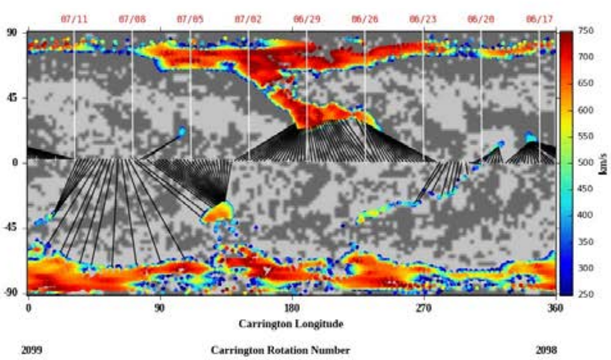
Coronal Field Map (21.5Rs)



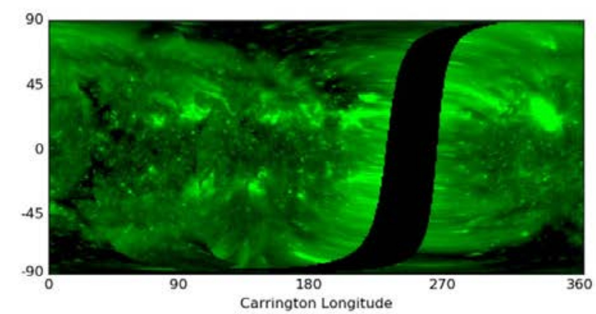
Predicted vs Obs. IMF Polarity



Derived Coronal Holes



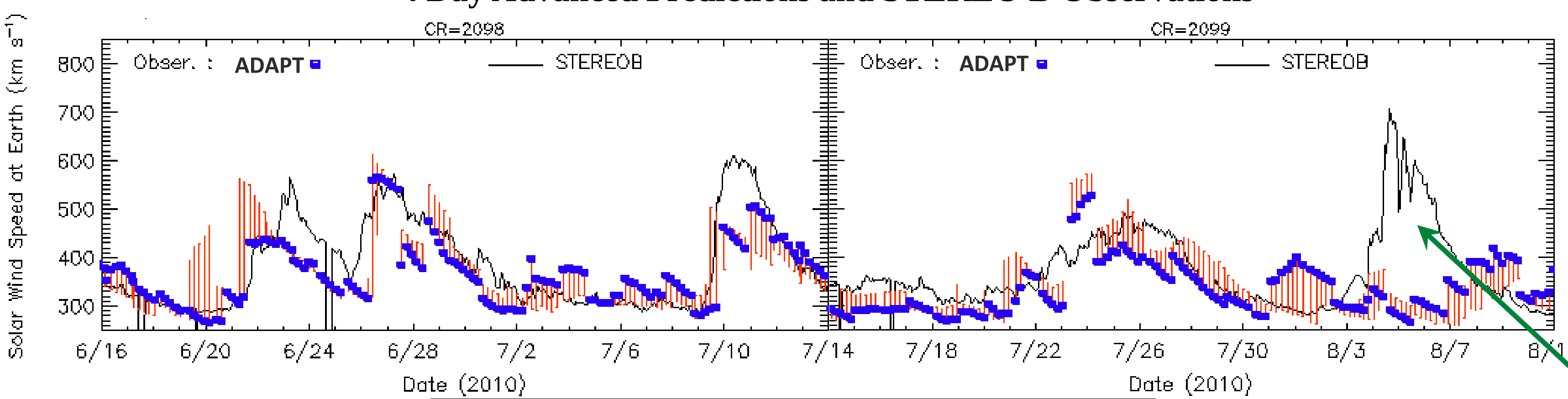
STEREO A&B – SDO/AIA (EUV)



WSA Solar Wind Speed vs Observations at STEREO B (With & Without Far-Side Active Region Inserted)

Without Far-Side Active Region Inserted

4 Day Advanced Predictions and STEREO B Observations



Arge, Henney, Gonzalez-Hernandez, Toussaint, Koller, & Godinez, *Solar Wind 13*, 2013

