Coronal & Solar Wind Modeling with WSA & ADAPT

Heliophysics Summer School
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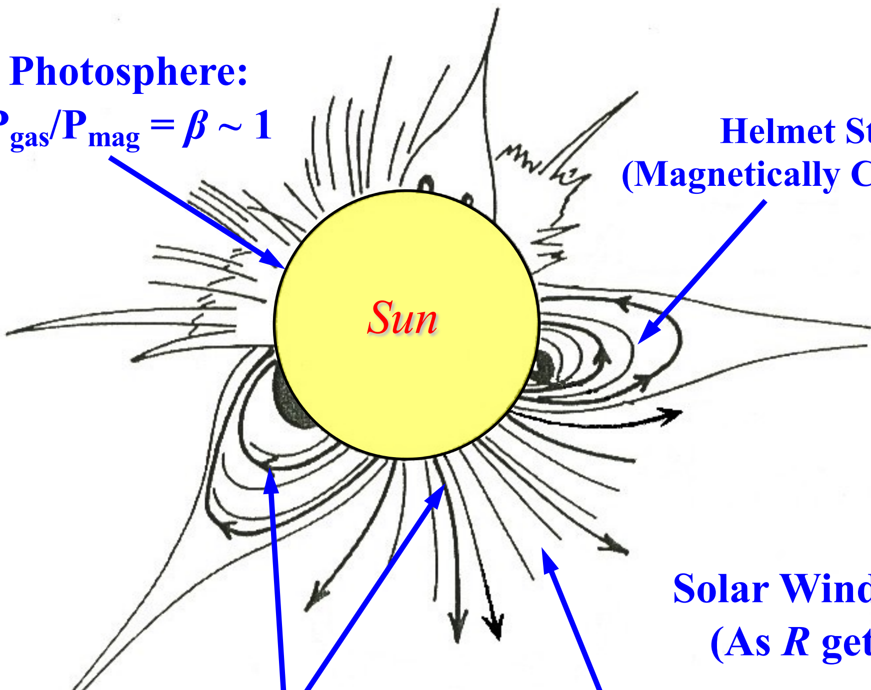
Outline

- Brief refresher on 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 & constraining WSA (& other coronal/solar wind models)
- Forecasting magnetic connectivity between spacecraft with Sun.

The Solar Magnetic Field

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



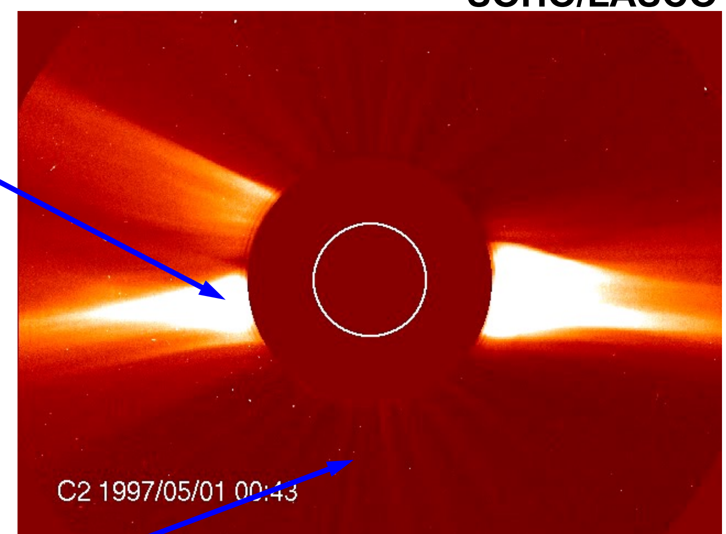
Helmet Streamer
(Magnetically Closed Region)

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

Corona: $\beta << 1$

Coronal Hole
(Magnetically "Open" Region)

SOHO/LASCO



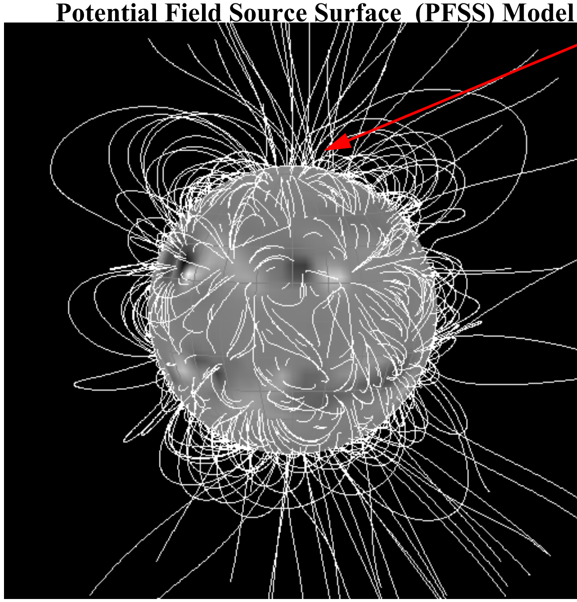
Coronal Holes

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

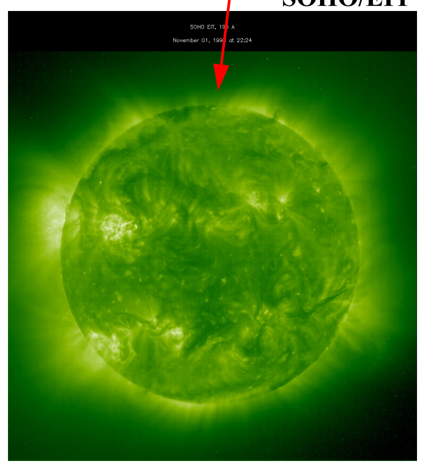
Observation Definition: Regions of low emission in the solar corona.

Coronal Hole

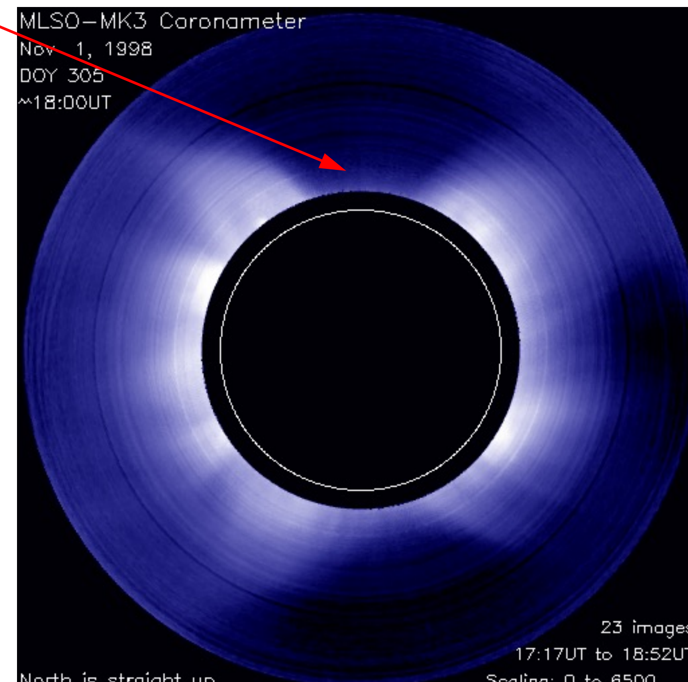
Potential Field Source Surface (PFSS) Model



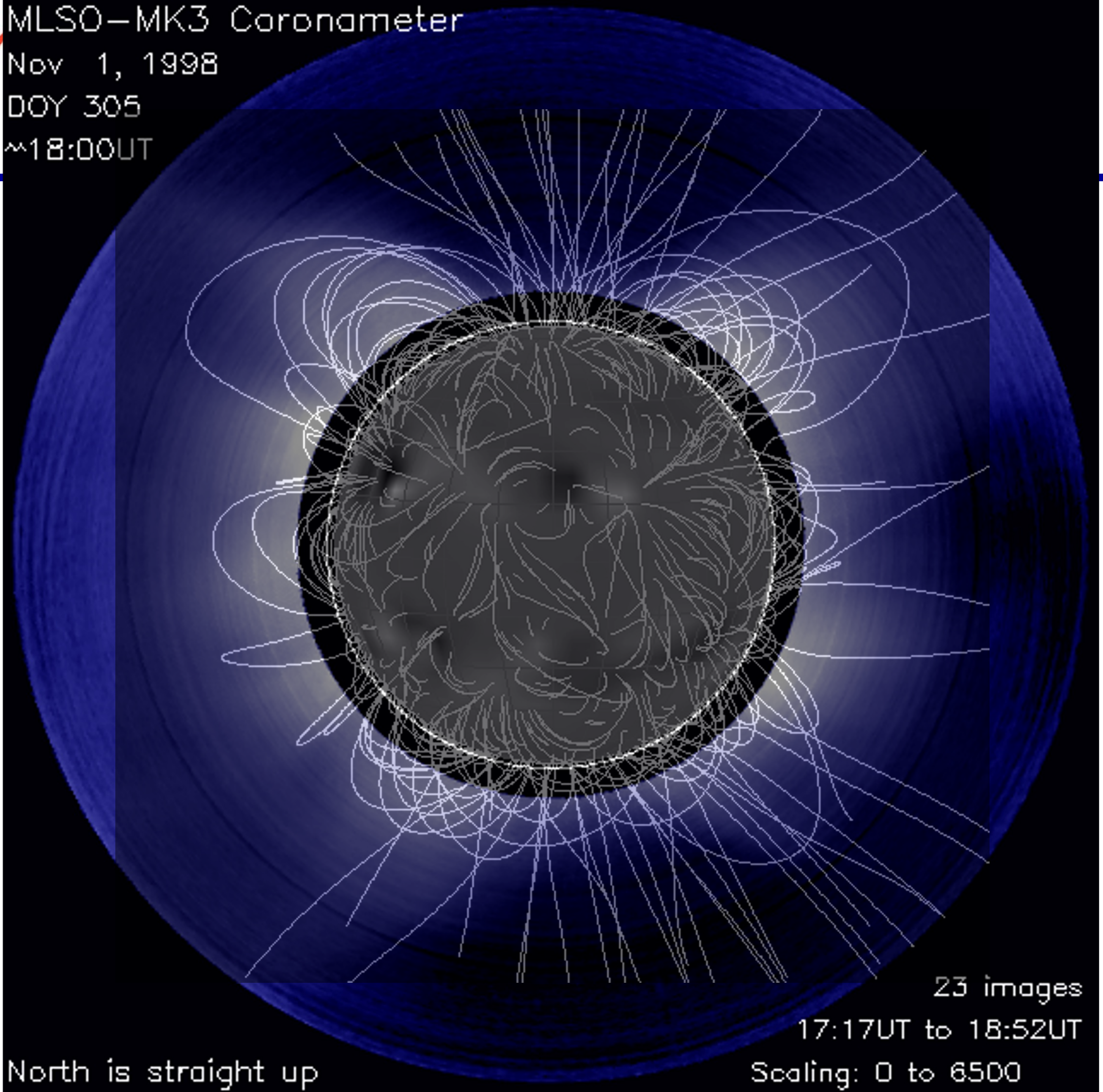
SOHO/EIT



MLSO-MK3



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


MLSO–MK3 Coronameter
Nov 1, 1998
DOY 305
~18:00UT
23 images
17:17UT to 18:52UT
North is straight up
Scaling: 0 to 6500

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.

