Coronal Modeling with WSA & ADAPT

Space Weather Training 2020

May 8, 2020

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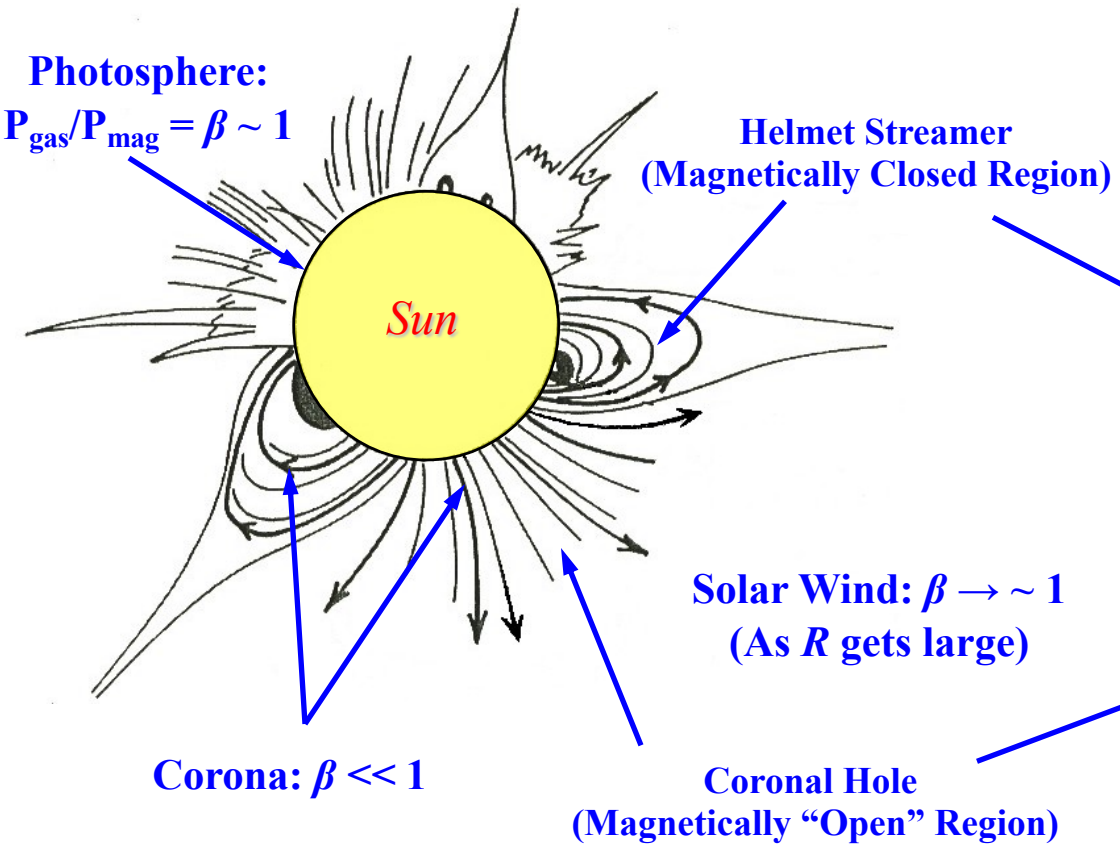
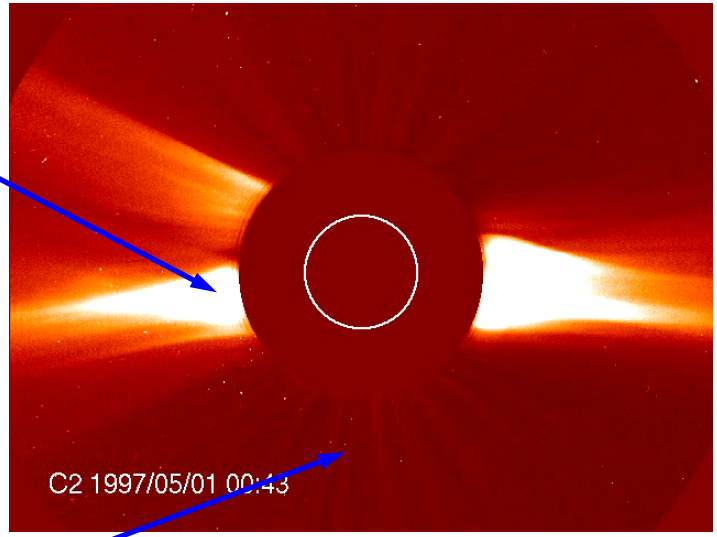
Outline

- The corona and solar wind
- Predicting the solar wind using magnetic flux tube expansion factor and coronal hole boundary distance
- 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
- Validating WSA

The Solar Magnetic Field



SOHO/LASCO



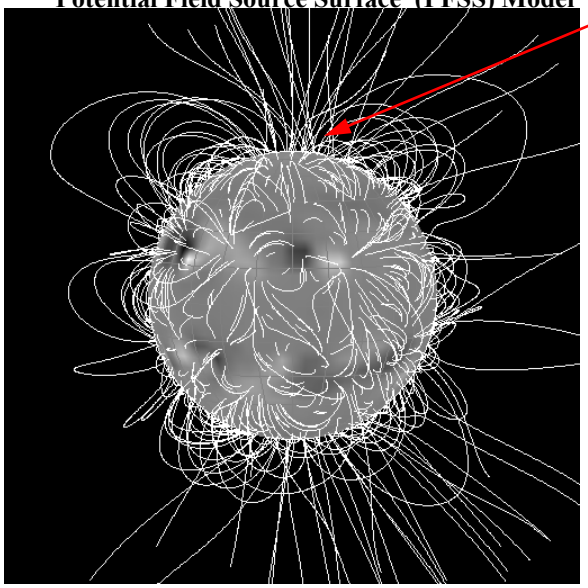
Coronal Holes

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

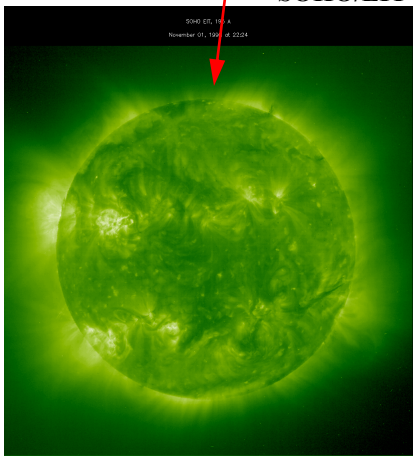
Observation Definition: Regions of low emission in the solar corona.

Coronal Hole

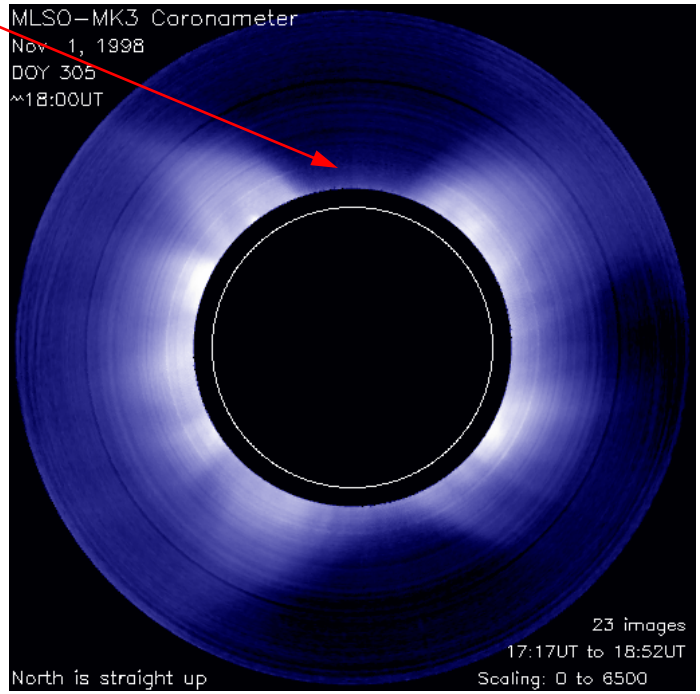
Potential Field Source Surface (PFSS) Model



SOHO/EIT



MLSO-MK3



Coronal holes are important because they are a major source of the solar wind and thus help link 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.

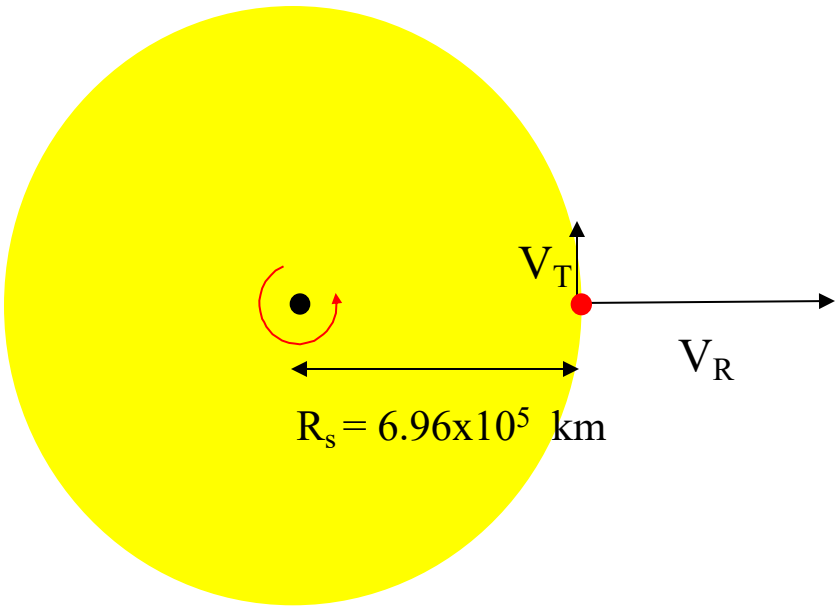
Two Types:

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



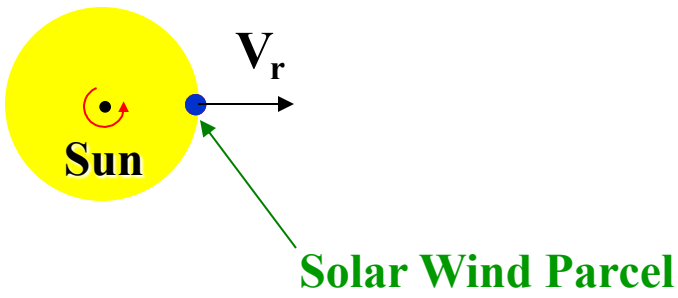
$T_{Sun} = 25.38$ days $= 2.192832x10^6$ sec

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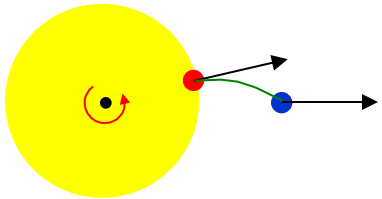

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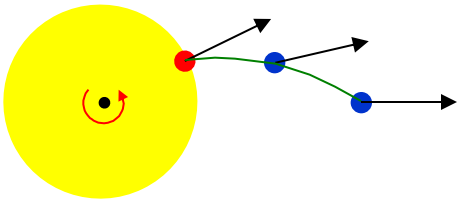