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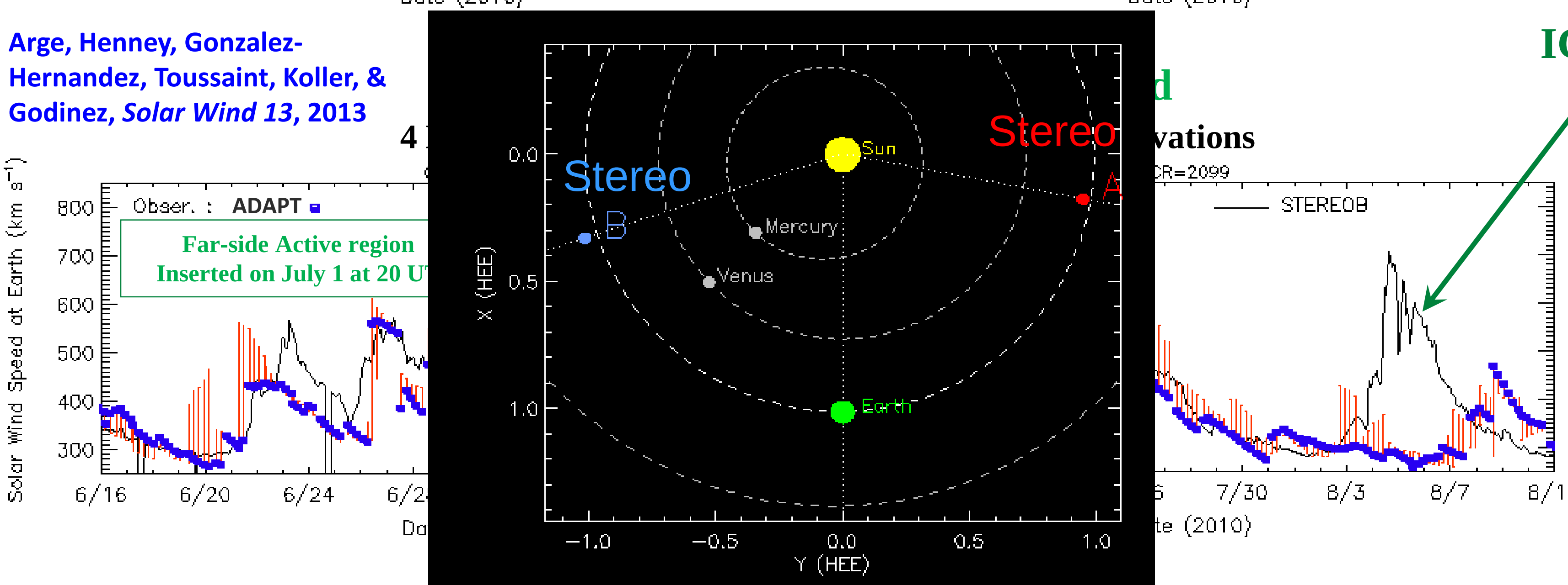