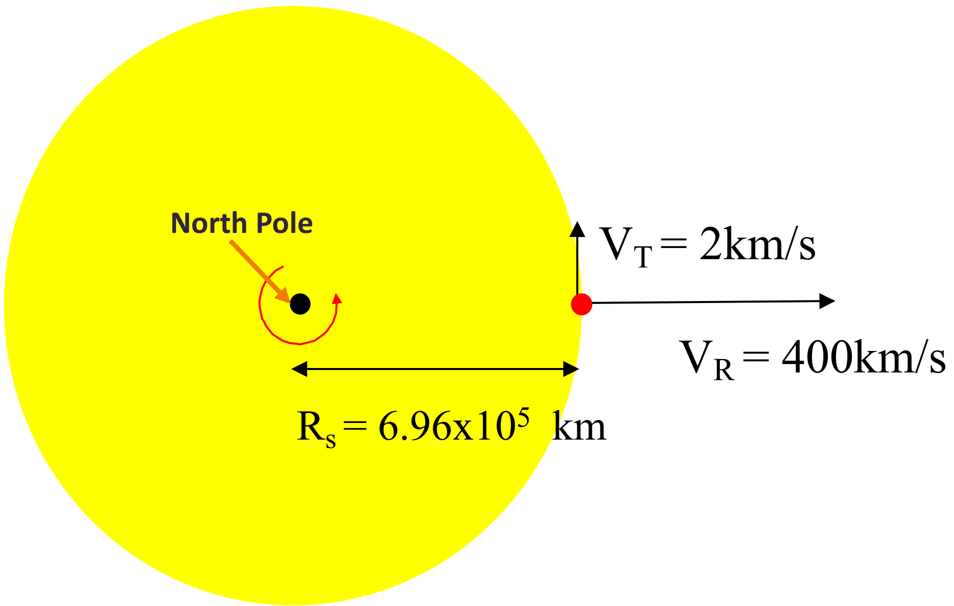
Two Types:

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



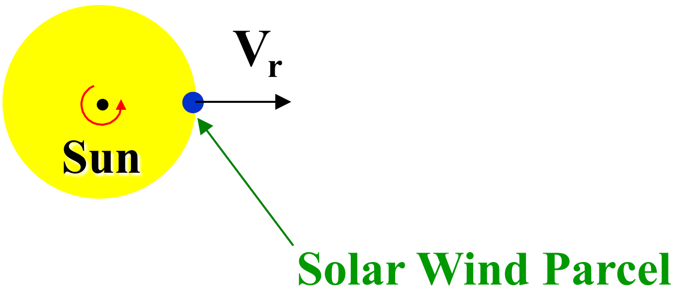
$T_{Sun} = 25.38$ days $= 2.192832\text{x}10^6$ sec

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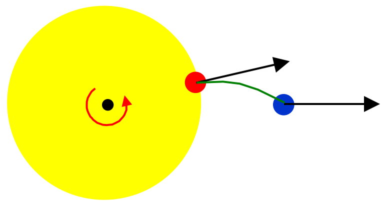

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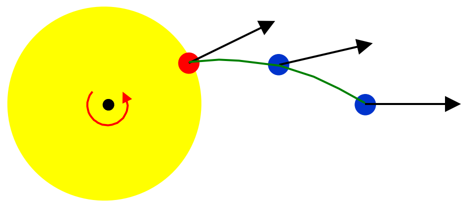

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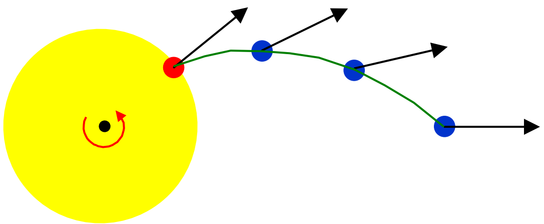

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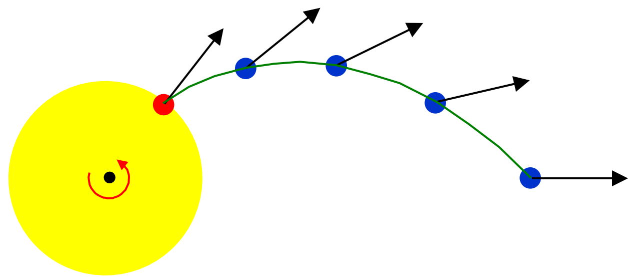
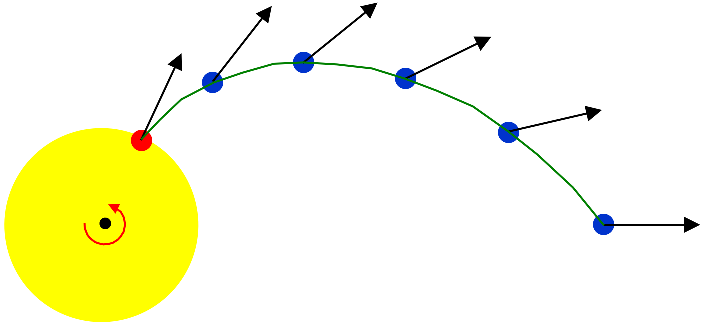
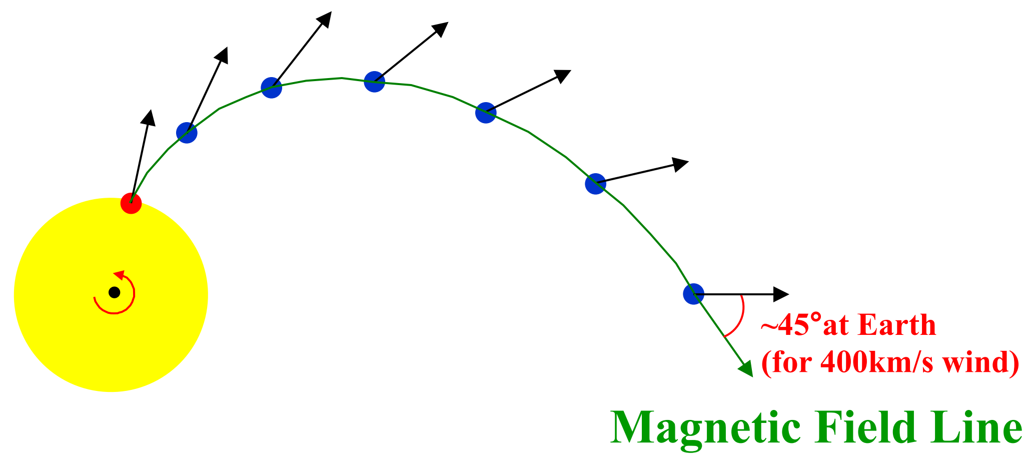


The Solar Wind and the Interplanetary Magnetic Field (Formation of the Parker Spiral)



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**.

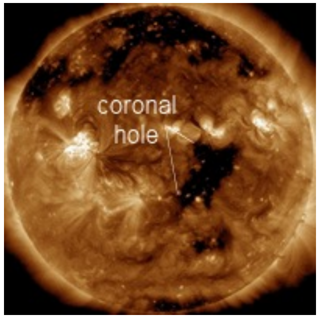
$$\nabla \cdot \mathbf{B} = 0$$

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

$$\Rightarrow \quad B_r = B_o \left(\frac{r_o}{r}\right)^2 \sim r^{-2}, \qquad B_\varphi = \frac{-B_o \Omega r_o^{\,2}}{v_r r} \sim r^{-1}$$

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).



   ⇒ 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 ⟶ Small f_s

Brief Historical Background Cont'd

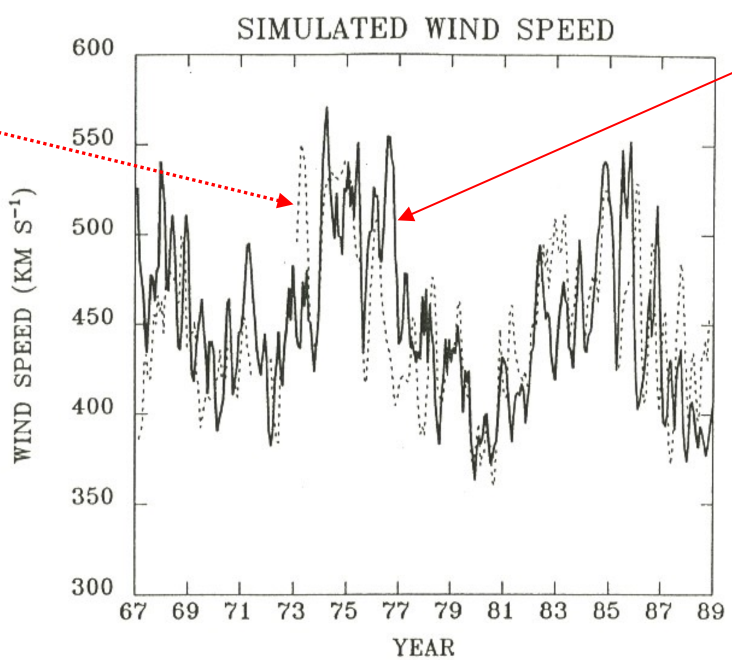
3. *Wang & Sheeley* (1990) simulate the solar wind speed at Earth for ~20 year period (1967-1988).

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

   ii) Correlation between observed & simulated wind speed found.

Observed Speed ....

Simulated speed ———



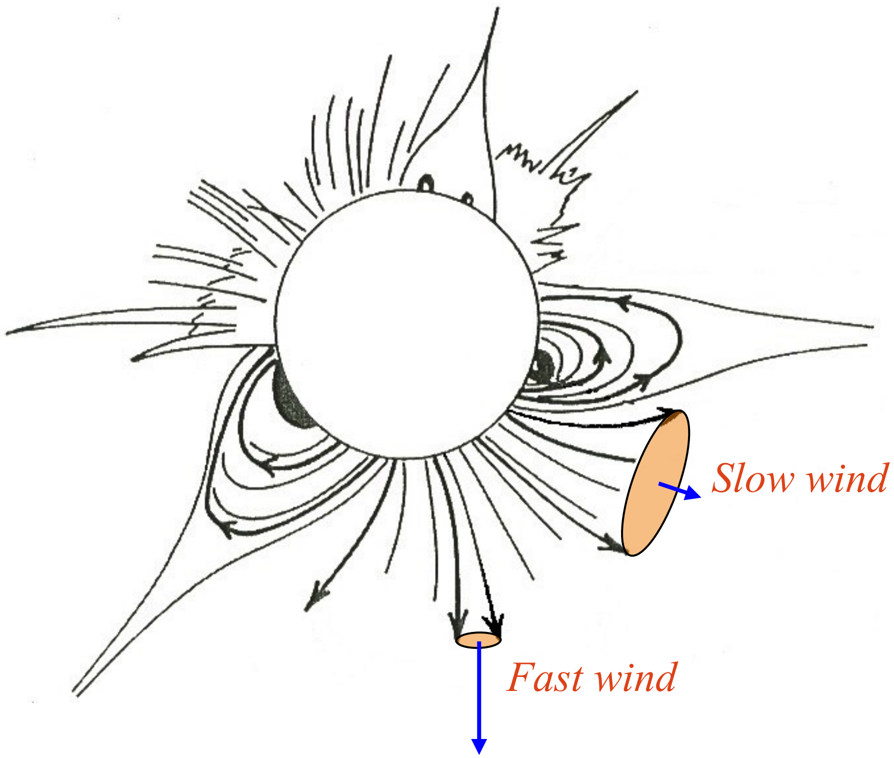
Wang & Sheeley, *ApJ*, ***355***, 726, 1990.

Brief Historical Background Cont'd

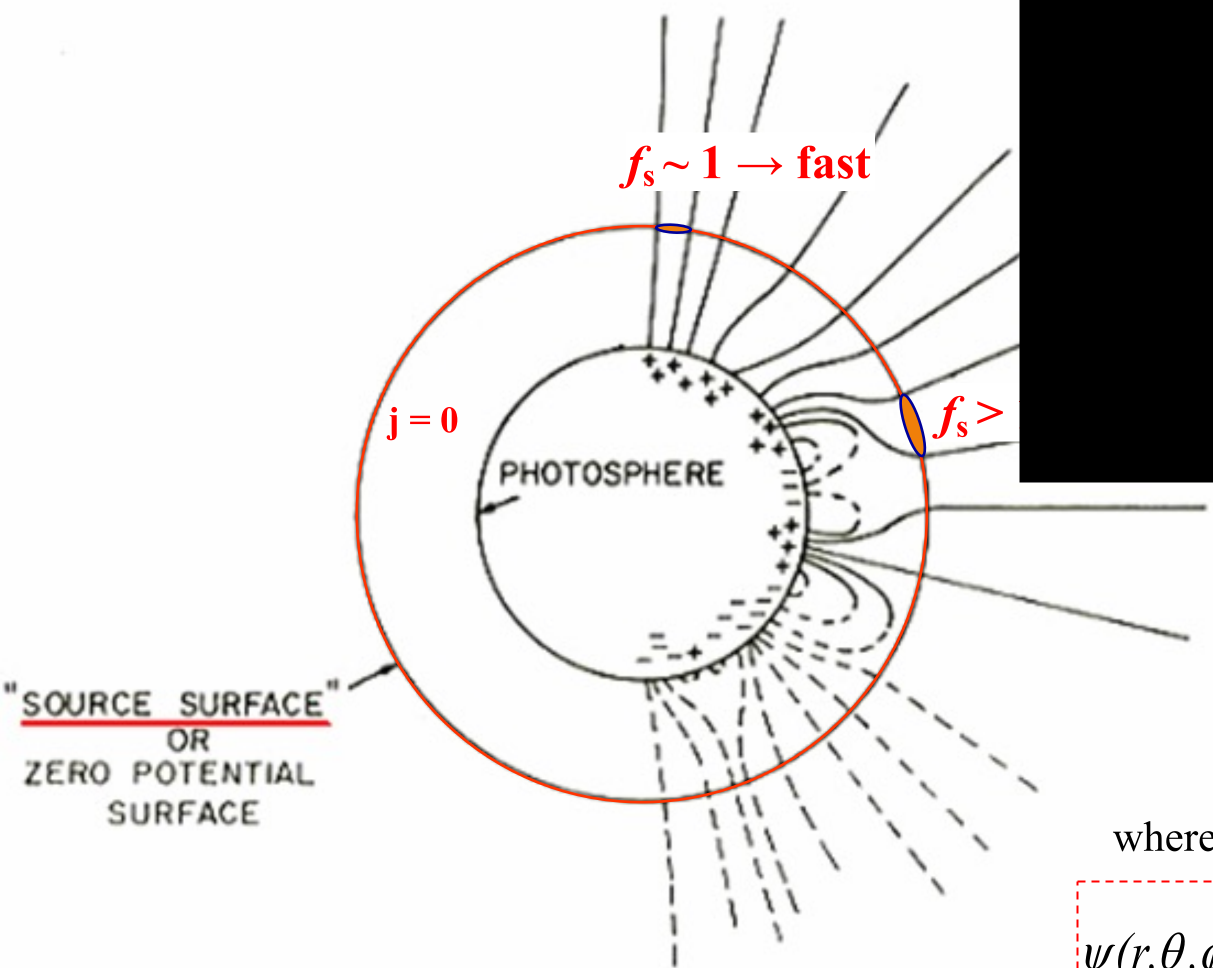
iii) Conclude: fast & slow solar wind originate from coronal holes.