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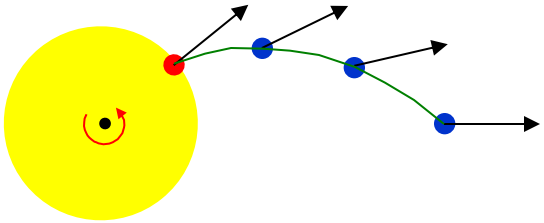

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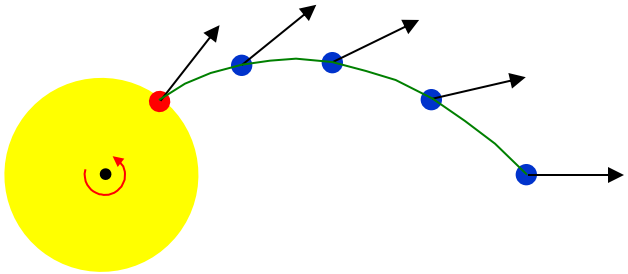

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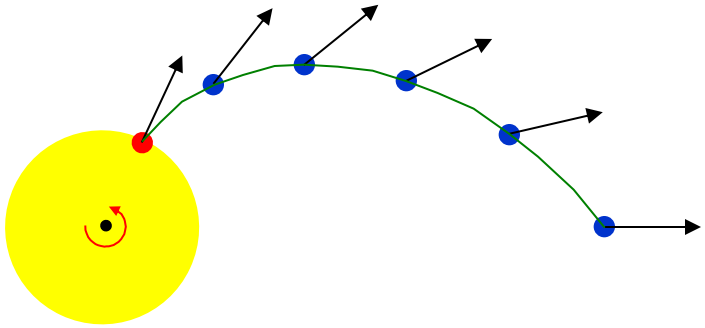
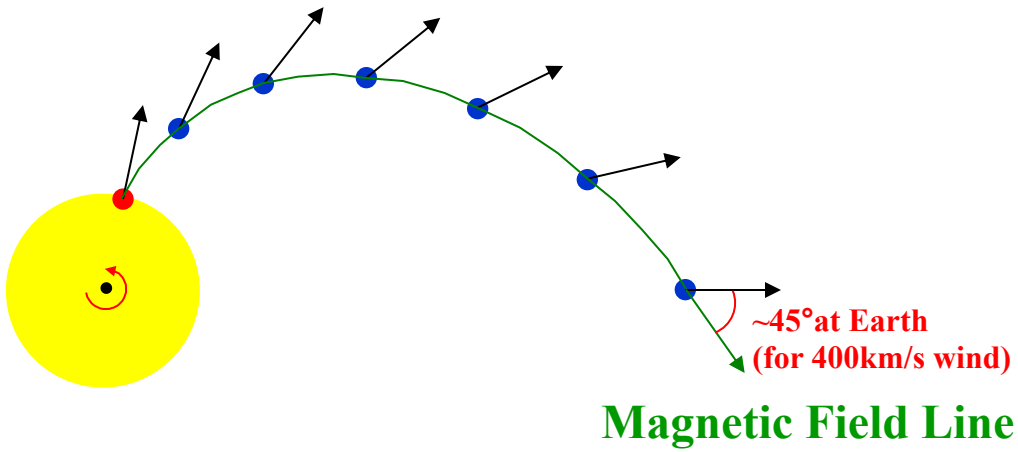


The Solar Wind and the Interplanetary Magnetic Field (Formation of the Parker Spiral)



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.

$$\left.\begin{array}{l} \nabla \cdot \mathbf{B} = 0 \\ \nabla \times (\mathbf{V} \times \mathbf{B}) = 0 \end{array}\right\} \Rightarrow \begin{array}{l} B_r = B_o \left(\frac{r_o}{r}\right)^2 \sim r^{-2} \\ B_\varphi = \frac{-B_o \Omega r_o^{\,2}}{v_r r} \sim r^{-1} \end{array}$$

(Frozen in flux condition)

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:

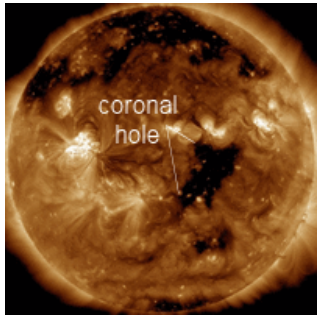
High-speed solar wind streams are associated:

- 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 and 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

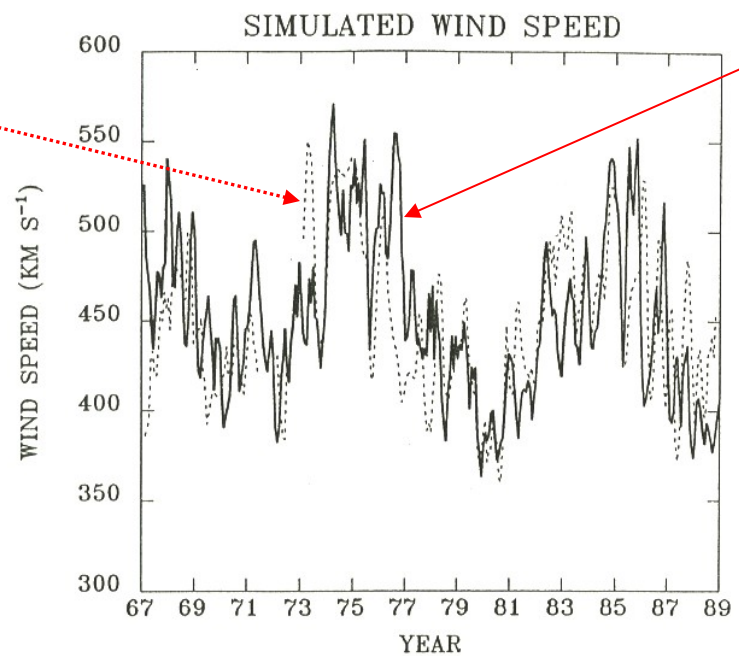
3. *Wang & Sheeley* (1990) simulate the solar wind speed at Earth for ~20 year period (1967-1988).

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

   ii) Correlation between observed & simulated wind speed found.

Observed Speed

Simulated speed



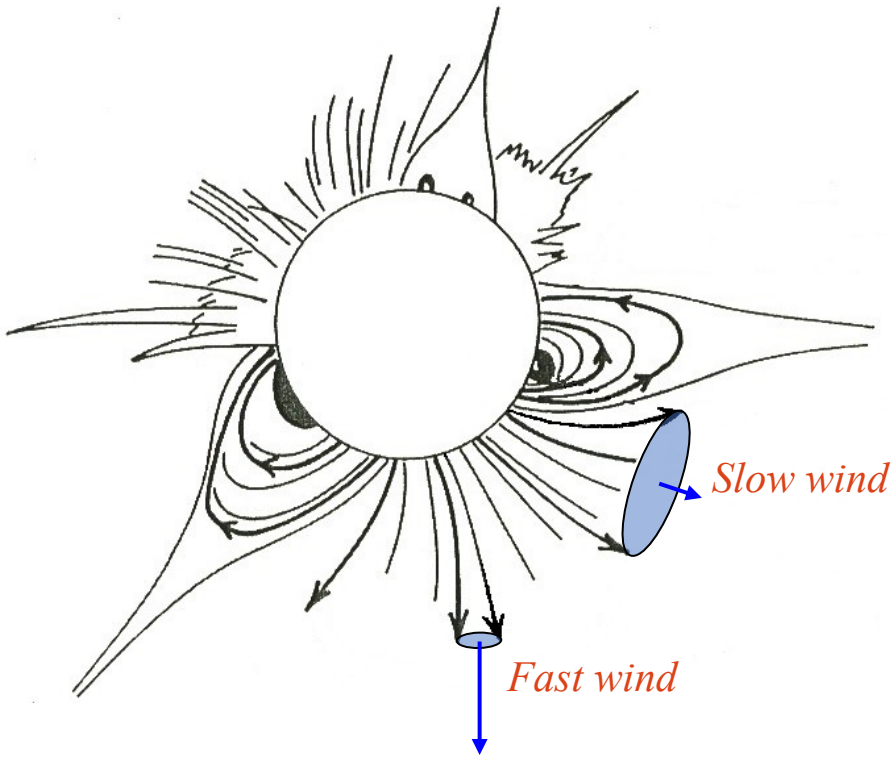
Wang & Sheeley, *ApJ*, ***355***, 726, 1990.

Brief Historical Background Cont'd

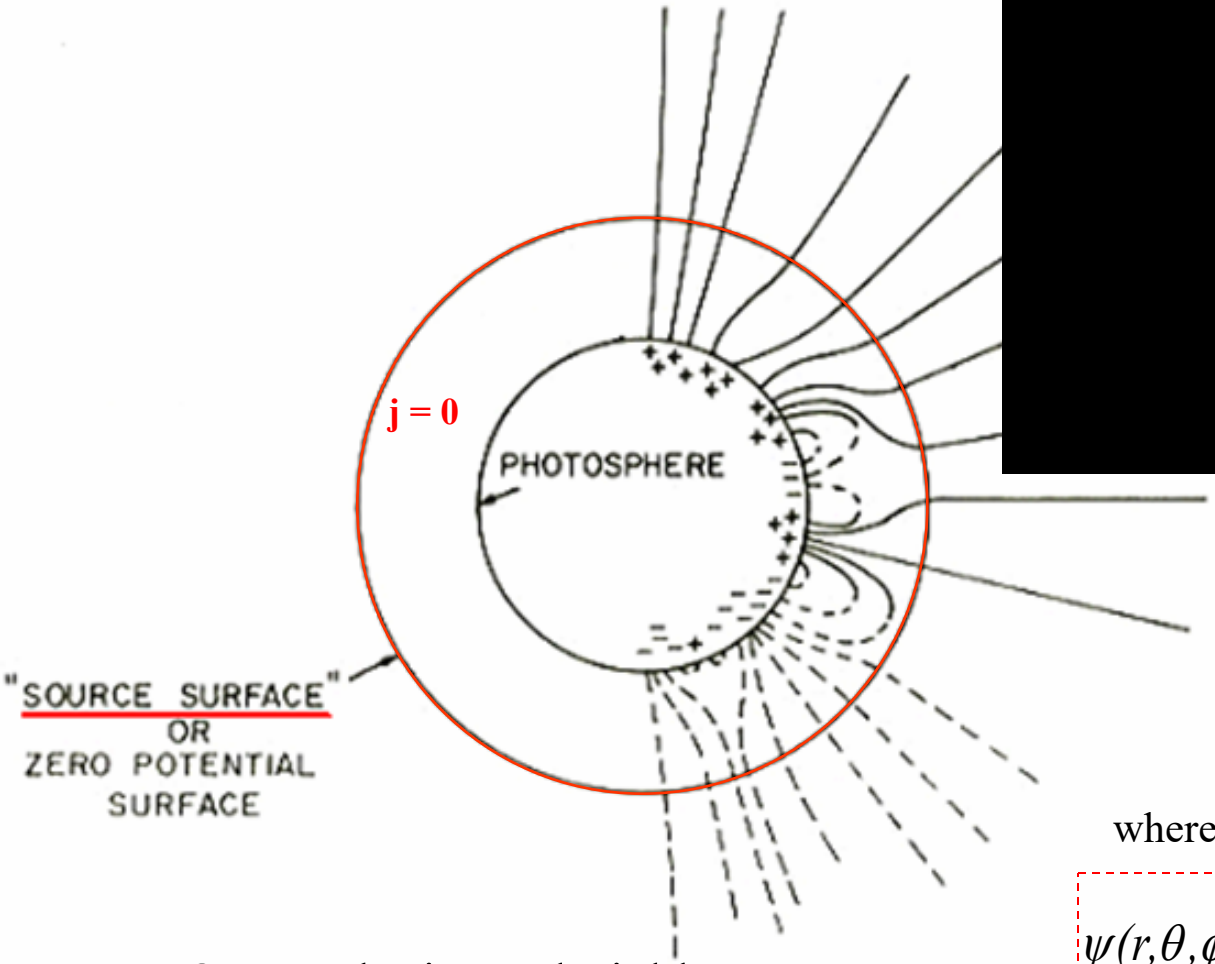
iii) Conclude: fast & slow solar wind originate from coronal holes.