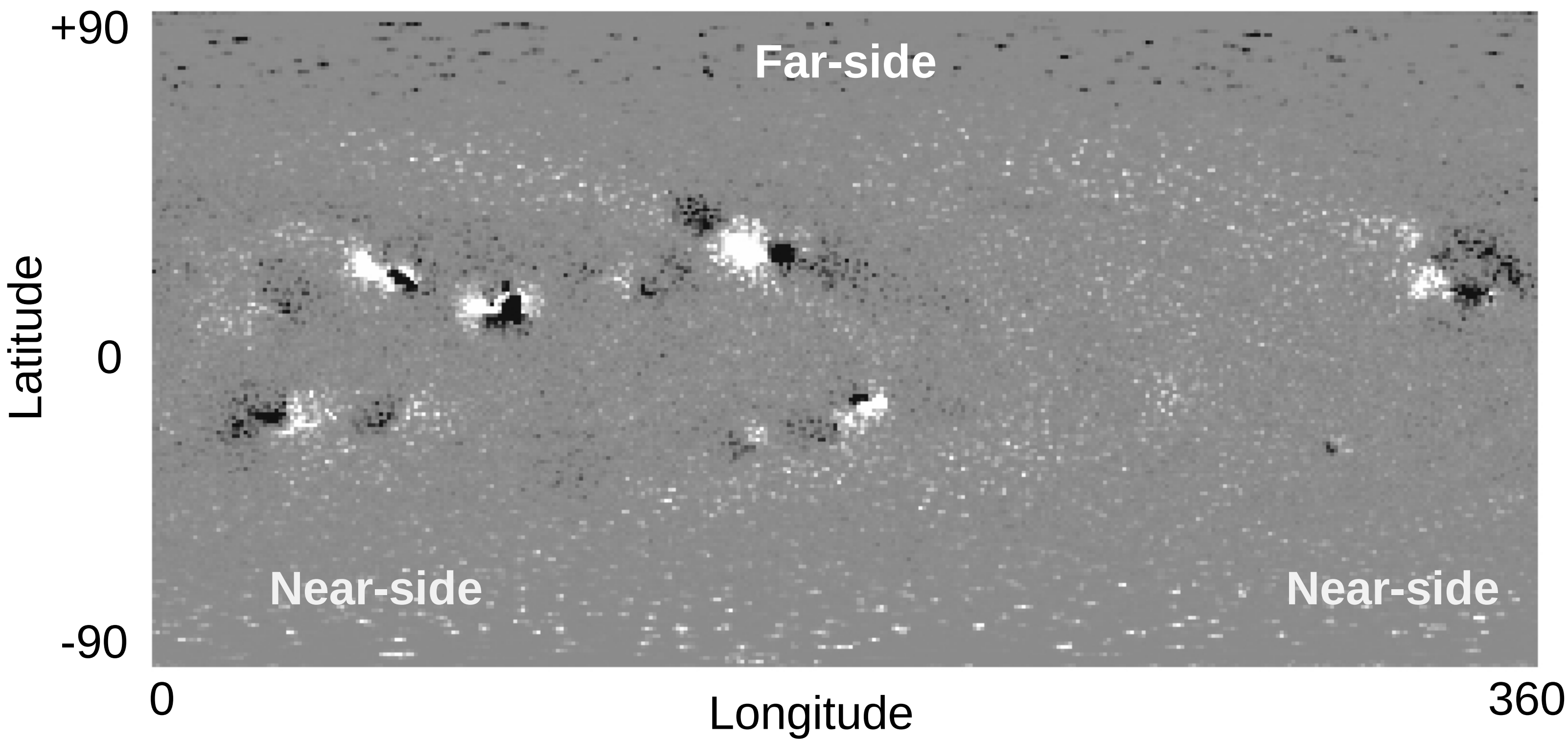
Data Assimilation: Model Forecast

$$\text{Analysis} = X_a = X_f + \omega\,(y - H(X_f))$$

$$\text{Weight} = \omega = \sigma_f^2 / (\sigma_f^2 + \sigma_y^2),$$

(σ_f^2 and σ_y^2 are the variances of the model forecast ensemble & observed data respectively.)

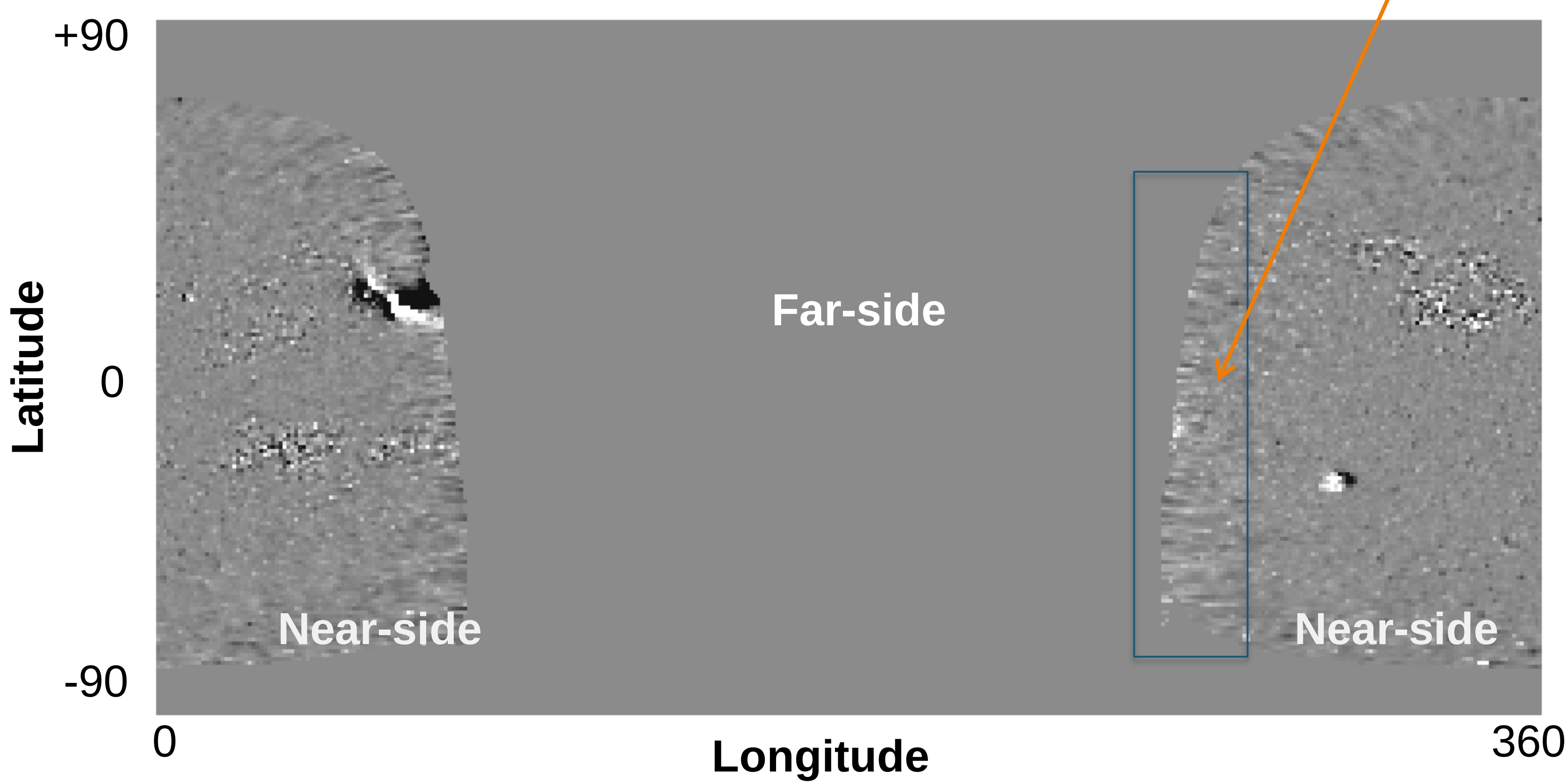
Example forecast realization from the ensemble, X_f (*at time t_{obs}*):