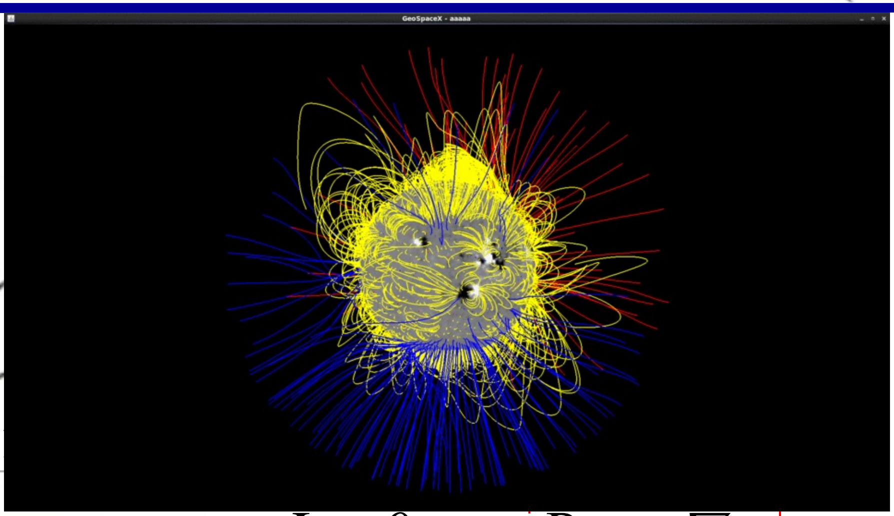
Fast wind ⟶ *central regions of coronal holes* ***(Small** f_s**)***

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,

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

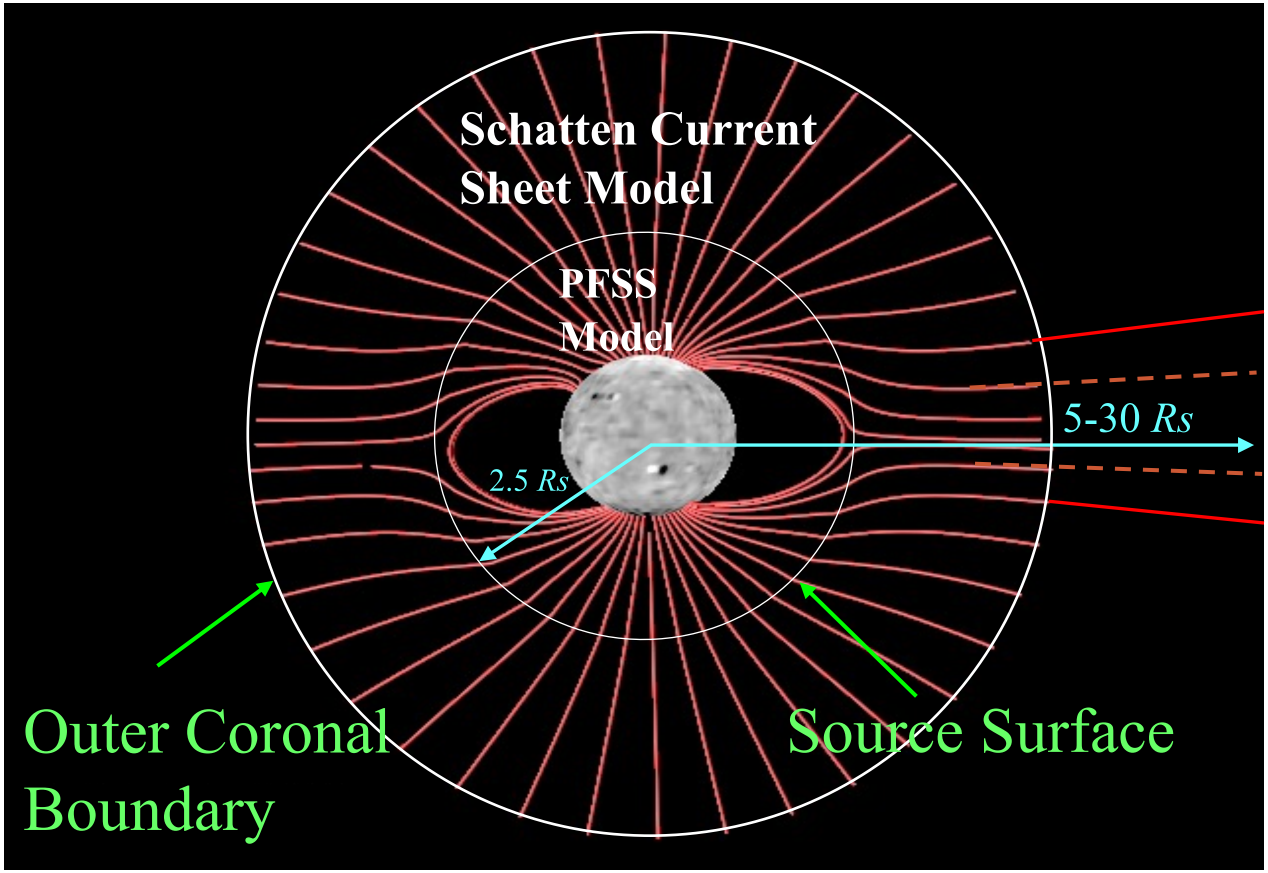
——— Outward Directed Field

- - - - - Inward Directed Field

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

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)

Driver to Solar Wind Models such as:

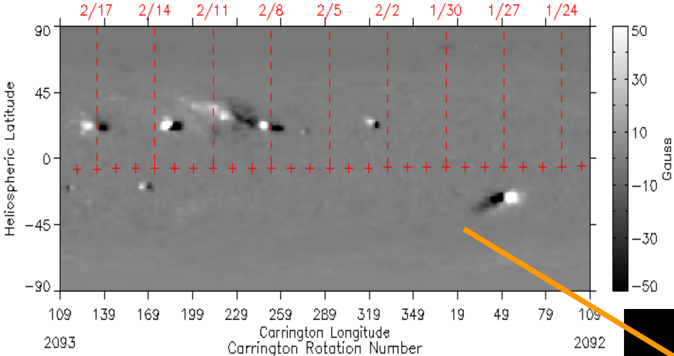
1) WSA 1D Kinematic
2) ENLIL
3) Gamera
4) MS-FLUKSS
5) EUHFORIA

(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.**

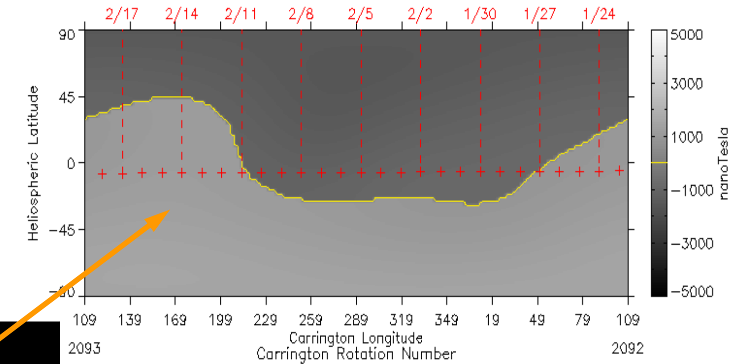
WSA Coronal Solution

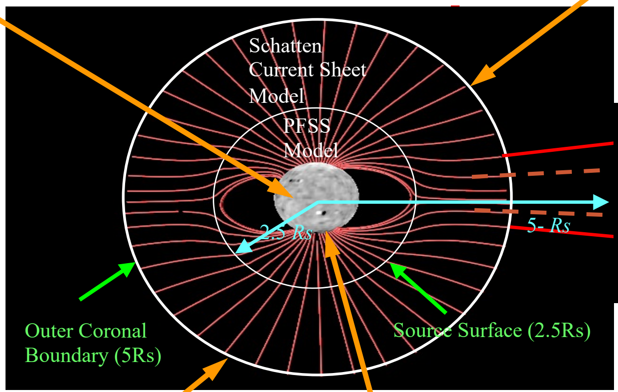
MODEL INPUT: Observed Photospheric Field



MODEL OUTPUT

Field at Outer Coronal Boundary (5.0 R_s)

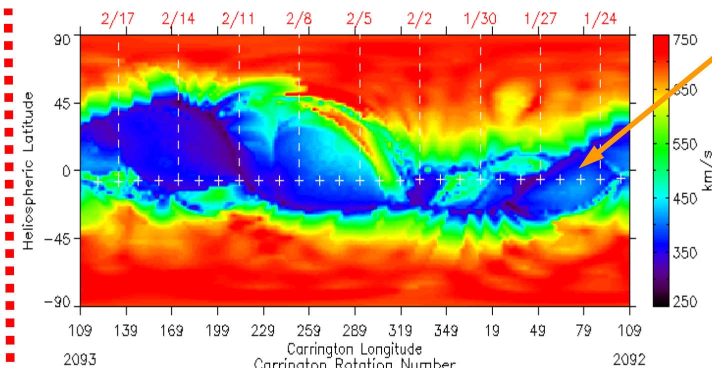




Solar Wind Model
(e.g., WSA 1D Kinematic model, Enlil, & LFM-Helio, MS-FLUKSS, & HAF)
(5-30*Rs* to 1AU)

MODEL OUTPUT

Predicted Solar Wind Speed (5.0 R_s)

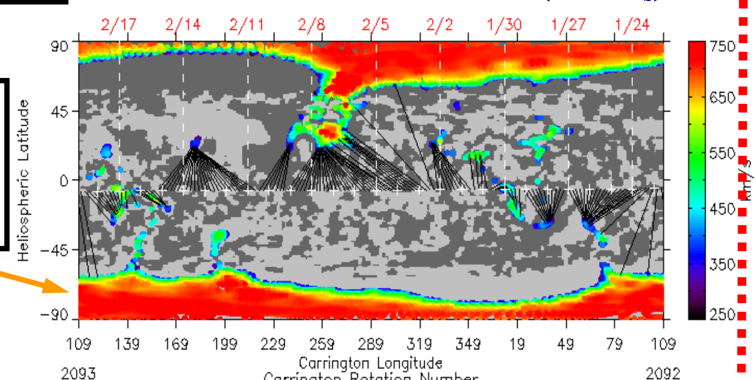


$$V_{\text{solar wind}} \sim f(f_s, \theta_b)$$

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

MODEL OUTPUT

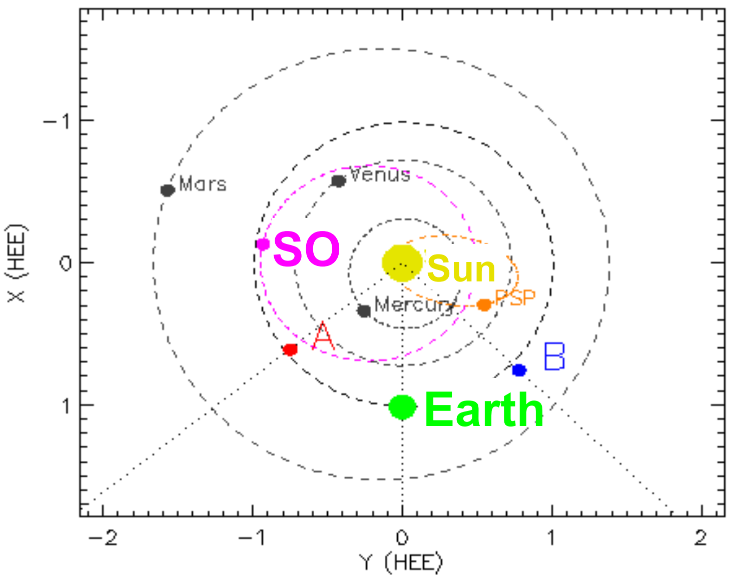
Derived Coronal Holes (1.0 R_s)