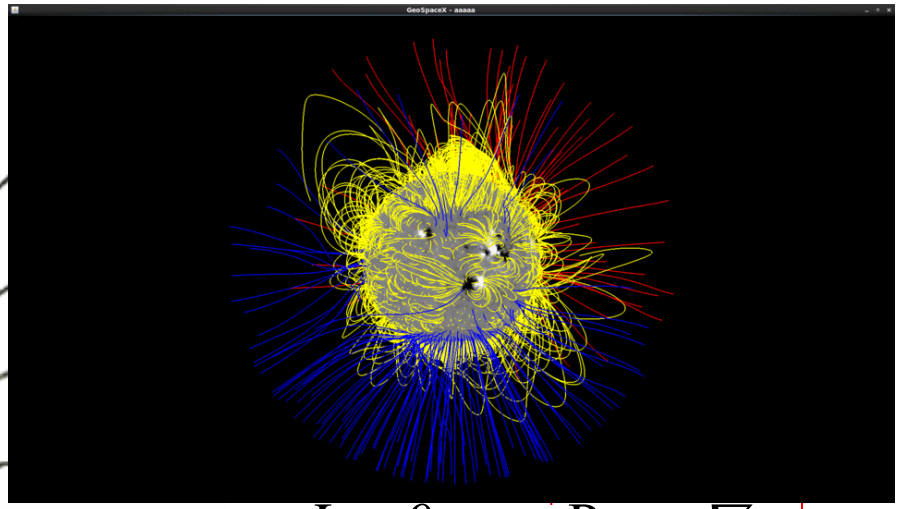
Fast wind → *central regions of coronal holes* (***Small*** f_s)

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



Potential Field Source Surface (PFSS) Model of the Corona





$$J = 0 \Rightarrow B = -\nabla\psi$$

$$\nabla \cdot B = 0$$

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

where,

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

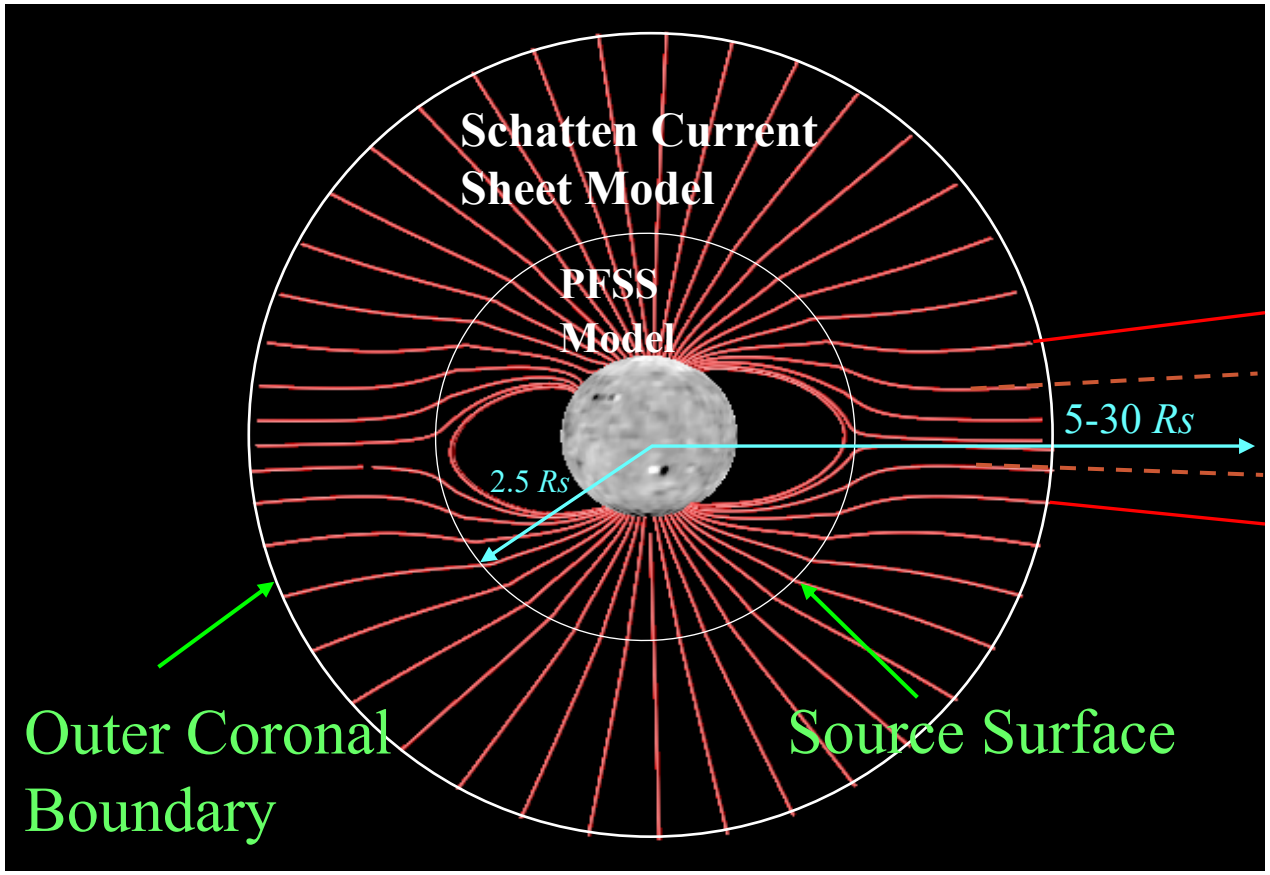
Coefficients A_{lm} and B_{lm} are determined from the *boundary conditions*.

——— Outward Directed Field

- - - - - Inward Directed Field

Schatten, Cosmic Electrodynamics, 2, 232, 1971.

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:

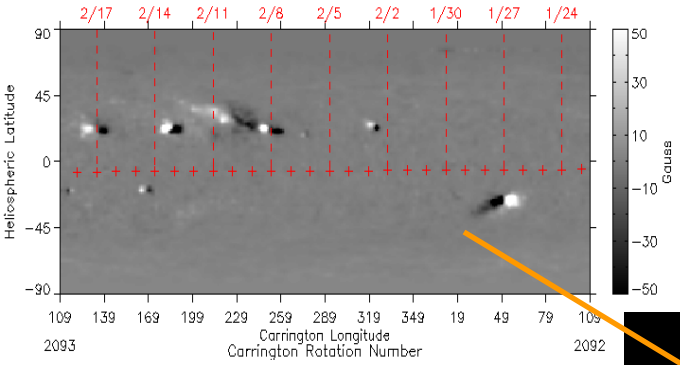
1) WSA 1D Kinematic
2) ENLIL
3) Gamera
4) MS-FLUKSS
5) HAF

(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.**

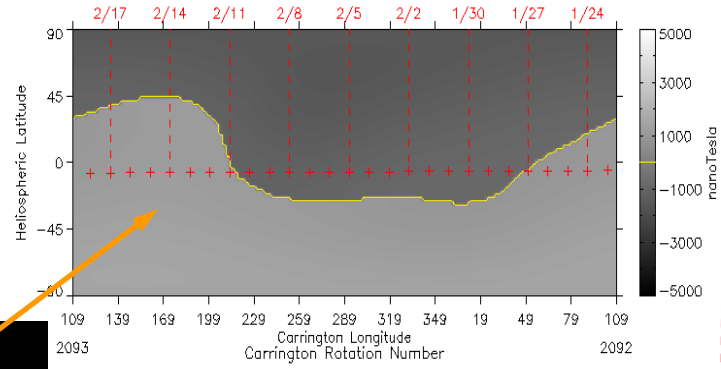
WSA Coronal Solution

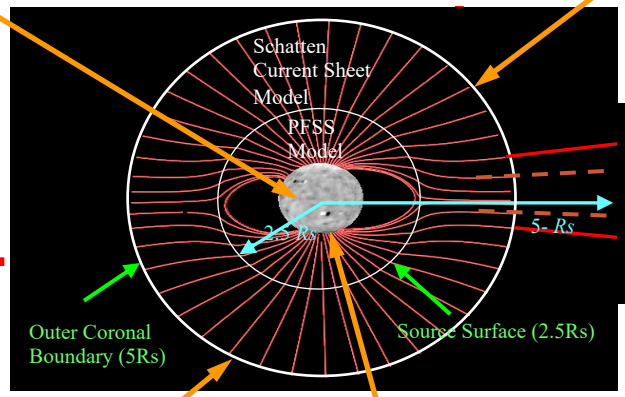
MODEL INPUT: **Observed Photospheric Field**



MODEL OUTPUT

Field at Outer Coronal Boundary (5.0 R_s)

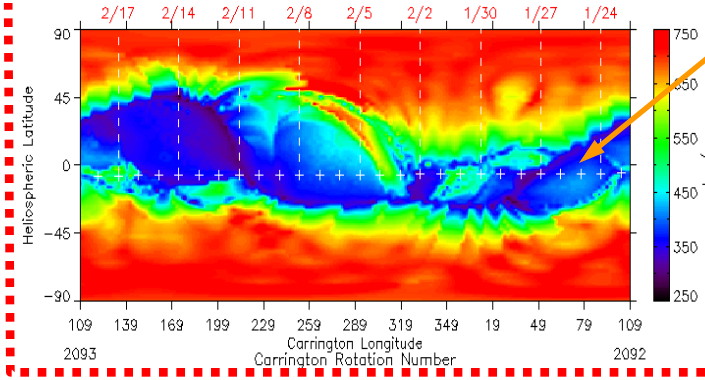




Solar Wind Model
(e.g., WSA 1D Kinematic model, Enlil, & LFM-Helio, MS-FLUKSS, & HAF)
(5-30*Rs* to 1AU)

MODEL OUTPUT

Predicted Solar Wind Speed (5.0 R_s)