Data Assimilation: Innovation

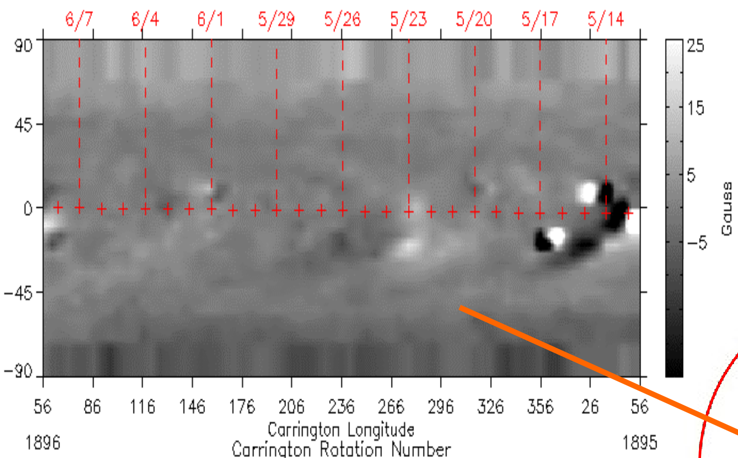
Innovation = **Observations** – **Model** = (y – $H(x_f)$), *at time t_{obs}*

Solar East-limb:
region of > 13-day temporal discontinuity;
leads to large field strength/polarity offsets



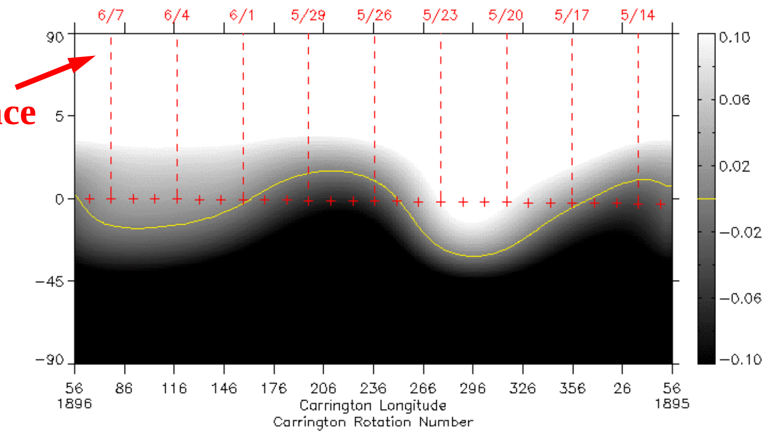
Results Using the PFSS Model

MODEL INPUT: Observed Photospheric Field

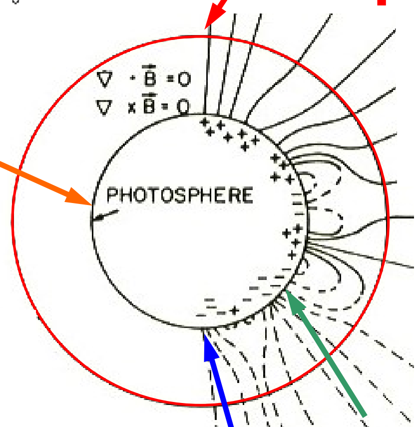


MODEL OUTPUT

"Source Surface" or Coronal Field (2.5 $R_\odot$)