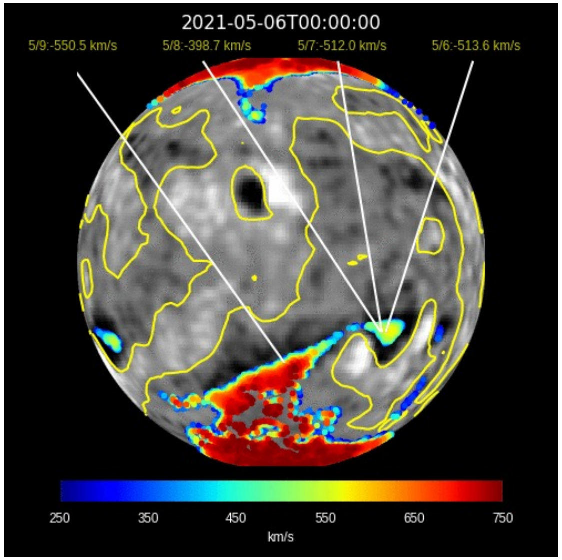
WSA Simulations for Solar Orbiter
May 2021

WSA Predictions at SolO May 2021

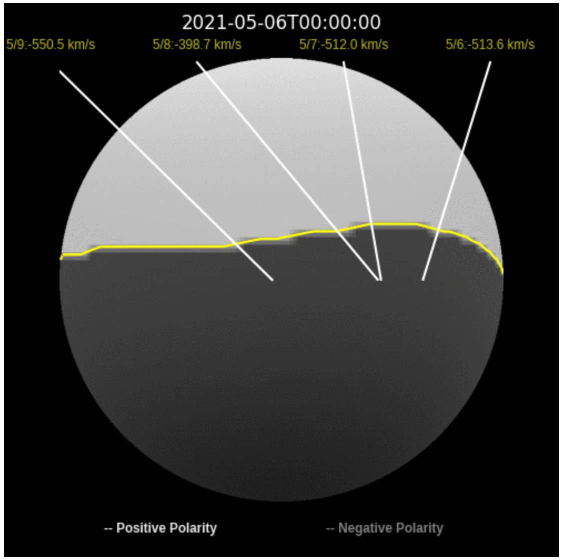
Satellite Locations May 2021



Predicted SW speed & IMF polarity at SolO + Coronal holes



Coronal Field at 5Rs + SW connectivity



Solar Orbiter needs predictions (several days in advance) of the s/c-Sun magnetic connectivity to support their remote sensing campaigns.

Empirical Relationships

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

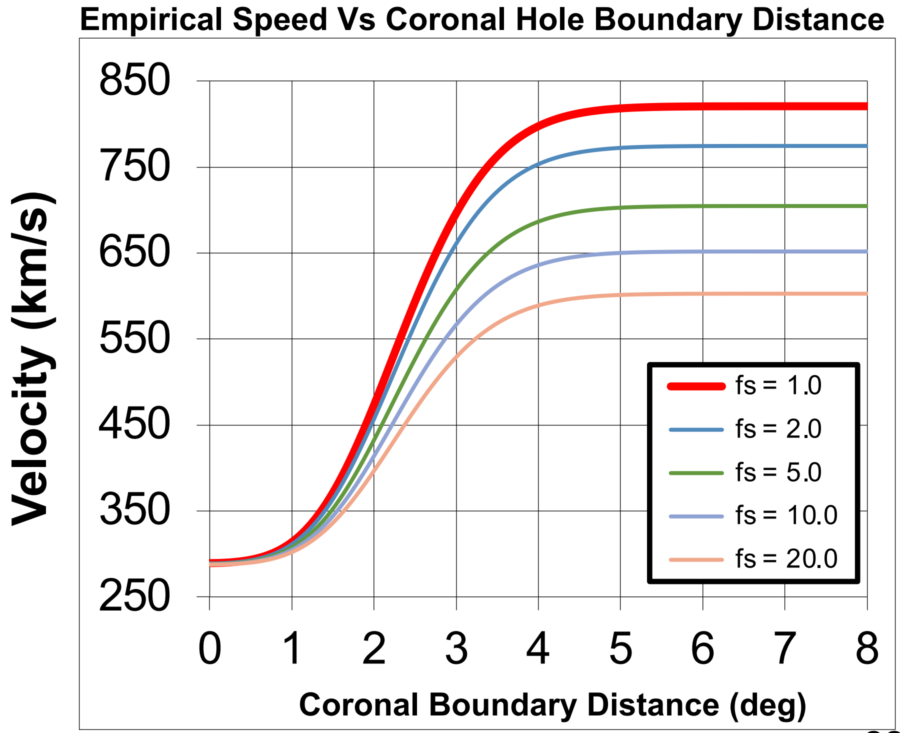
New:

$$V(f_s, \theta_b) = 285 + \frac{625}{(1+f_s)^{2/9}}\left\{1.0 - 0.8e^{-\left(\theta_b/2\right)^2}\right\}^3 \quad \text{km s}^{-1}$$

Where:

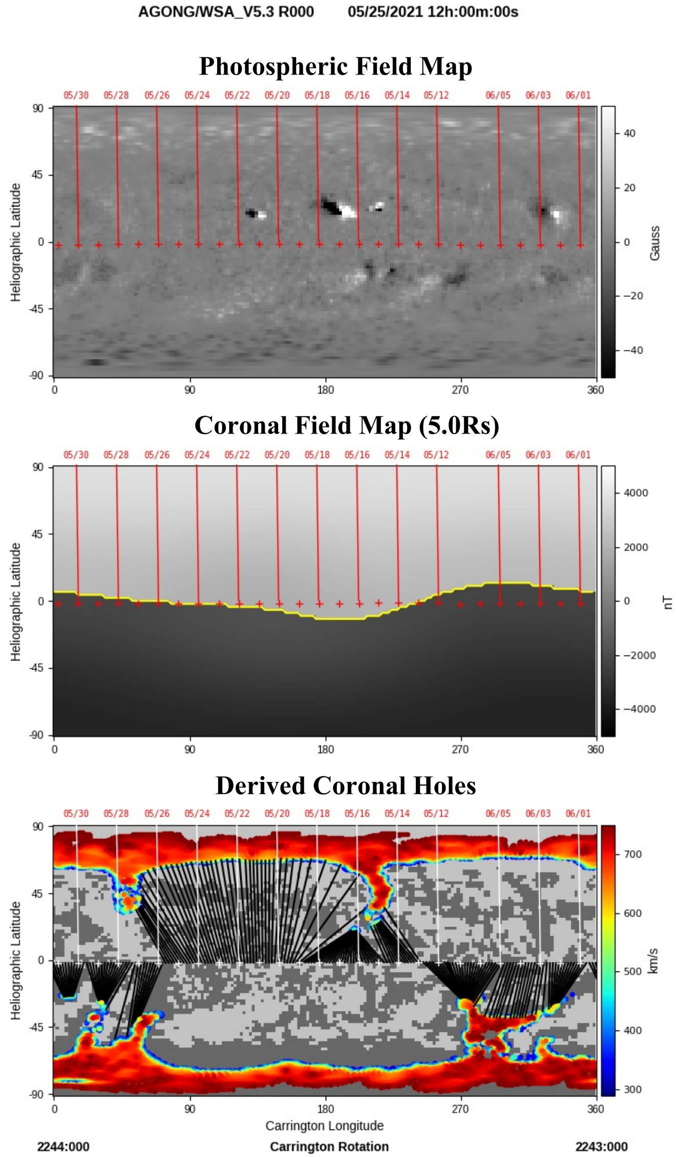
f_s = Magnetic field expansion factor.

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



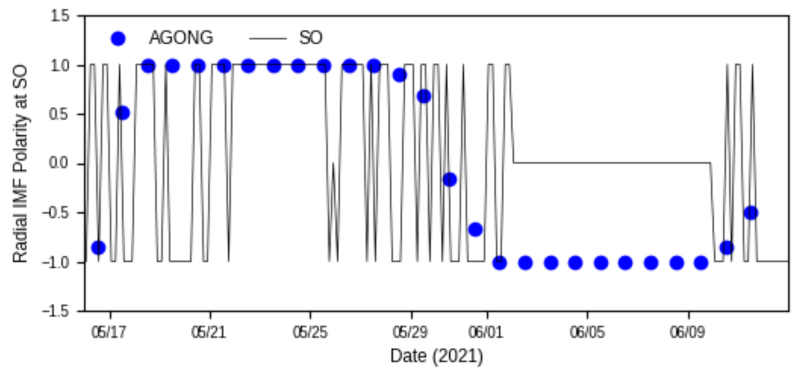
WSA Solar Wind Predictions at Solar Orbiter (May 2021)

WSA Coronal Solution & ADAPT Input Map



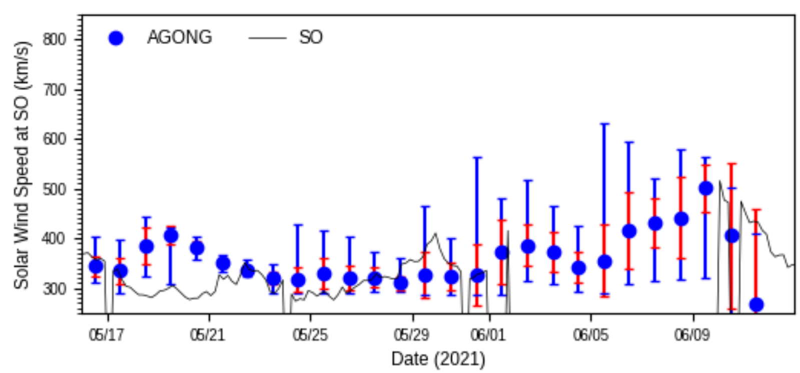
WSA Solar Wind Predictions at SolO

WSA IMF Polarity Predictions vs Obs.



Created 2021 September 28 1227 UTC

Predicted vs Obs. Solar Wind Speed



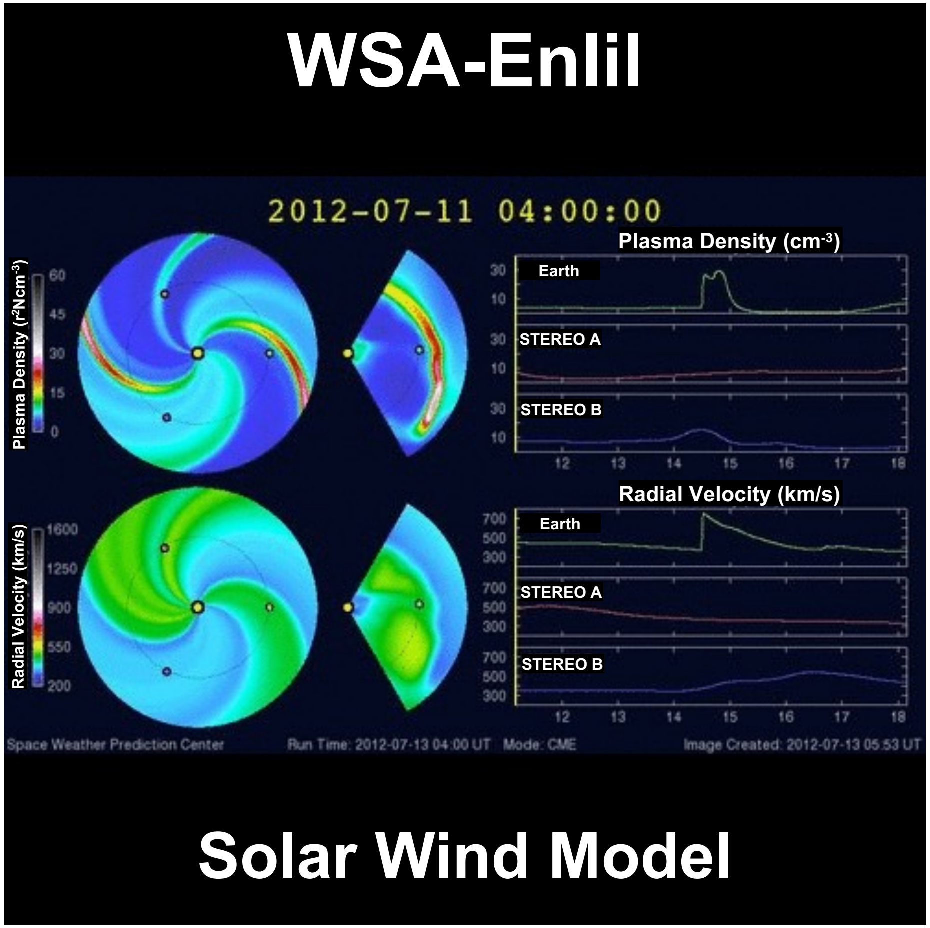
Created 2021 September 28 1227 UTC

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.
  - Upgrading from WSA 2.2 to 5.4
- Community effort requiring coordinated, long-term effort by AFRL, NOAA, & CISM.