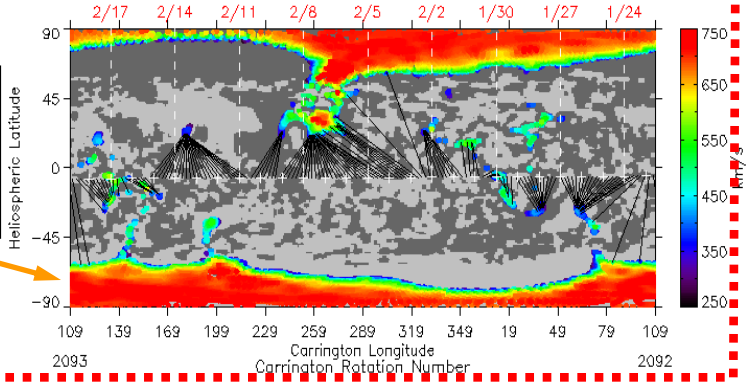


$$V_{\text{solar wind}} \sim f(f_s, \theta_b)$$

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

MODEL OUTPUT

Derived Coronal Holes (1.0 R_s)



Empirical Relationships

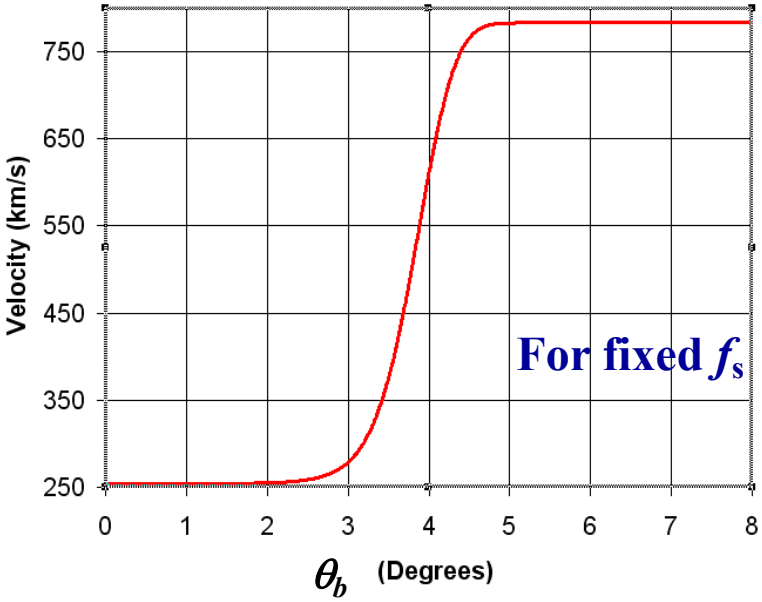
Old: $V(f_s) = 285 + 650/(f_s)^{5/9}$ km s^{-1}

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.

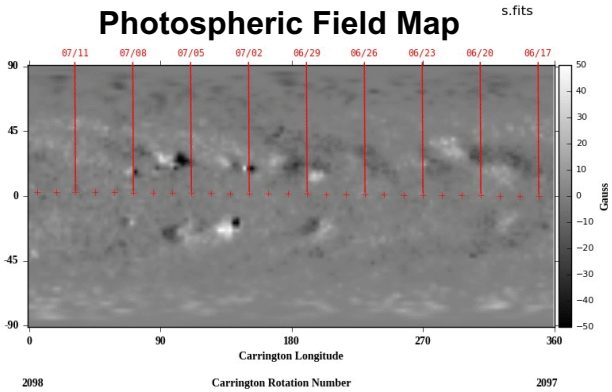
θ_b = Minimum angular distance that an open field footpoint lies from nearest coronal hole boundary.



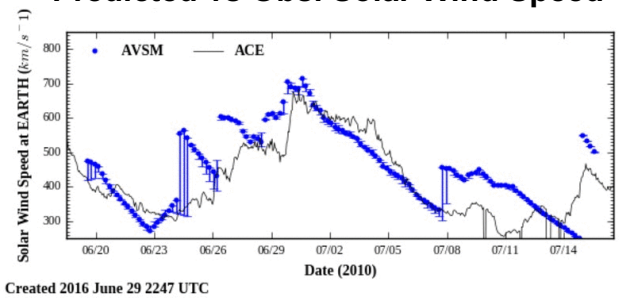
ADAPT-VSM (Realizations 1-12)

(July 8, 2010)

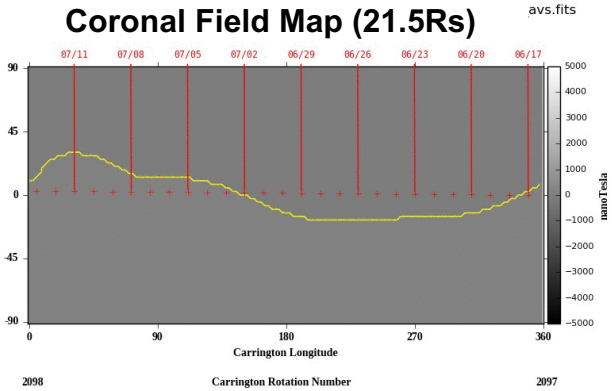
Photospheric Field Map



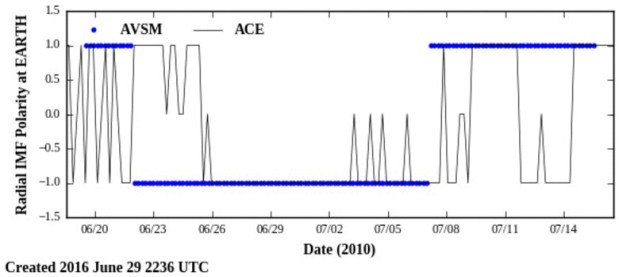
Predicted vs Obs. Solar Wind Speed



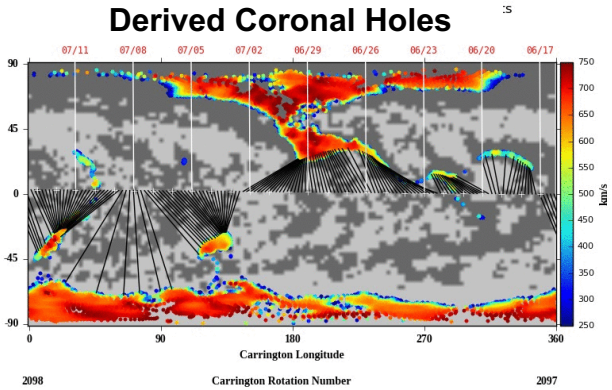
Coronal Field Map (21.5Rs)



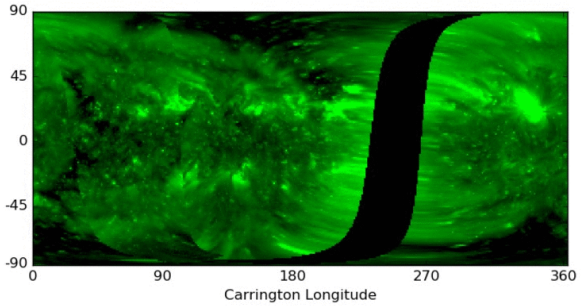
Predicted vs Obs. IMF Polarity



Derived Coronal Holes



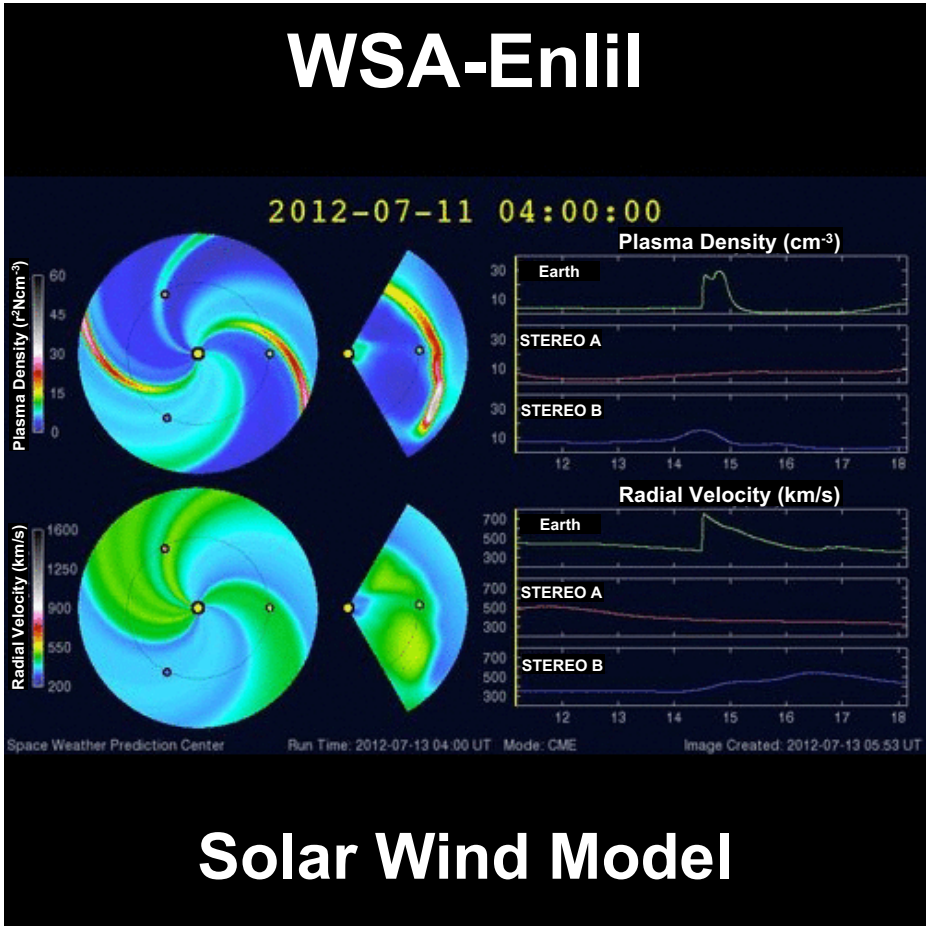
STEREO A&B – SDO/AIA (EUV)



Nation's Operational Solar Wind/CME Forecast Model (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.

- **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!

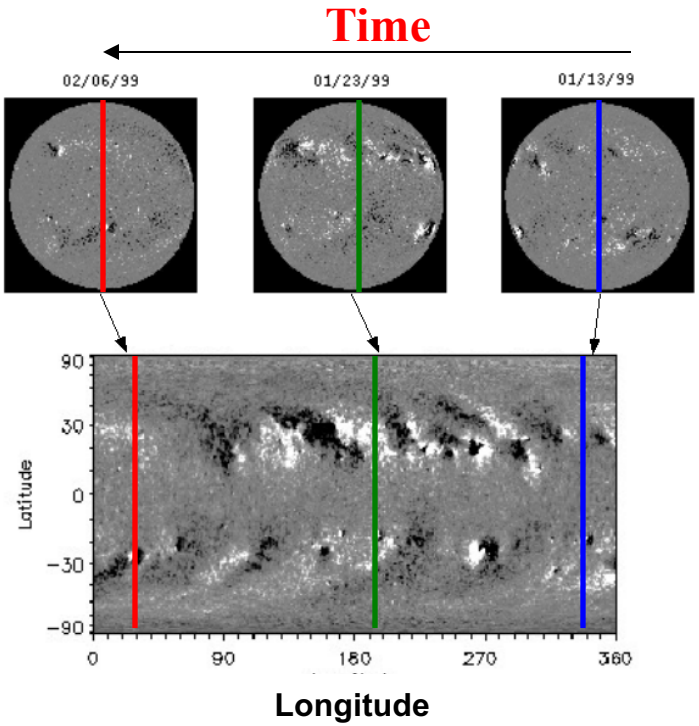
Pizzo et al., Space Weather, 2011

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.