Source Surface



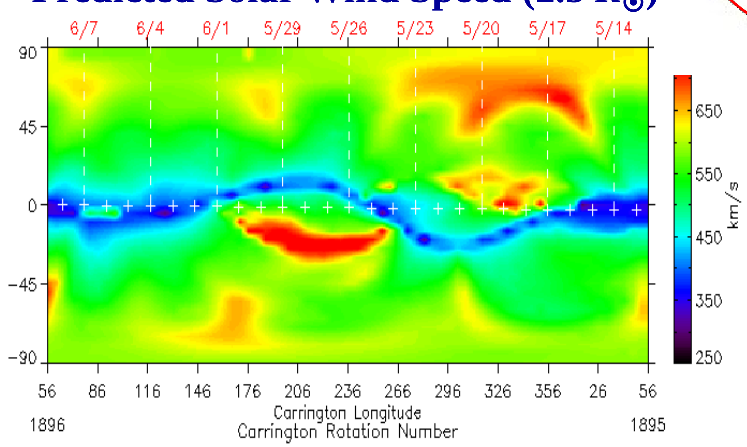
$$f_s = (R_\odot/R_{ss})^2[B^P(R_\odot)/B^P(R_{ss})]$$

Closed Field Footpoint

Open Field Footpoint

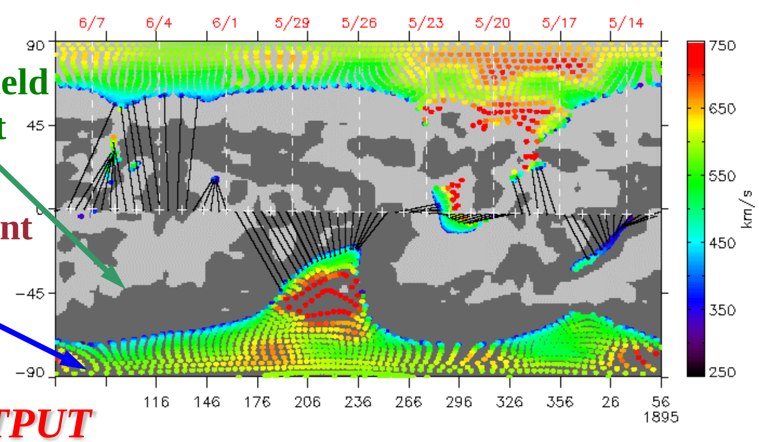
MODEL OUTPUT

Predicted Solar Wind Speed (2.5 $R_\odot$)