CISM
CENTER FOR INTEGRATED SPACE WEATHER MODELING

- **Available for runs on demand at NASA/CCMC.**



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

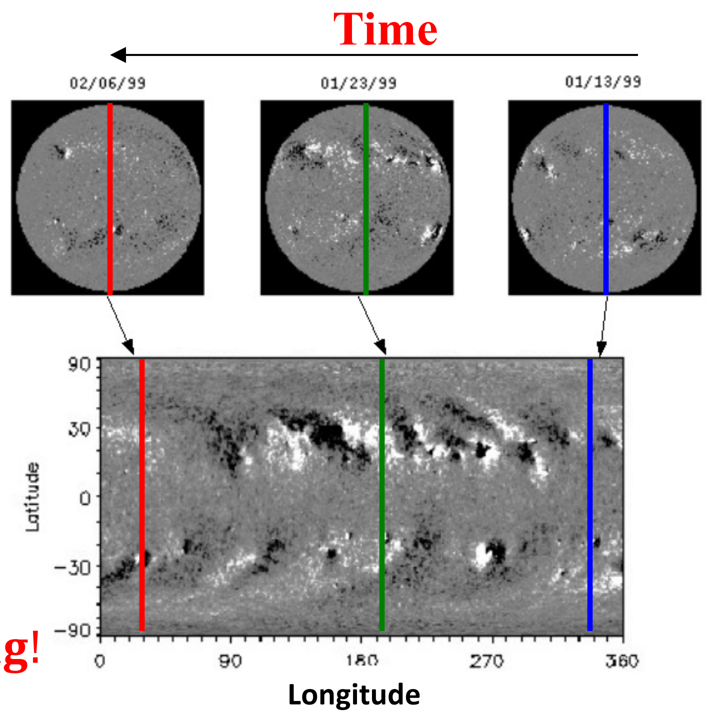
Pizzo et al., Space Weather, 2011

Difficulties, Uncertainties, and Challenges with Photospheric Magnetic Field Boundary Conditions

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

"Traditional" Carrington maps typically:

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



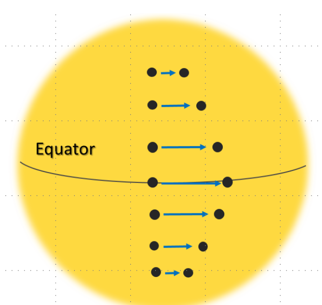
Carrington rotation 1 starts from November 9, 1853.

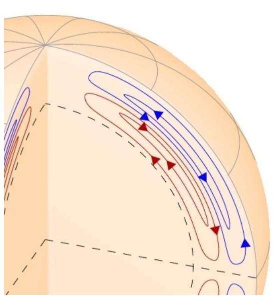
Do NOT account:

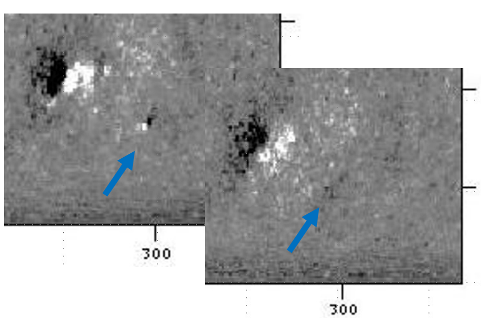
- **Differential rotation**
- **Meridional poleward flows**
- **Supergranulation diffusion**
- **Flux emergence**

Flux Transport Models take these into account!

Lack of 4π obs. make modeling challenging!

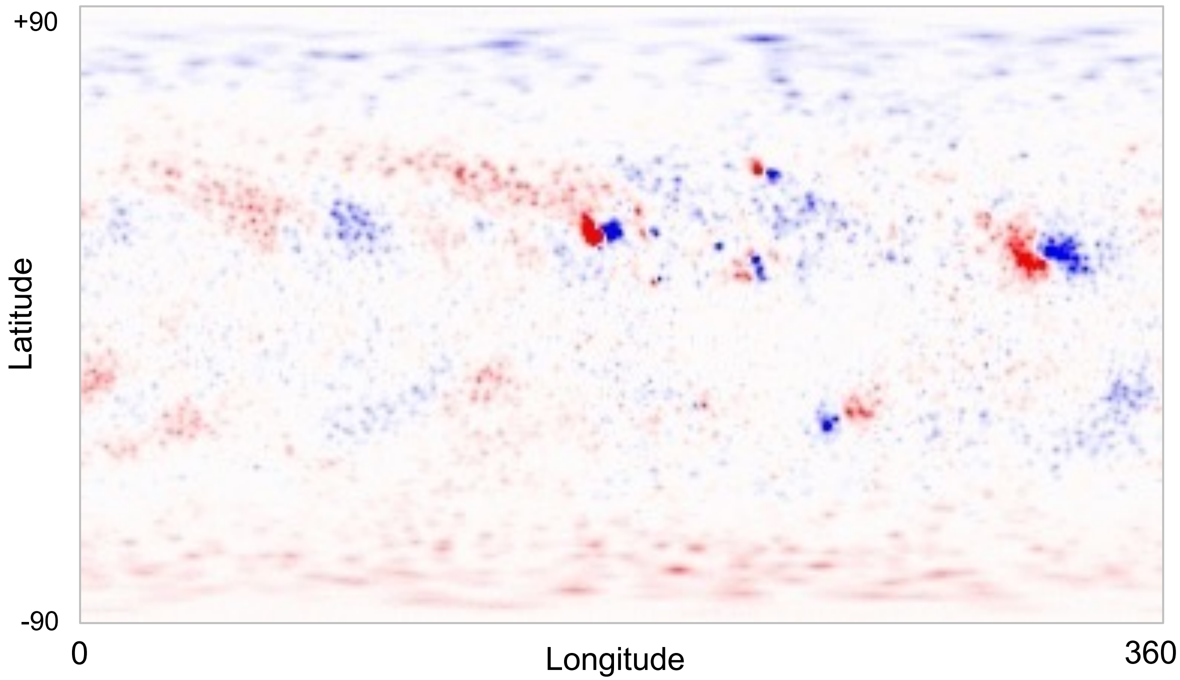






Air Force Data Assimilative Photospheric Flux Transport (ADAPT) Model

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.



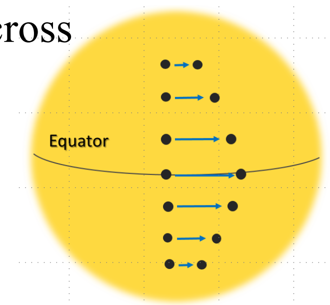
Sun's surface magnetic field (*movie length ~60 days*)

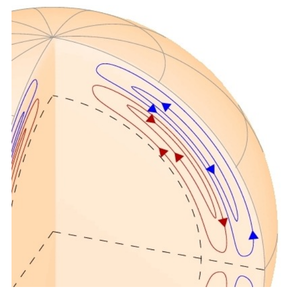
Provides more realistic estimates of the instantaneous global photospheric magnetic field distribution than those provided by traditional synoptic maps.

ADAPT Ensemble Model:Flux Transport & Data Assimilation

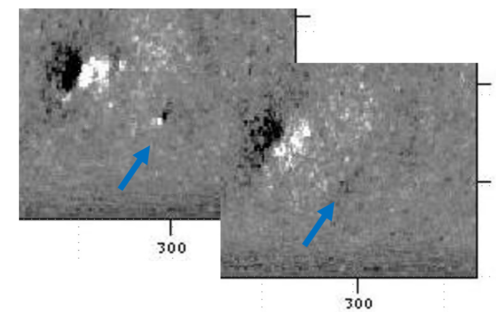
- **ADAPT Magnetic Flux Transport:** accounts for known surface flows across the surface of the sun:
  - **Differential rotation**
  - **Meridional poleward flows**
  - **Supergranulation diffusion**

  to align old data with observations.





Credit: Zhao et al. 2014

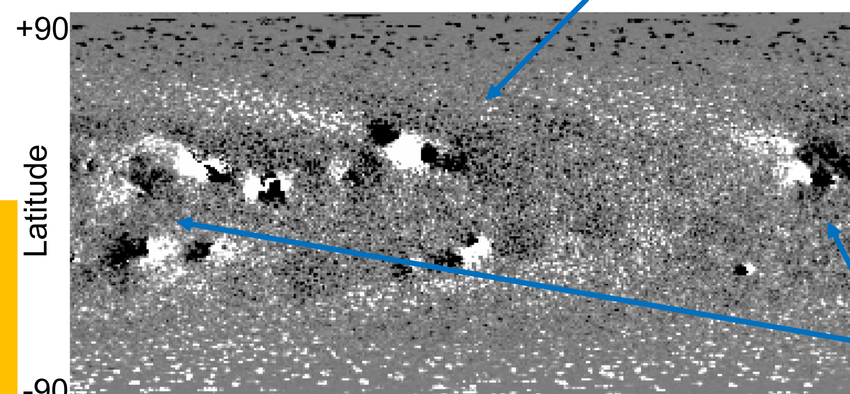


- **ADAPT Data Assimilation:**

  Assimilates observations using the **ensemble least-squares** estimation method, utilizing the variances of the model forecast ensemble & observed data.

- **ADAPT is an Ensemble Model**
  Ideally, the ensemble realistically represents the spread in possible global photospheric magnetic field states.

Movie of 12 ADAPT model realizations representing the transport uncertainty for given instant in time



New Data (earth-side)

ADAPT global map ensemble example

For more information regarding ADAPT data assimilation see:
Hickmann, Godinez, Henney, Arge 2015, Solar Physics, 209, 1105

Observational Issues, Problems, & Impacts Resulting From the Lack of Global Solar Magnetic Field Observations

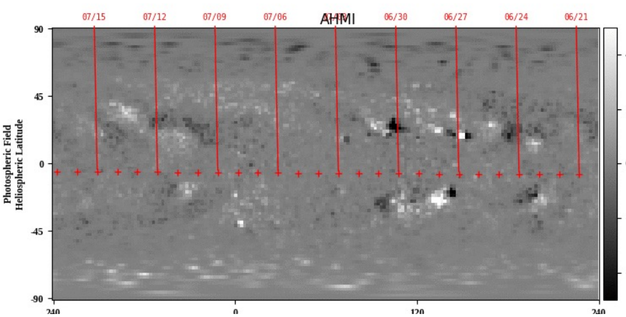
Observational Issue	Problems	Impact
Missing solar far-side magnetic field measurements	Active Regions (AR) on solar far-side not included or partially included in photospheric magnetic field maps	• ARs affect global magnetic field configuration • Partial incorporation of ARs at limb produce nonphysical magnetic monopoles and time-dependent effects in coronal/SW models
Large uncertainties in magnetic field measurements near limb	Unreliable polar magnetic field estimates	• Coronal/Solar Wind model solutions highly sensitive to polar fields • Monopole moments introduced into maps

Quantifying Coronal & Solar Wind Model Uncertainty

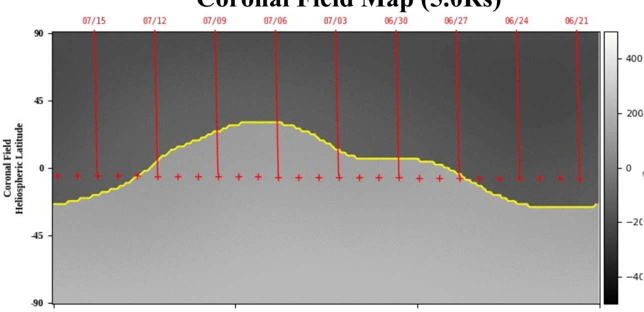
Predictions at STEREO B With & Without Far-Side Included)