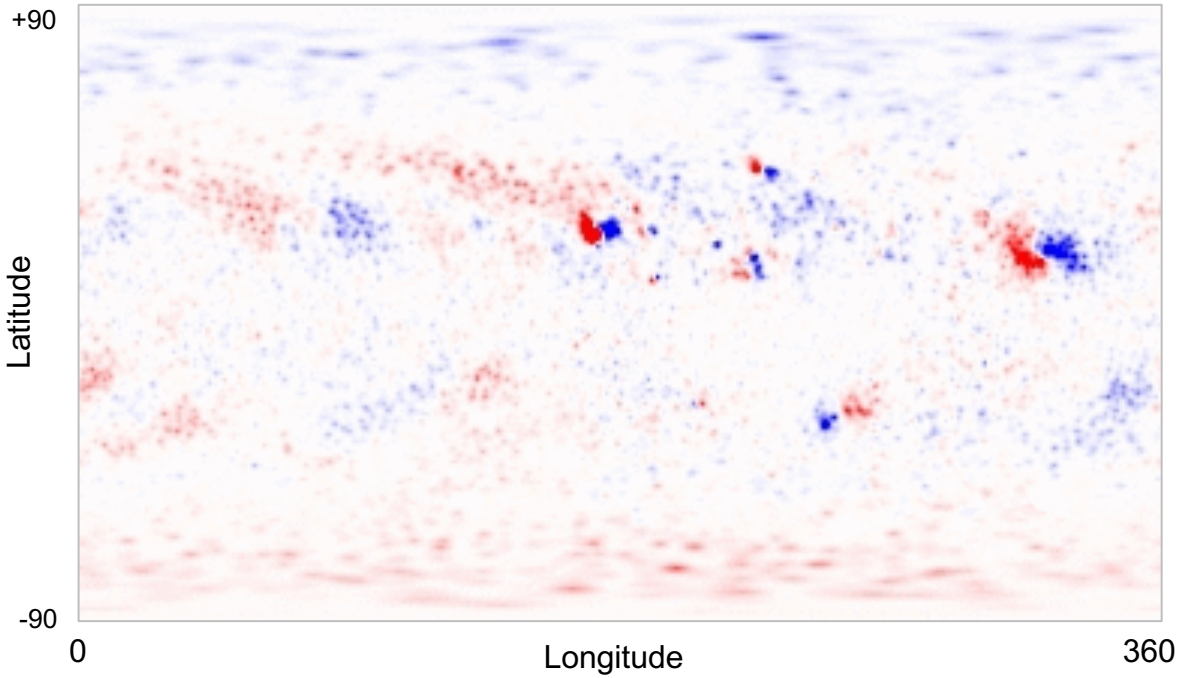


Carrington rotation 1 starts from November 9, 1853.

- **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*)

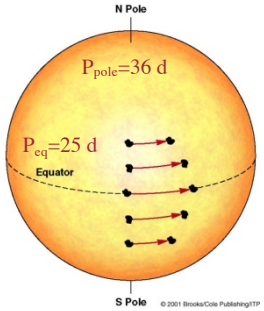
Provides more realistic estimates of the instantaneous global photospheric magnetic field distribution than those provided by traditional synoptic maps.

ADAPT Flux Transport Model

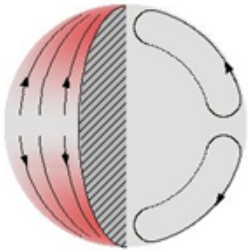
Overview: The ADAPT flux transport model (Arge et al. 2010, 2011, 2013; Henney et al. 2012 & 2014; Hickman 2015, Lee et al. 2013; Linker et al. 2013) is based on Worden & Harvey (2000), which *accounts for known flows in the solar photosphere.*

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

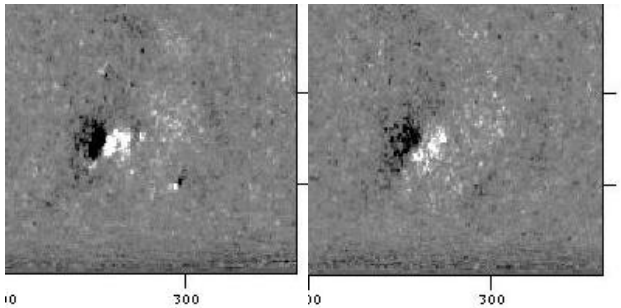
(1) Differential rotation



(2) Meridional flow



(3) Supergranular diffusion



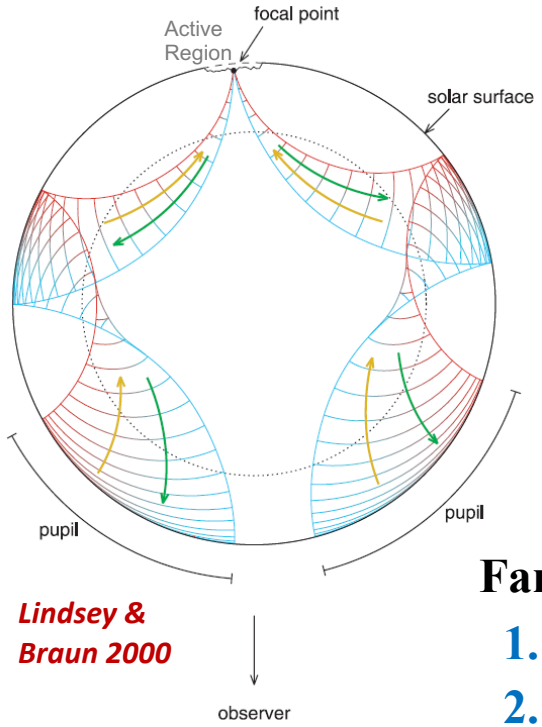
(4) Random flux emergence

(5) Data assimilation of new observations (LANL)

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

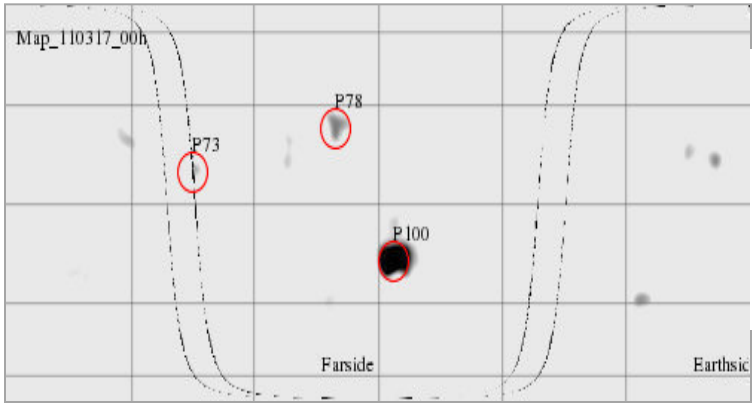
Incorporating Far-side Maps

Far-side detections are derived from helioseismic holography



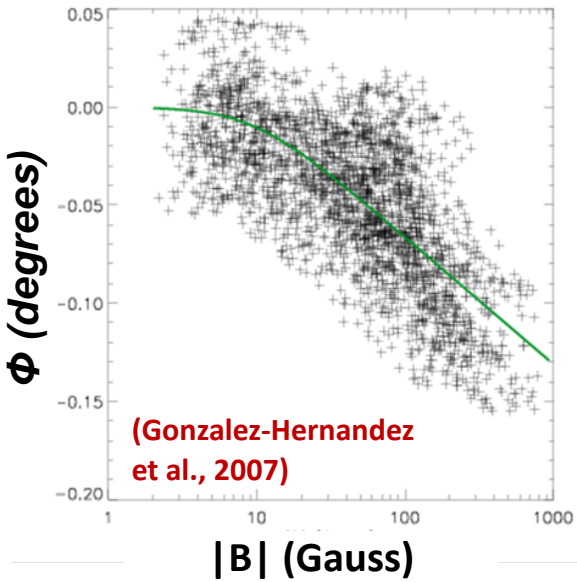
Lindsey & Braun 2000

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)**

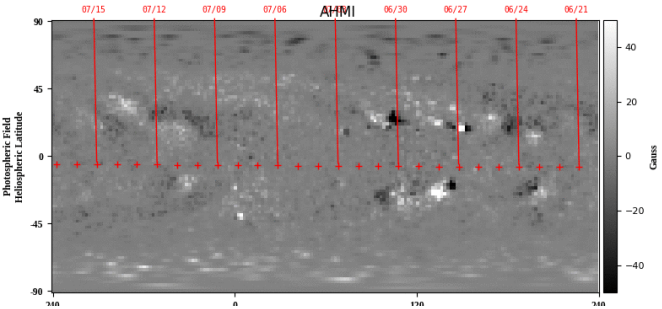
A "far-side ensemble" can be generated from these 3 factors.

Impact of Far-Side Fields

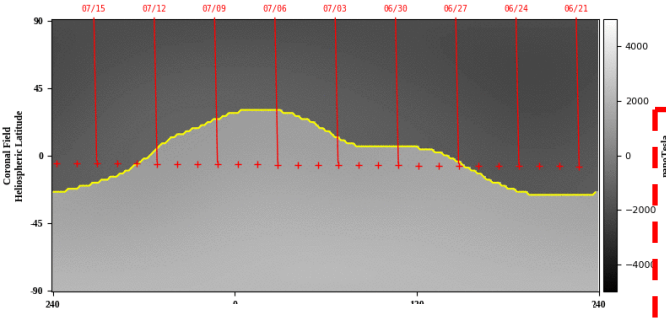
(WSA Predictions at STEREO B With & Without Far-Side Included)

STEREO B Coronal & Solar Wind Predictions *without* Active Region

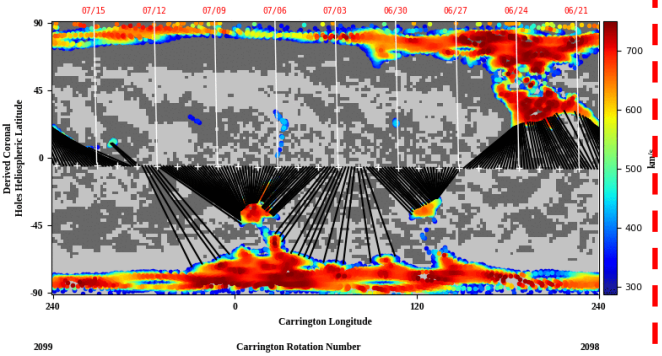
Photospheric Field Map

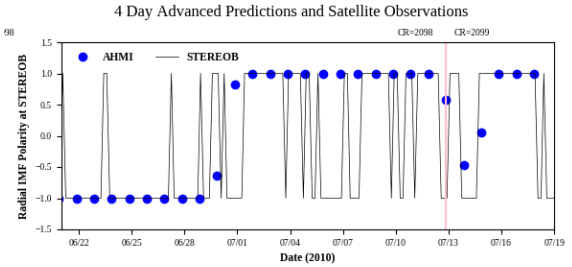


Coronal Field Map (5.0Rs)