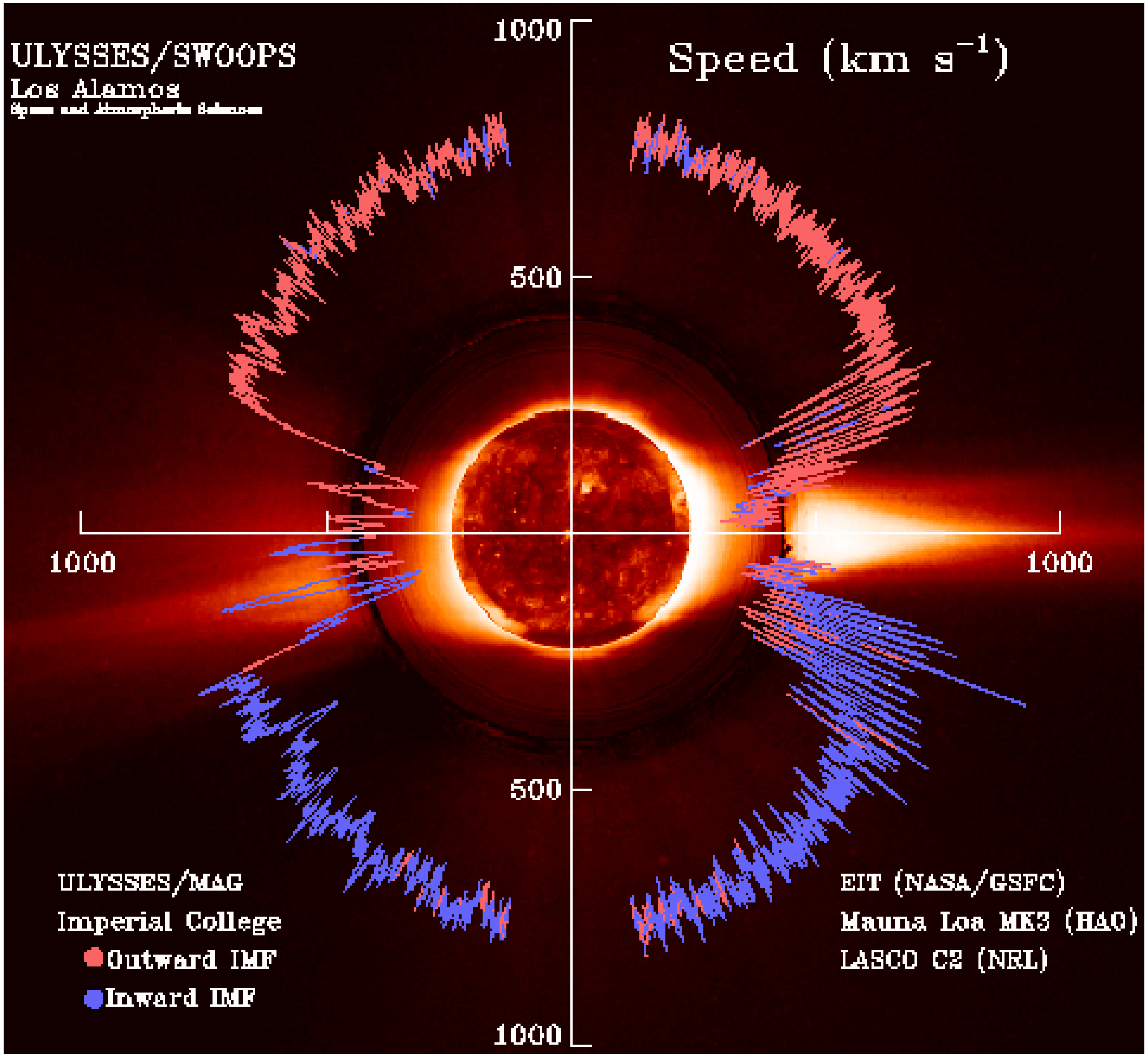
$$V \sim f_s^{-n}$$

Derived Coronal Holes (1.0 $R_\odot$)