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

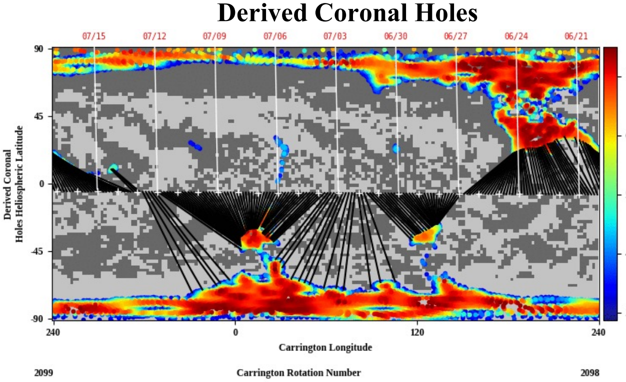
Photospheric Field Map

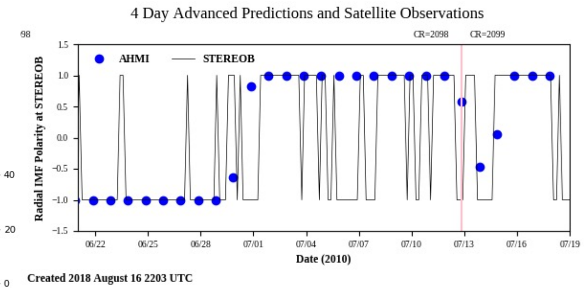


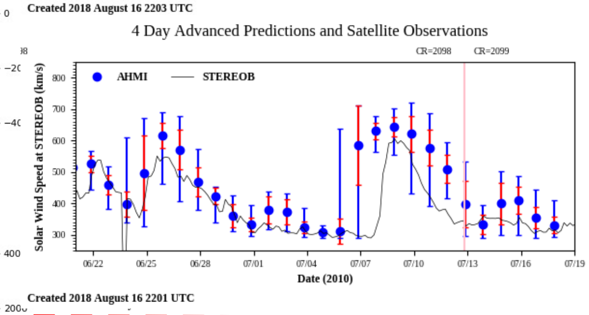
Coronal Field Map (5.0Rs)

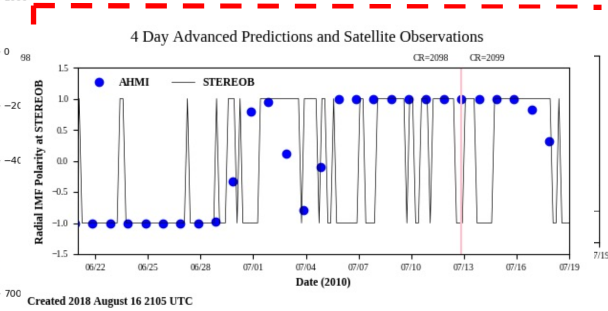


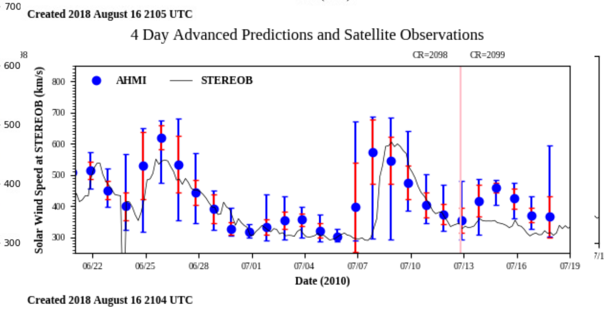
Derived Coronal Holes





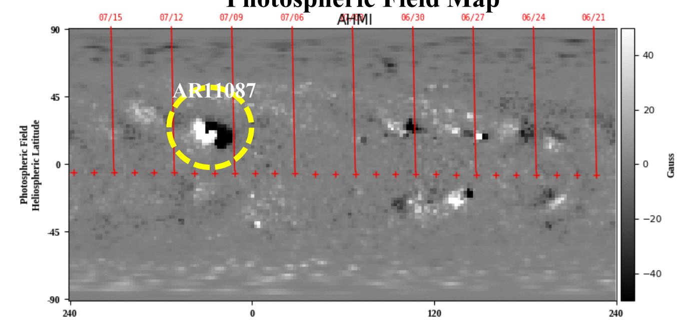




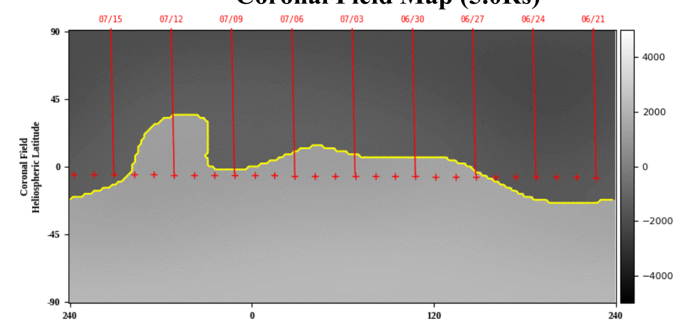


STEREO B Coronal & Solar Wind Predictions *with* Active Region

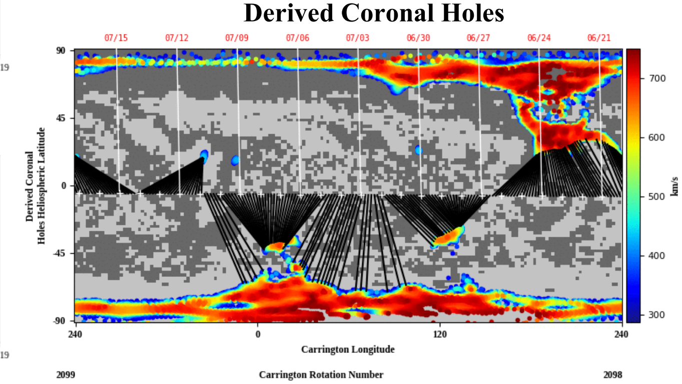
Photospheric Field Map



Coronal Field Map (5.0Rs)

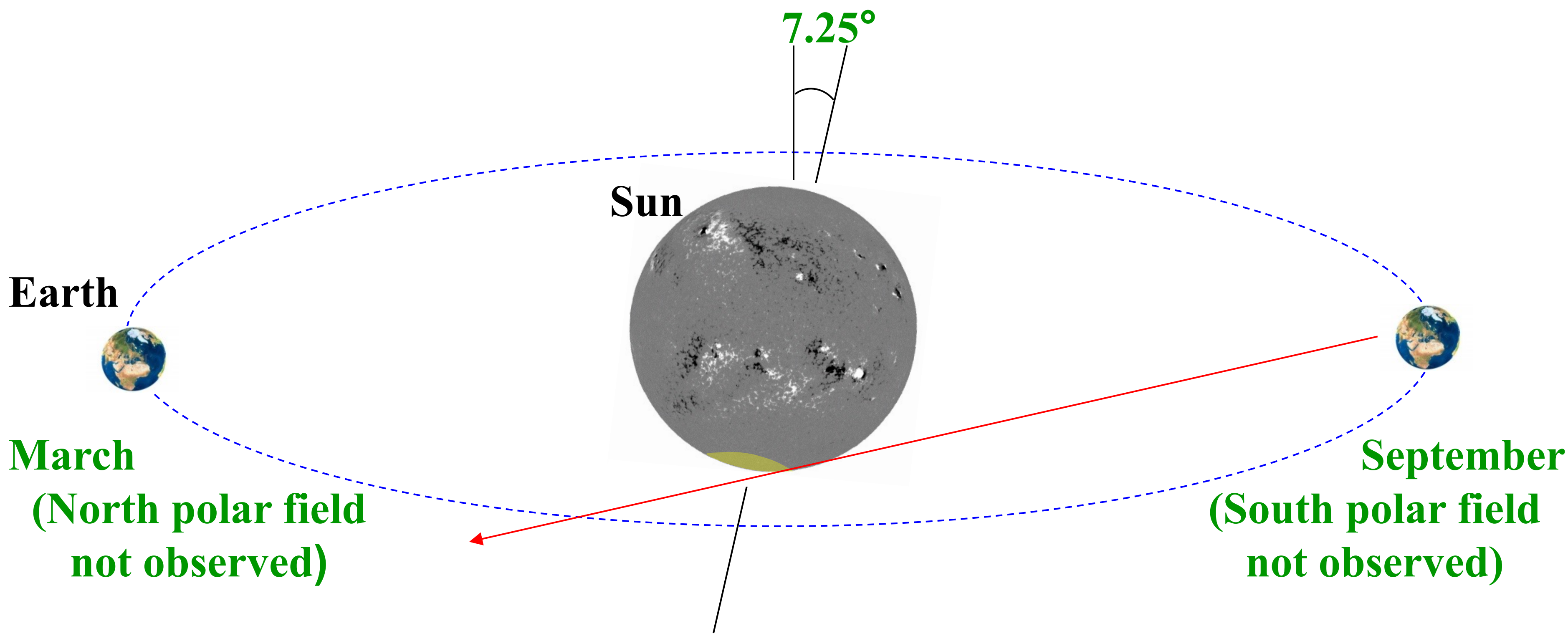


Derived Coronal Holes



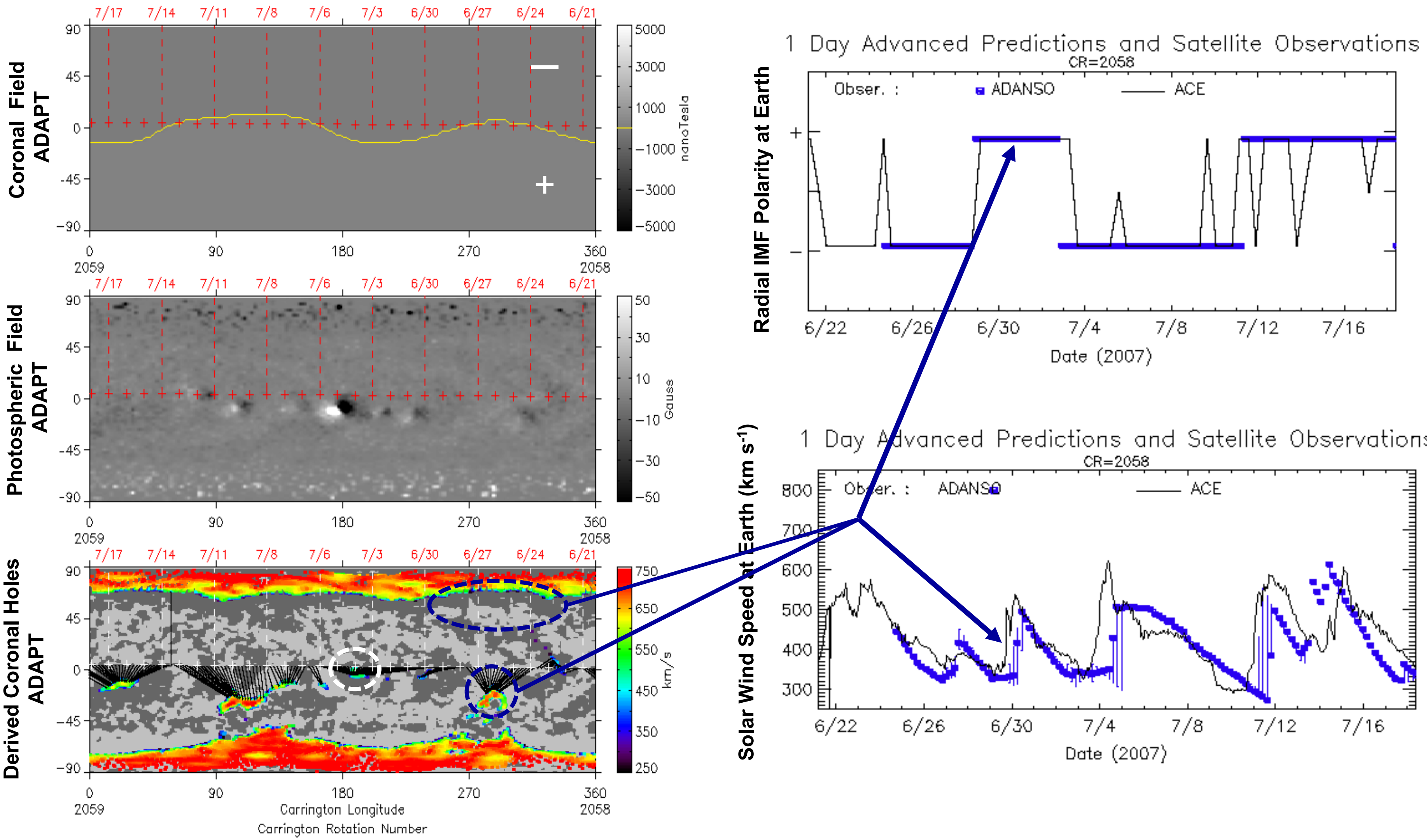
The Inclination of the Sun's Axis to the Ecliptic Impacts Measurements of the Photospheric Field

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.)