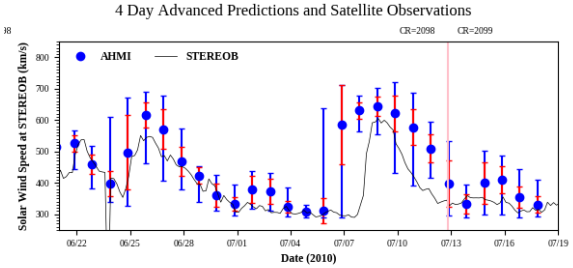


Derived Coronal Holes





Created 2018 August 16 2203 UTC



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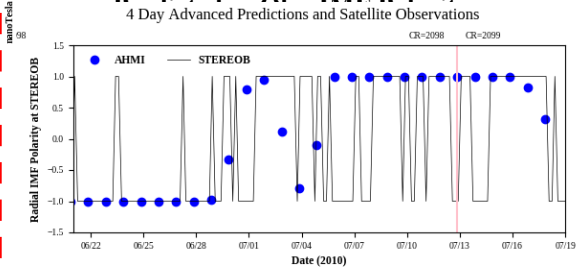
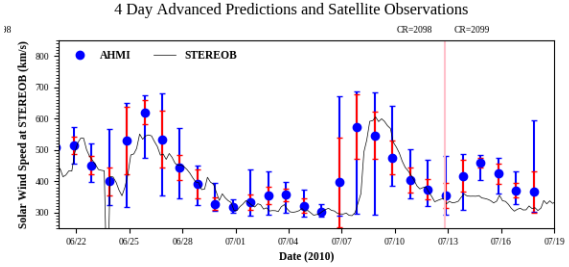


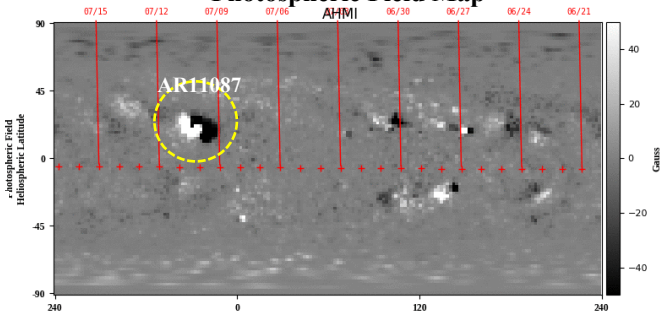
Created 2018 August 16 2105 UTC



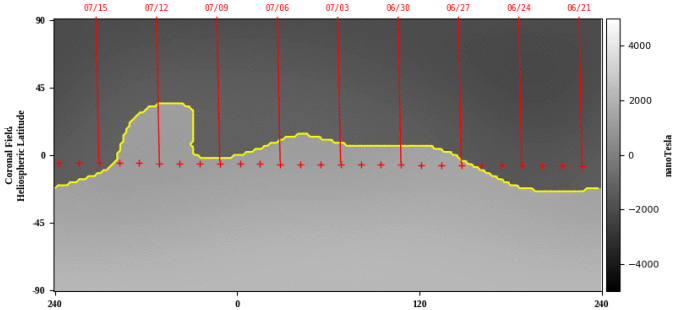
Created 2018 August 16 2104 UTC

STEREO B Coronal & Solar Wind Predictions *with* Active Region

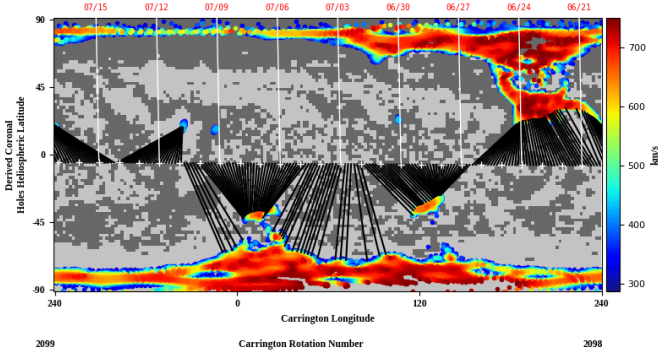
Photospheric Field Map



Coronal Field Map (5.0Rs)



Derived Coronal Holes



Ranking ADAPT Realizations & ADAPT-WSA Predictive Performance

Developed a methodology for objectively ranking WSA predictions derived from different ADAPT realizations

WSA Predictive Metric (WPM):

$$WPM = \frac{\textit{Fractional Correct IMF Polarity}}{\textit{RMS Velocity Residual}}$$

(over a given time period)

- *Combines IMF & velocity* predictive performance into *one metric*.
- Provides a
  - quantitative measure of performance
  - quick way to determined which ADAPT realizations are best.

Use WPM to calculate skill

$$\text{Skill} = 1 - \frac{WPM^{-1}}{WPM_{ref}^{-1}}$$

Where WPM_{ref}^{-1} =

- Persistence model
- Recurrence model
- Some other model

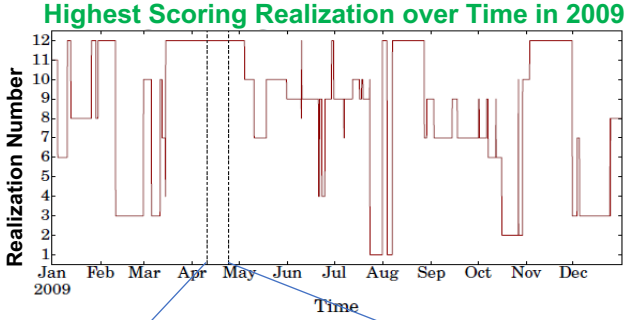


Figure 1: Plot of which realization has the highest score over time for the year of 2009. The figure highlights individual realizations performing better for extended periods.

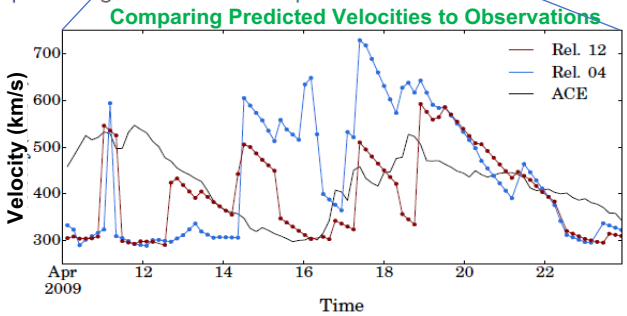


Figure 2: Plot comparing predicted velocities from the highest and lowest scoring realizations to ACE measurements from the marked area in Fig. 1. Realization 12 shows superior performance.

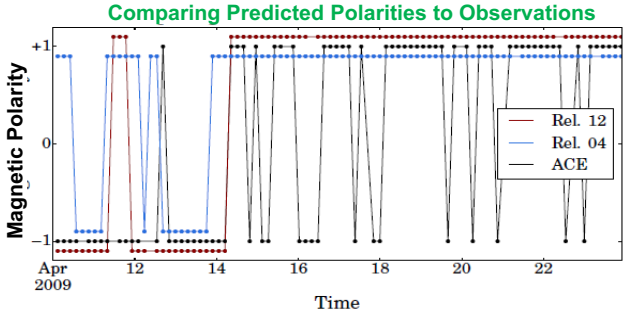
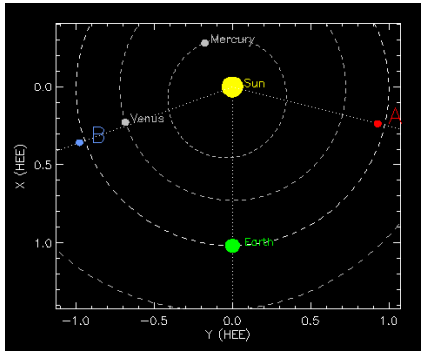


Figure 3: Similar to Fig. 2 with polarities instead of velocities. Realization 12 shows increased ability to predict the polarity, especially around April 12th and 14th.

Combined 27- Day ACE, STEREO A & B Score

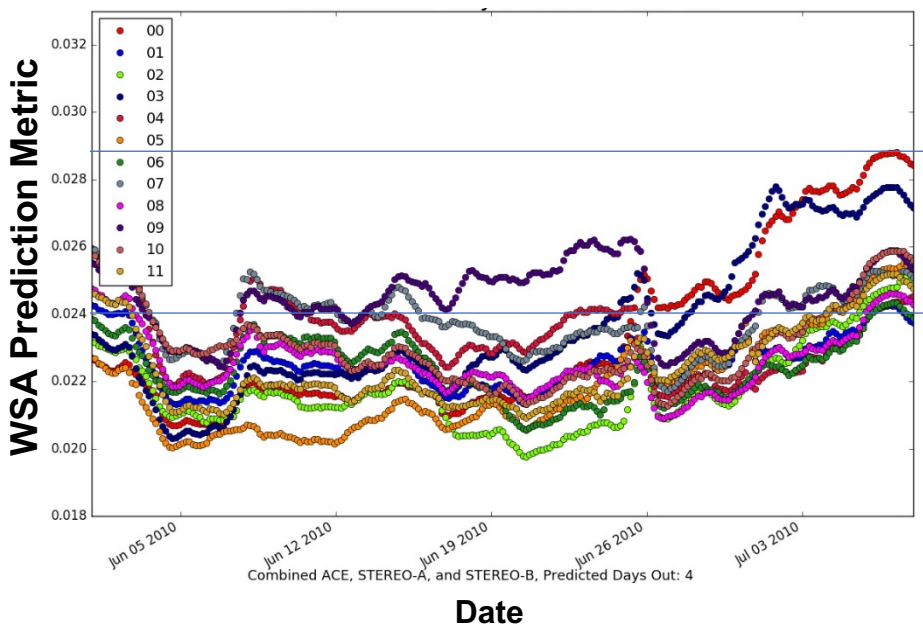
(4-day Out Predictions)

WSA Prediction Metric Scores *combined* for three Spacecraft

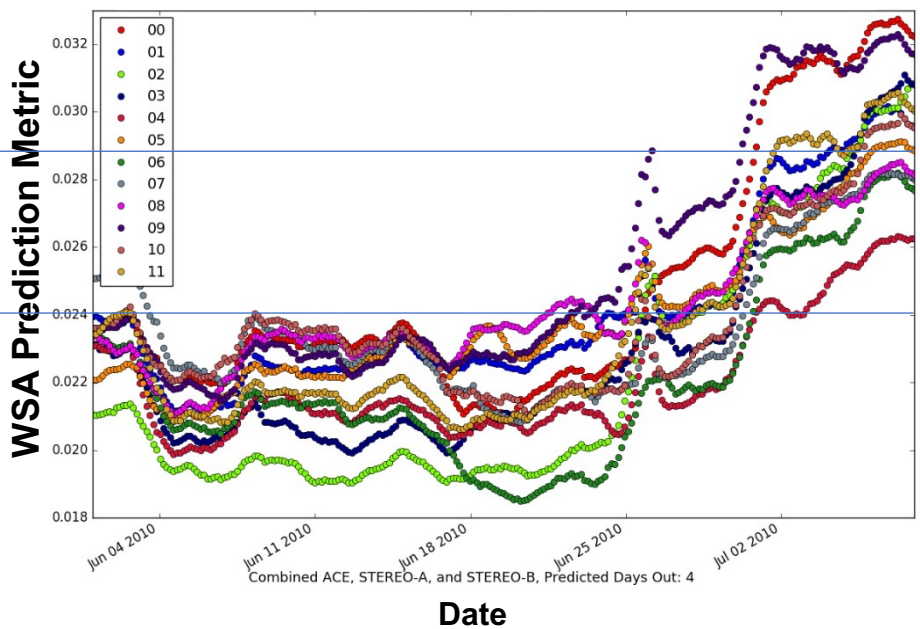


- Provides overall global score
- Assumes spacecraft measurements have equal quality/uncertainty
- Currently, 27-day windows *not* the same for each spacecraft