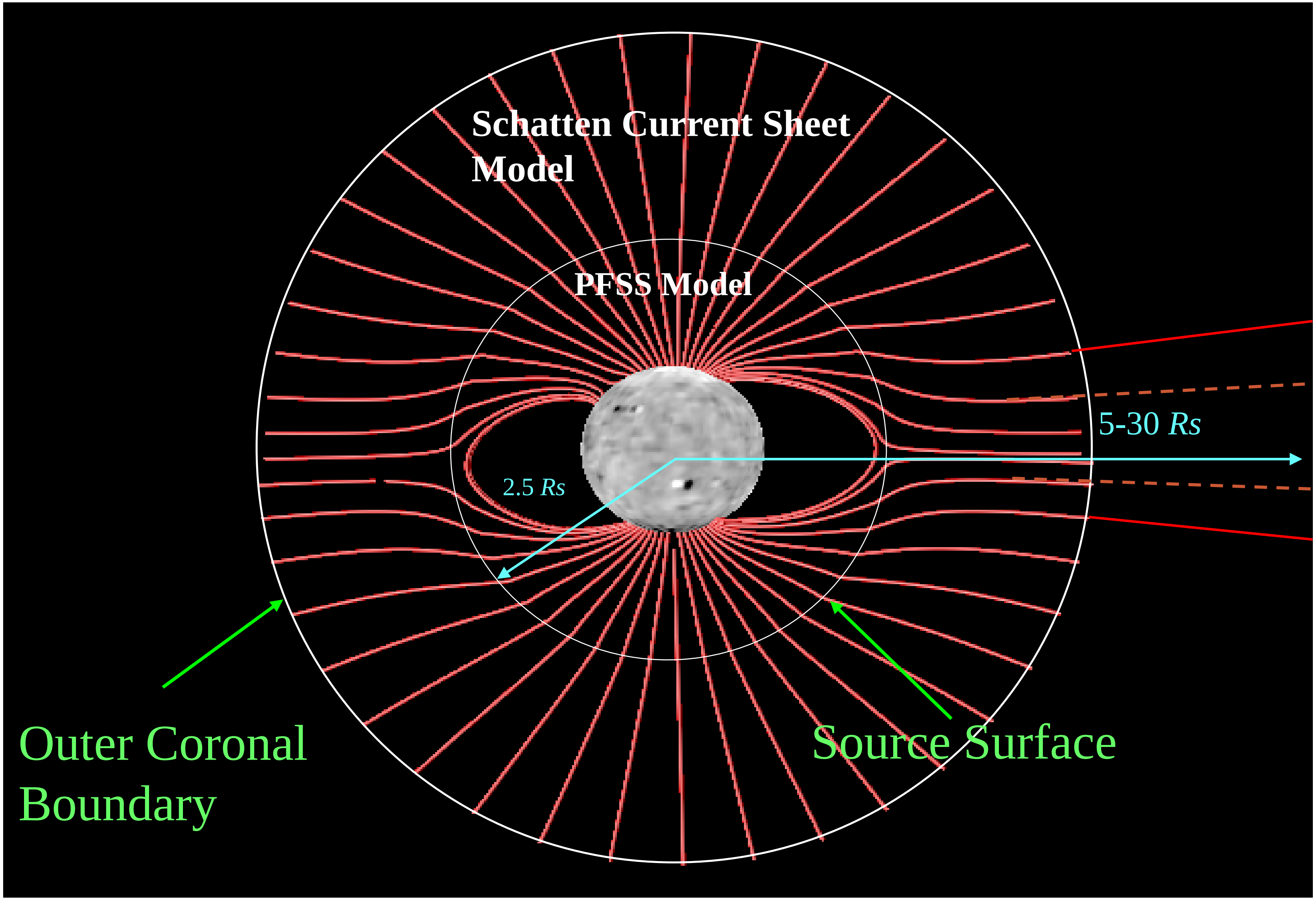


MODEL OUTPUT

ULYSSES Observations: Solar Minimum



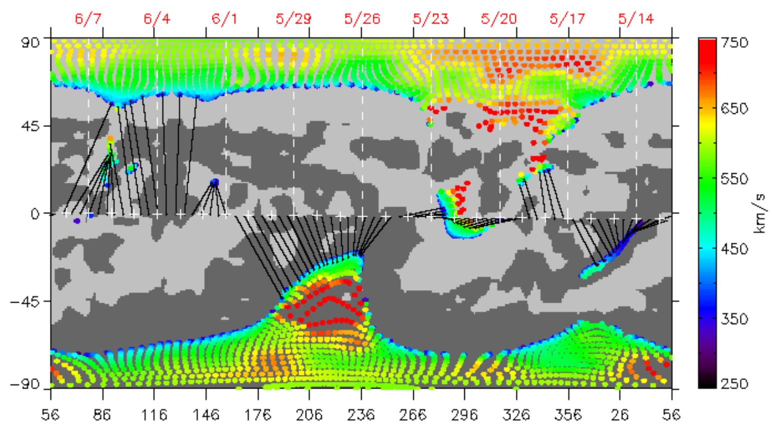
PFSS+ Schatten Current Sheet Model



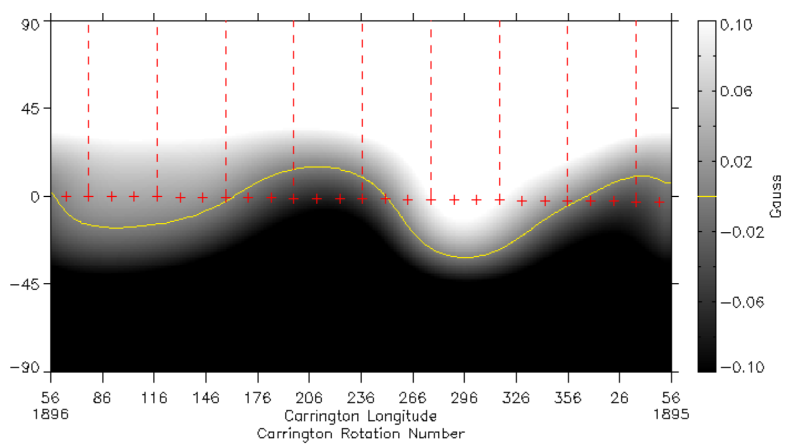
Comparison of PFSS and Coupled PFSS+SCS Models

PFSS MODEL (R = 2.5 $R_\odot$)