Impact of *Polar Fields* on WSA Coronal & Solar Wind Solutions
12 ADAPT Realizations for June 21, 2007 (Start of CR2058)



Ranking Magnetic Field Input Driver Maps & WSA Predictive Performance

Developed a methodology for *objectively* ranking WSA model predictions when using an *ensemble* of photospheric magnetic field input maps.

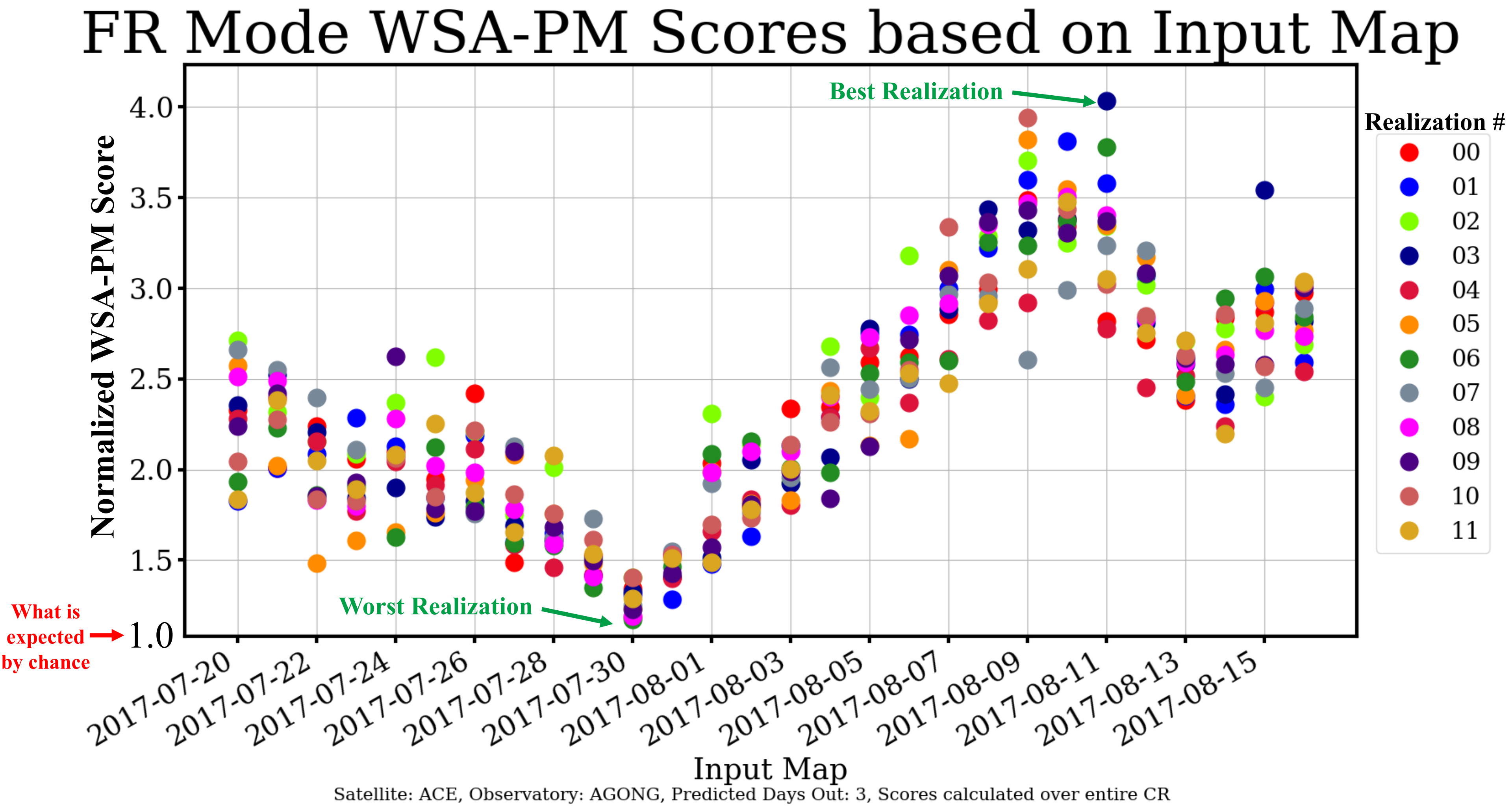
WSA Predictive Metric (WSA-PM):

$$\textit{WSA-PM} = \frac{\textit{Fractional Correct IMF Polarity}}{\textit{RMS Velocity Residual}}$$

Worst		Best
0	⟷	∞

- ***Combines IMF & velocity* predictive performance into *one metric***
- **Provides a quick way to determined the best model input driver maps.**

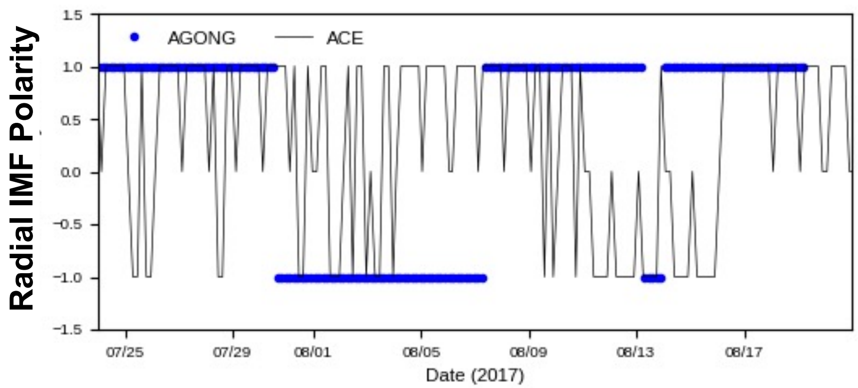
Normalized WSA-PM Scores Based on Input Map



Comparing WSA Solar Wind Predictions Using *Best* vs *Worst* Input Maps

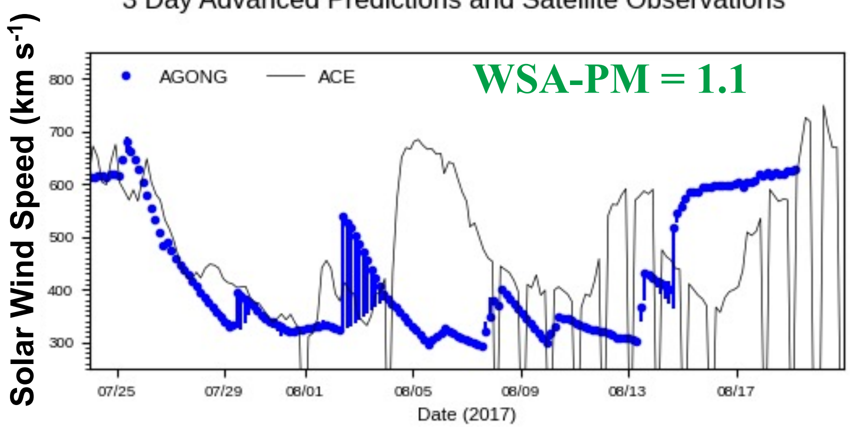
Worst ADAPT Map
(July 30 ADAPT Input Map)

3 Day Advanced Predictions and Satellite Observations



Created 2023 January 3 1800 UTC

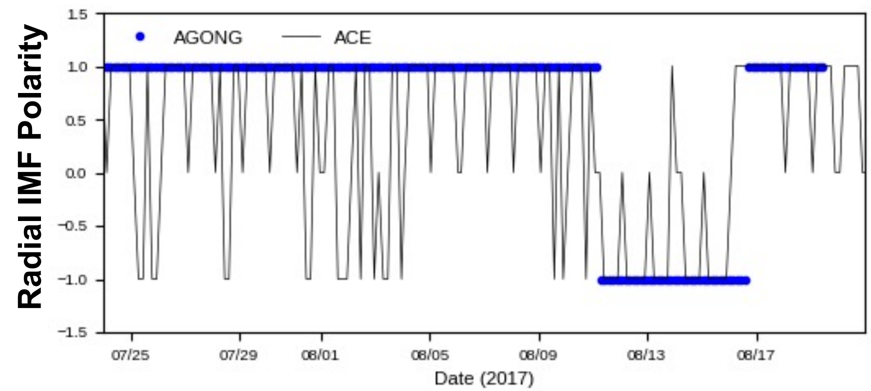
3 Day Advanced Predictions and Satellite Observations



Created 2023 January 3 1800 UTC

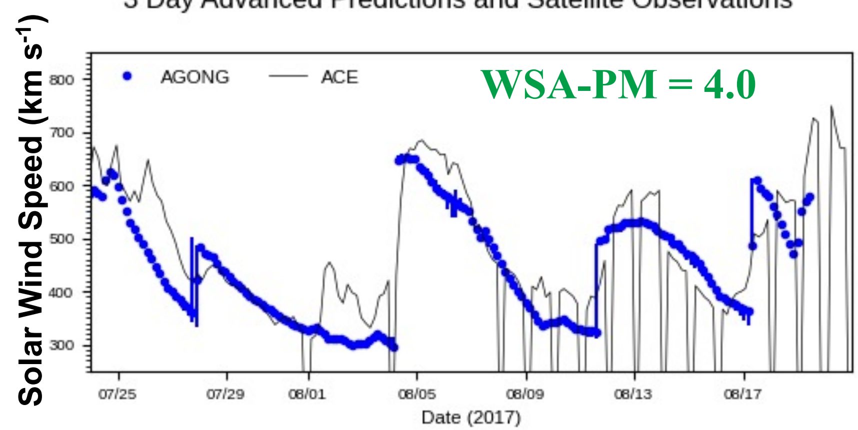
Best ADAPT Map
(Aug. 11 ADAPT Input Map)

3 Day Advanced Predictions and Satellite Observations



d 2023 January 3 1844 UTC

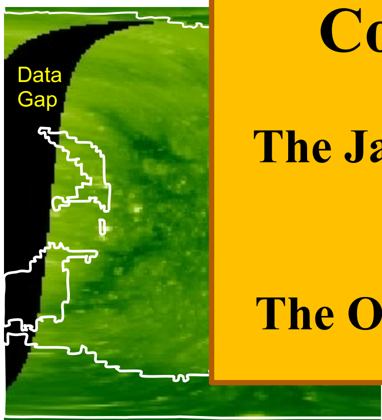
3 Day Advanced Predictions and Satellite Observations



d 2023 January 3 1845 UTC

Uncertainty Quantification Allows Models to be Constrained More Effectively

Traditional EUV CH Map vs Model



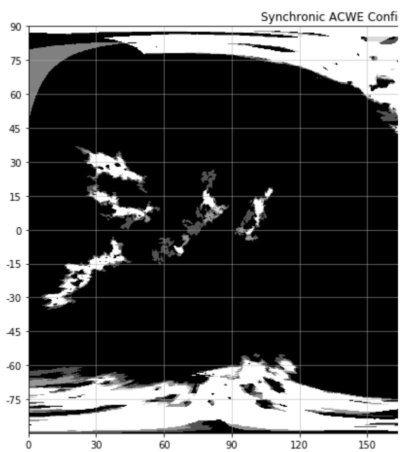
Ensemble of Model Solutions

Compare Obs. vs Model Quantitatively

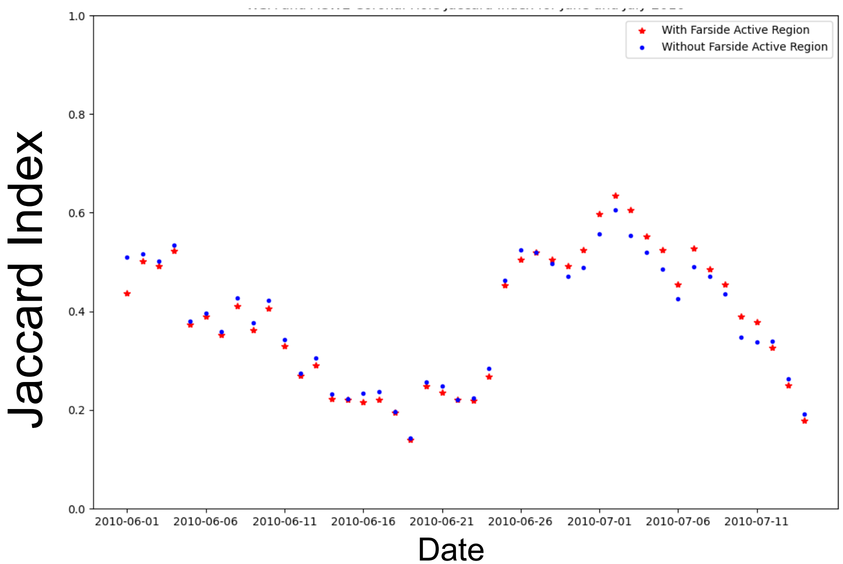
The Jaccard Similarity Metric: $$js(A,B) = \frac{|A \cap B|}{|A \cup B|}$$

The Overlap Coefficient Metric: $$oc(A,B) = \frac{|A \cap B|}{min(|A|,|B|)}$$

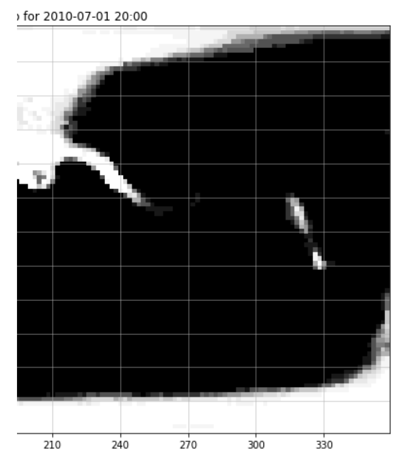
Obs. Coronal H[...]