Combined 27-Day Score *Without* RAR

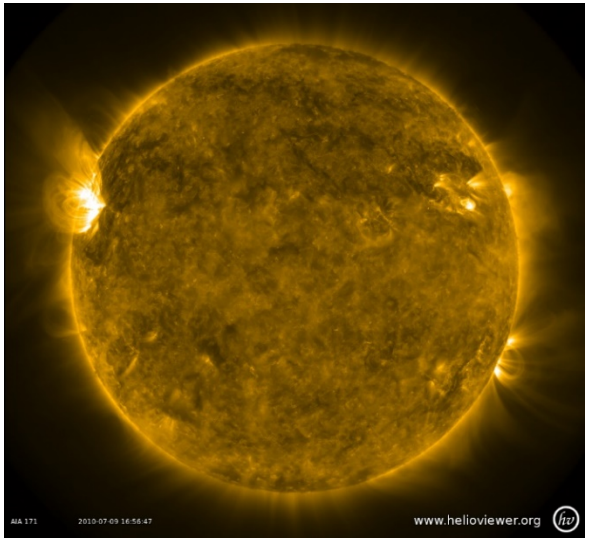


Combined 27-Day Score *With* RAR

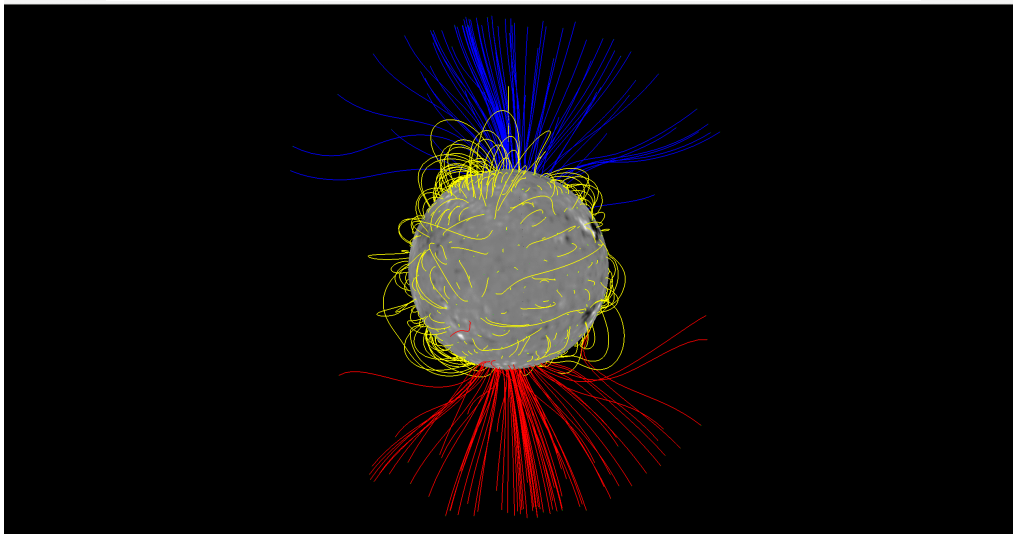


Comparing ADAPT-WSA Corona B Field Solutions with Observations

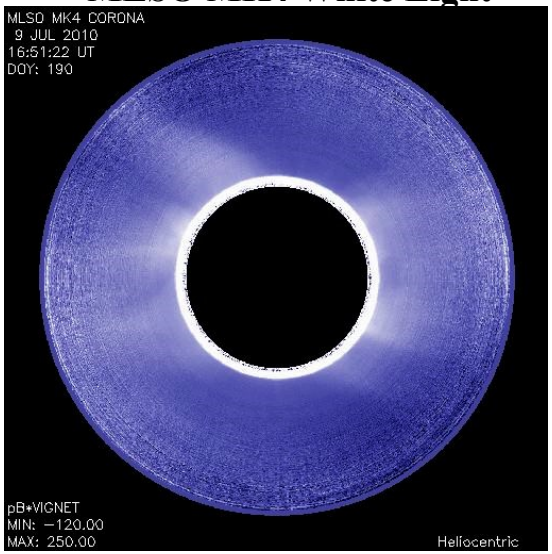
SDO AIA 171



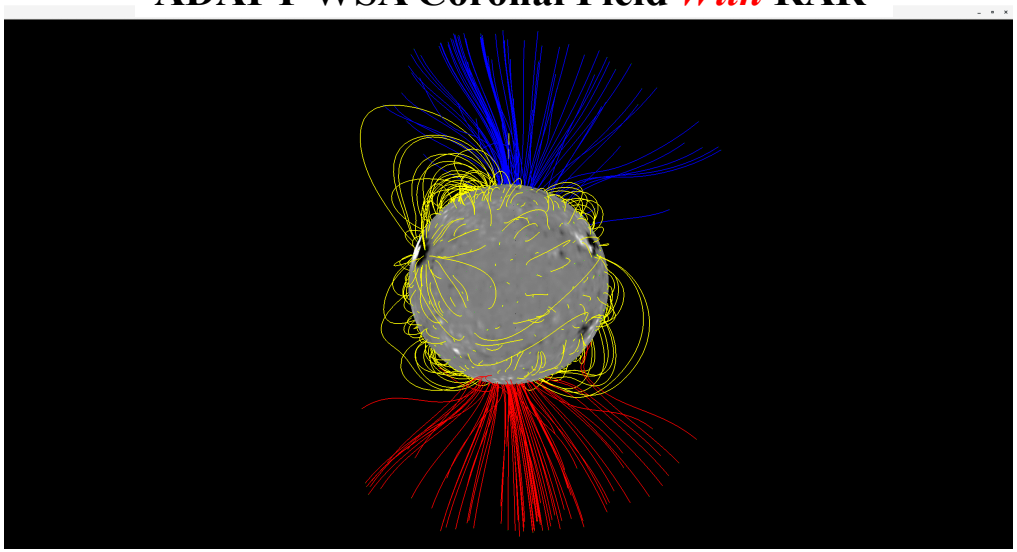
ADAPT-WSA Coronal Field *Without* RAR



MLSO MK4 White Light



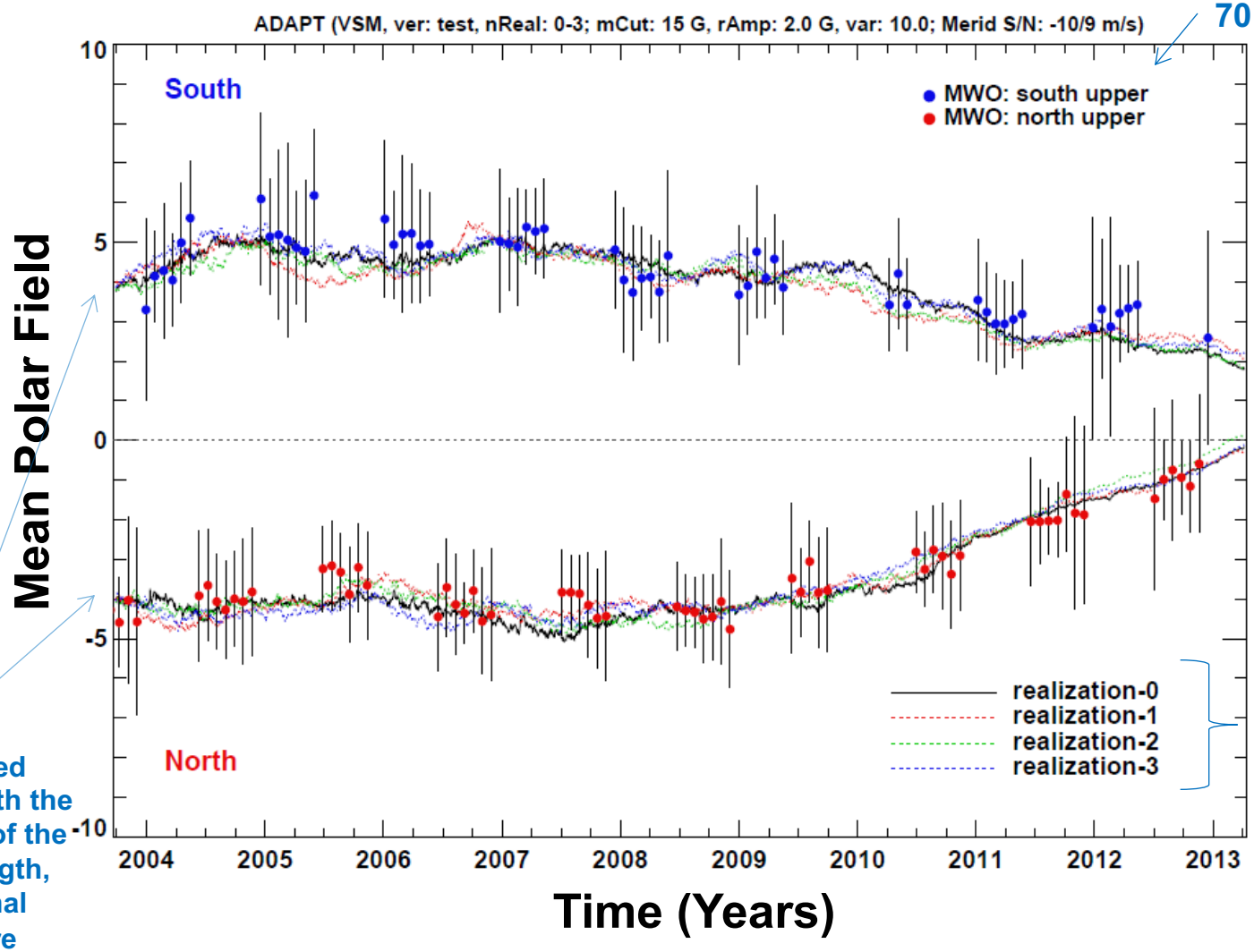
ADAPT-WSA Coronal Field *With* RAR



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.

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.