Derived Coronal Holes

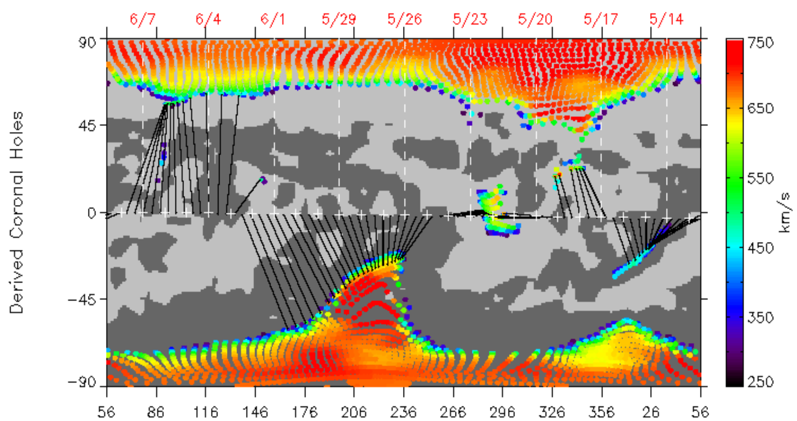


Coronal Field

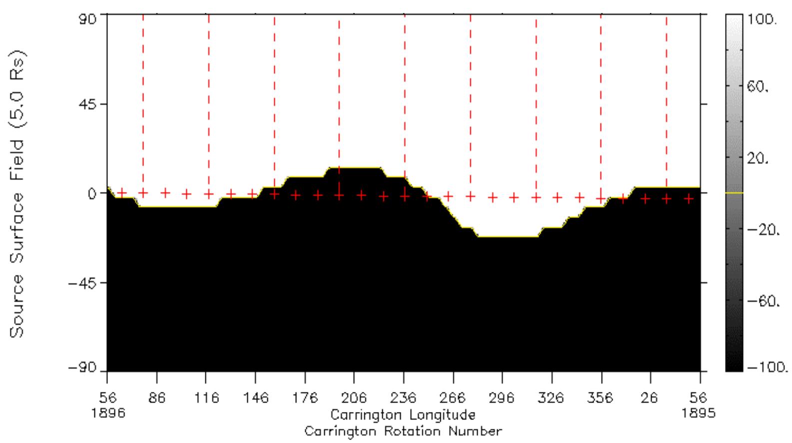


PFSS+SCS MODEL (R = 5.0 $R_\odot$)

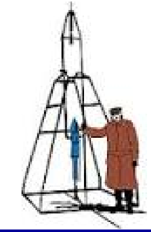
Derived Coronal Holes



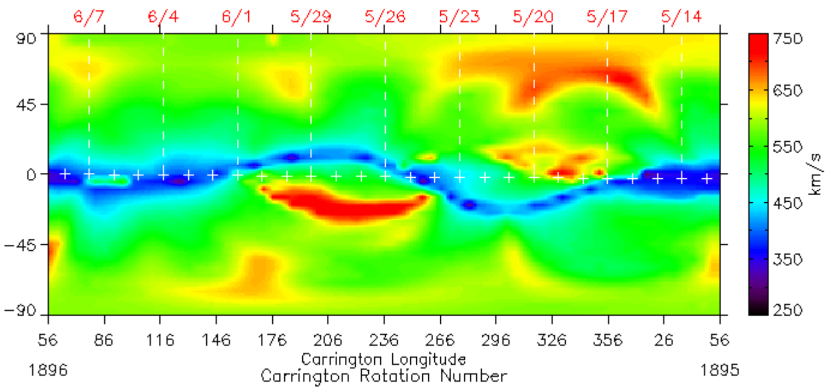
Coronal Field



Comparison of New & Old Empirical Solar Wind Speed Relationships

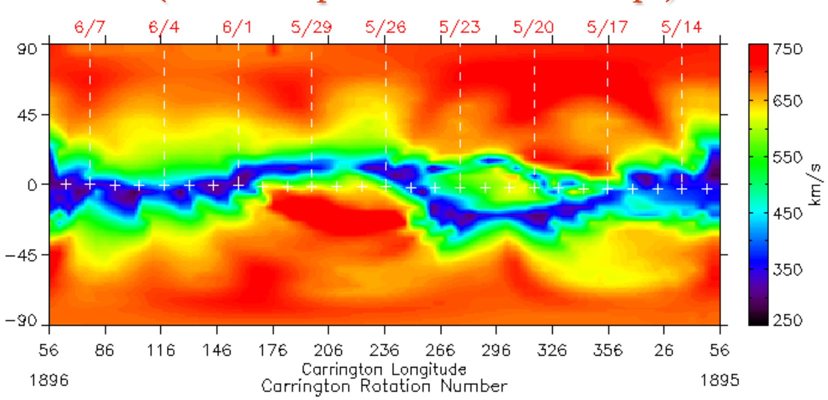


Predicted Solar Wind Speed at 2.5 $R_{\odot}$ (Old Empirical Relationship)

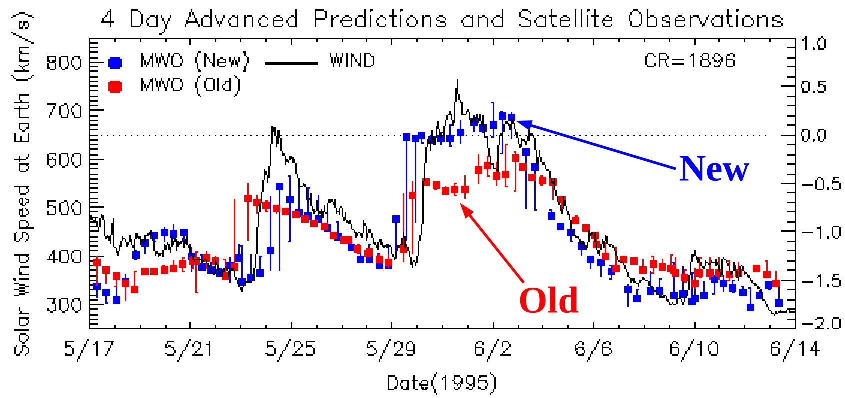


Time

Predicted Solar Wind Speed at 5.0 $R_{\odot}$ (New Empirical Relationship)



Predicted & Observed Solar Wind Speed at L1



Time

Predicted & Observed IMF Polarity at L1