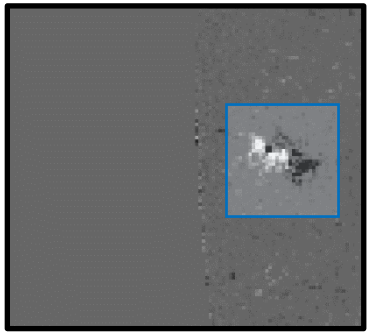
Reverse Active Region Modeling:
far-side "forensics"

Reconstruction of AR evolution:

1) Start with given AR on the east-limb
2) Estimate emergence from STEREO
3) Use mean evolution profile to reverse AR

1

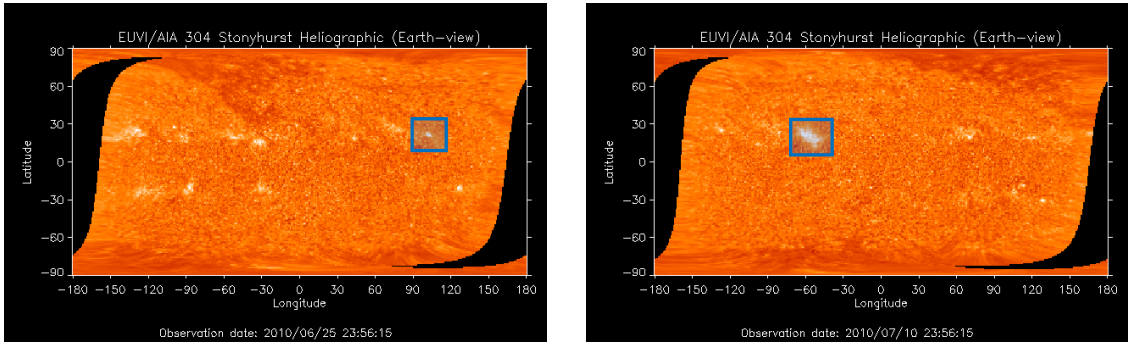
HMI Vector
10 July 2010 @ 1059 UT



AR11087

2

STEREO* EUVI (30.4 nm)

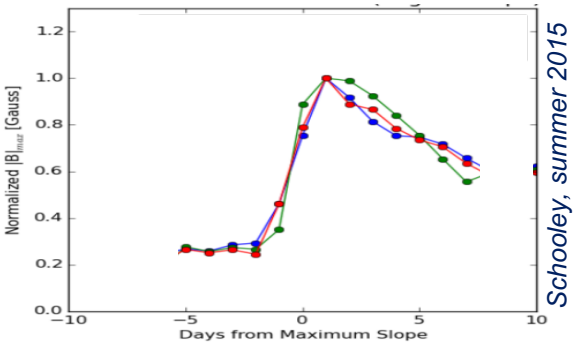


25 June 2010 ← 10 July 2010

Obs Time

3

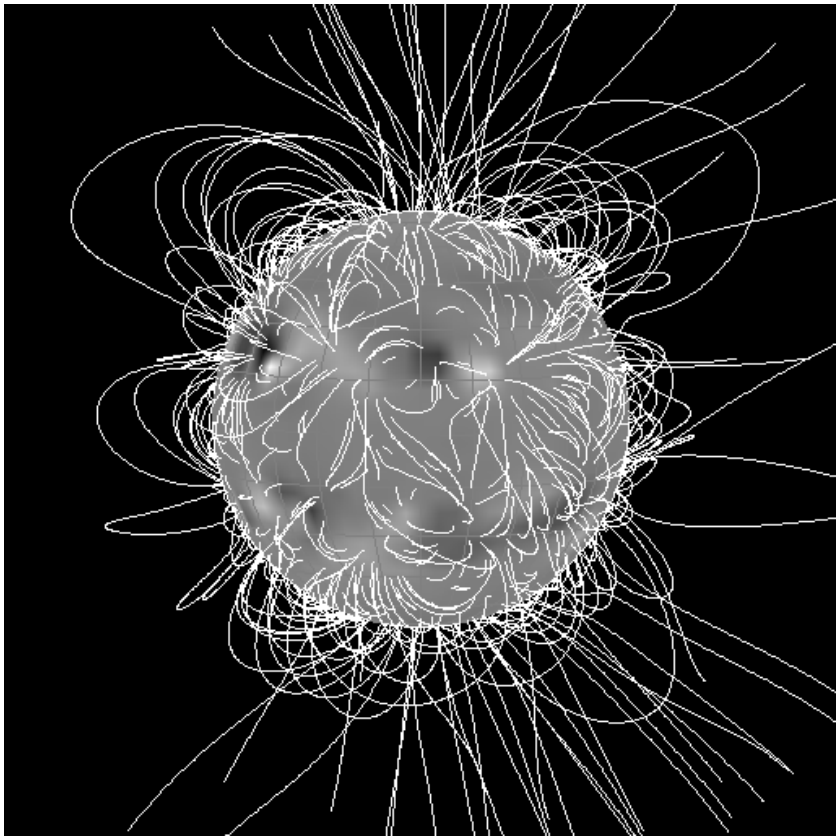
AR Evolution Profile



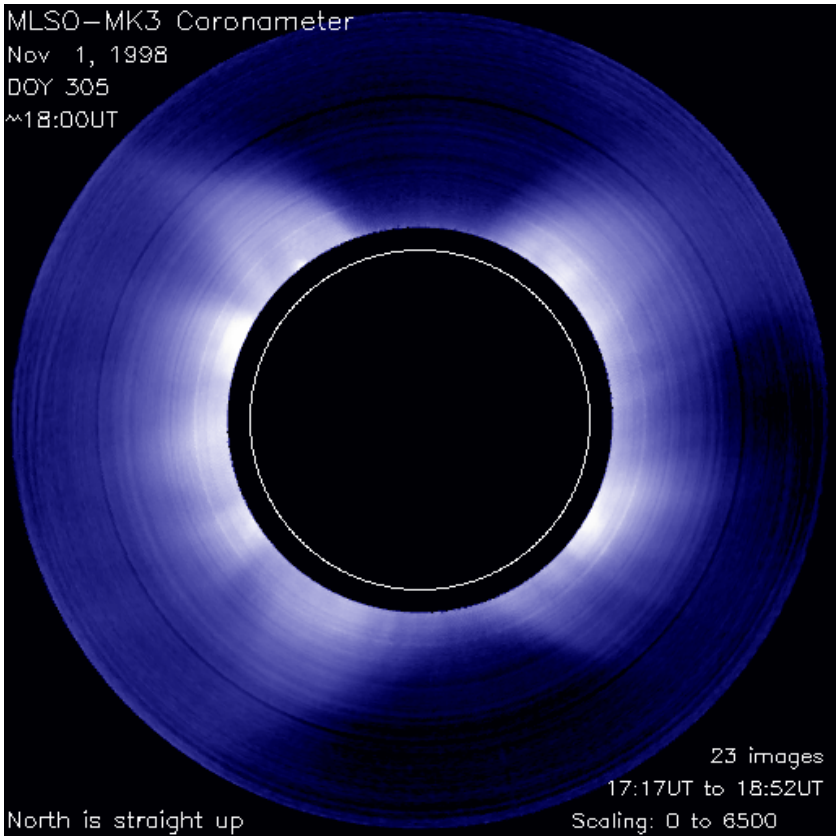
* Note: *only STEREO-A data is available after Oct 1, 2014, however, STEREO-B may become available at a later date.*

Global Coronal Field: Observations & Extrapolations

Photospheric field extrapolation (MWO)



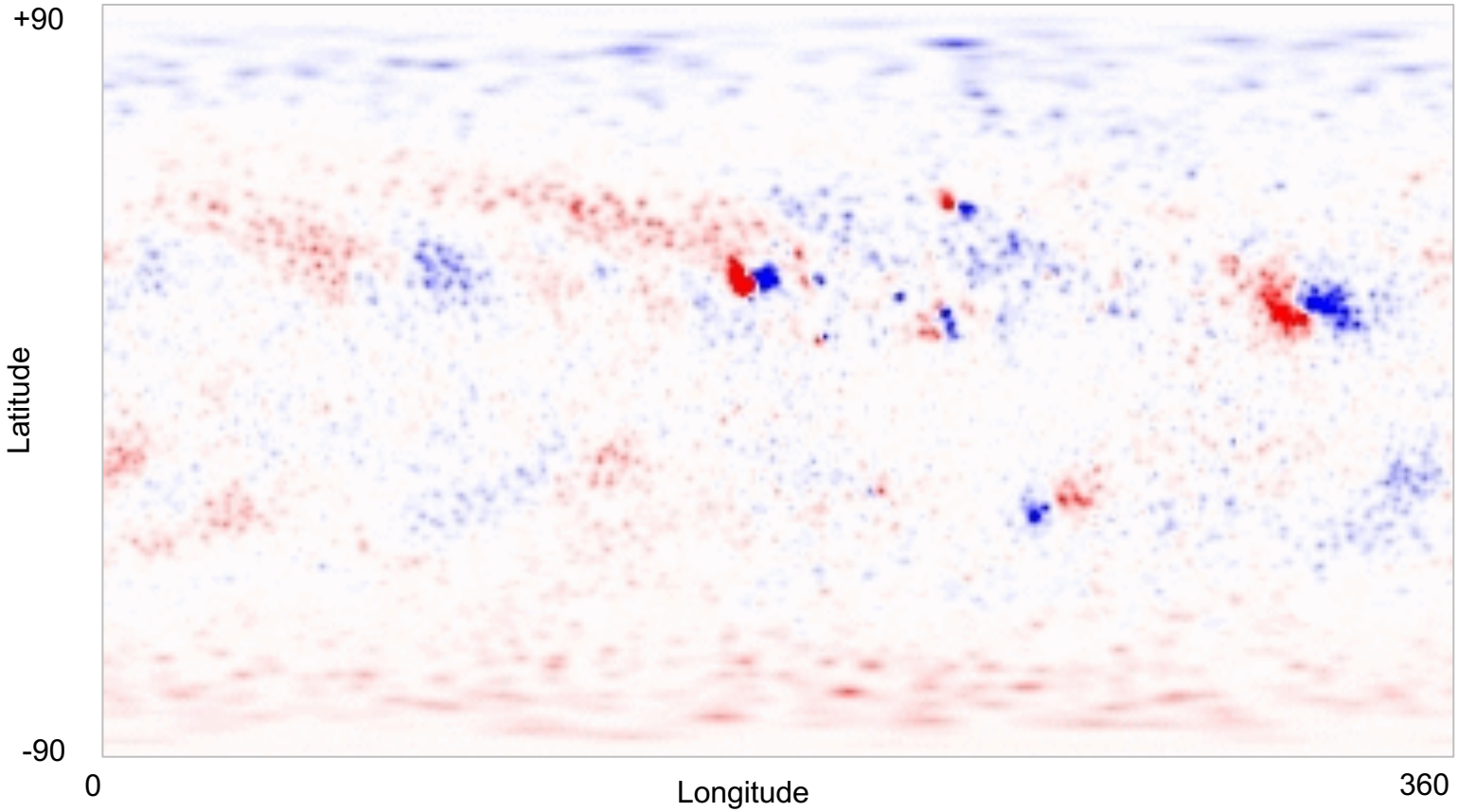
White light (pB) data HAO/MLSO/Mk3



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

ADAPT HMI Vector with RARs*: The Movie (May 1, 2010 – May 10, 2011)

ADAPT global map movie (realization 1 @ 24 hour cadence)



** Reverse Active Region modeling w/ HMI-Vector seed data, and global maps with 70% monopole damping*

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