WSA & ACWE Coronal Hole Jaccard Index for June & July 2020



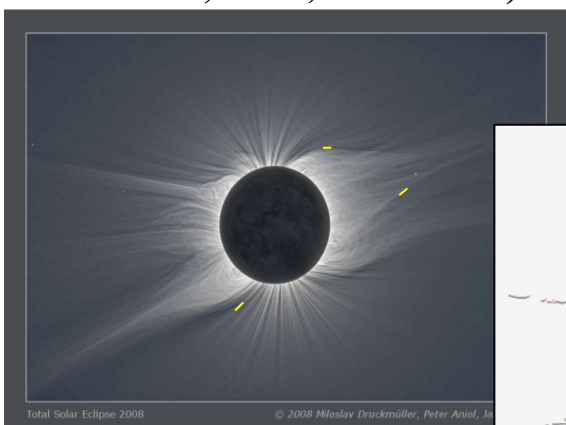
[...]s /w Uncertainties



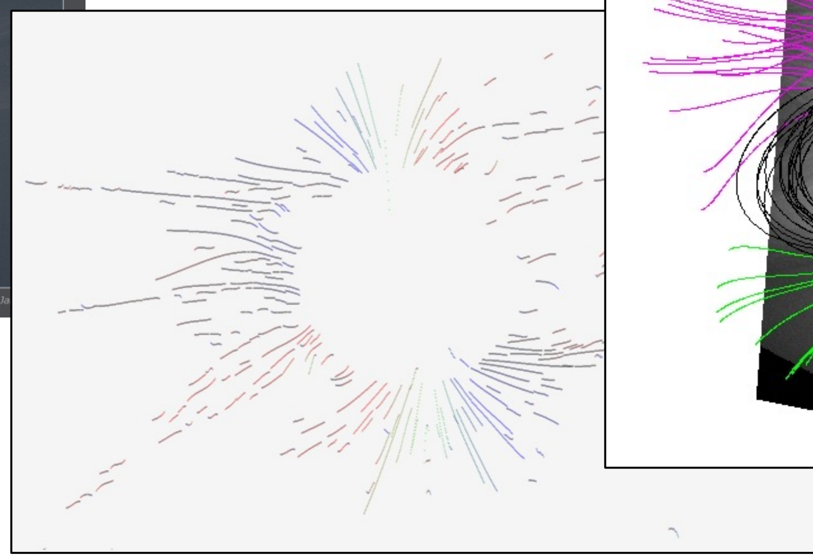
Leisner & Zhang (GMU) Boucheron & Grajeda (NMSU)

Using Coronal Images to Validate Coronal Models

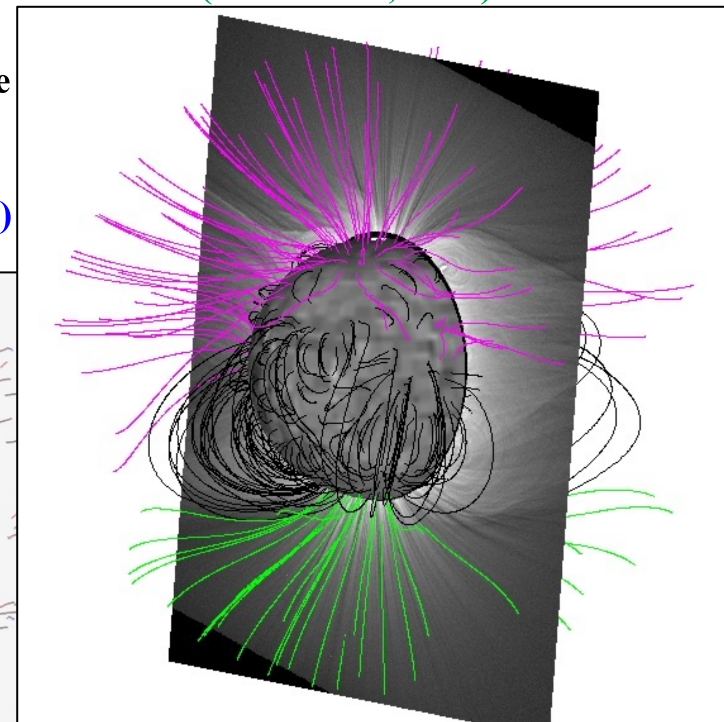
01 Aug 2008 Total Solar Eclipse Observation (Druckmüller, Aniol, & Sládeček)



Vadim Uritsky's automated line segmentation *QRaFT code* (See Jones et al. 2020 Uritsky full publication in prep)



Model Compared to Line Segments (Jones et al., 2017)

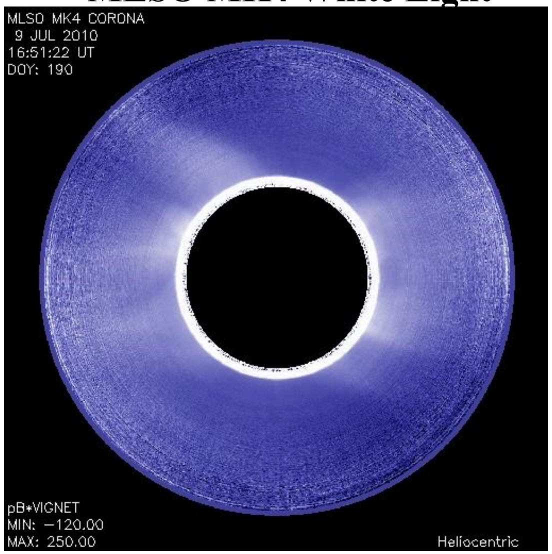


Quantitatively compare observationally derived coronal structures (e.g., field lines, streamers, etc.) with model derived structures.

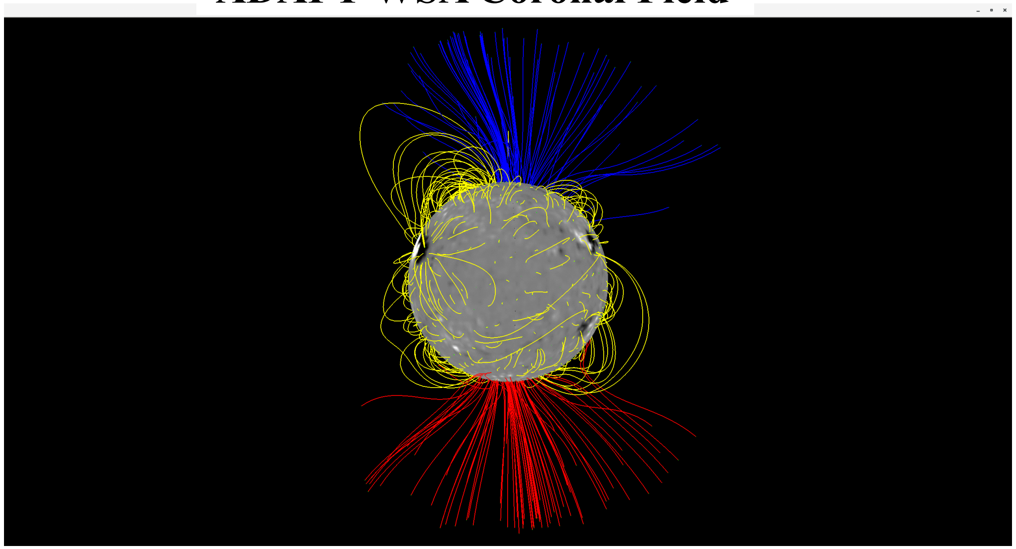
Chris Rura and Vadim Uritsky (CUA) have validated QRaFT using MAS and FORWARD codes

Comparing ADAPT-WSA Corona Magnetic Field Solutions with Observations

MLSO MK4 White Light



ADAPT-WSA Coronal Field

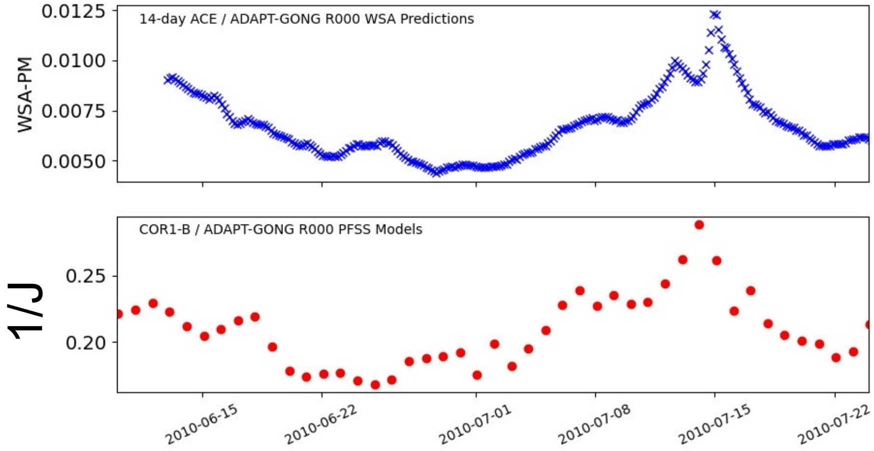


Discrepancy between orientation of features seen in images $\{\theta_o\}$ and magnetic field model $\{\theta_m\}$:

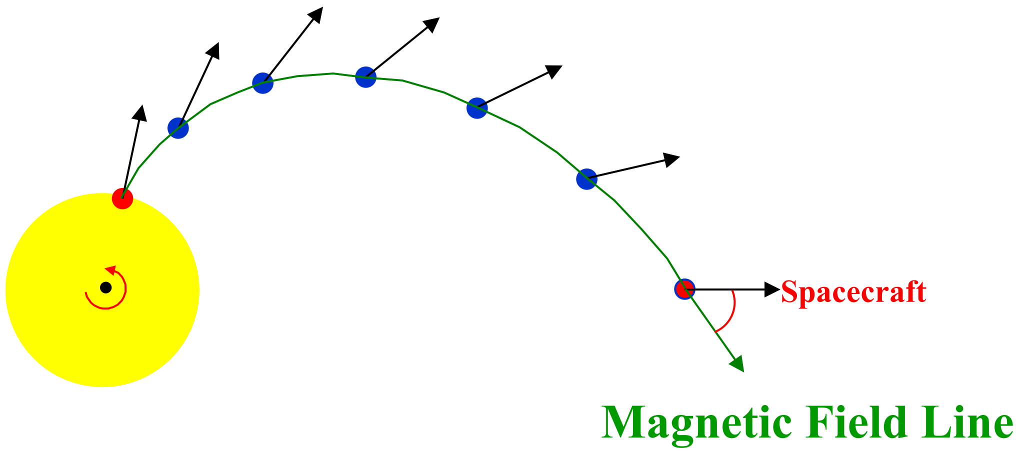
$$J = \beta \sum_{k=1}^{N} |\theta_{o,k} - \theta_{m,k}|^d$$

- **Assumes obs. features lie in the image plane**
- **Assumes constraints are equally valid**
- **Decreases with better model quality**

For more details see Jones et al. (2017 and 2020)

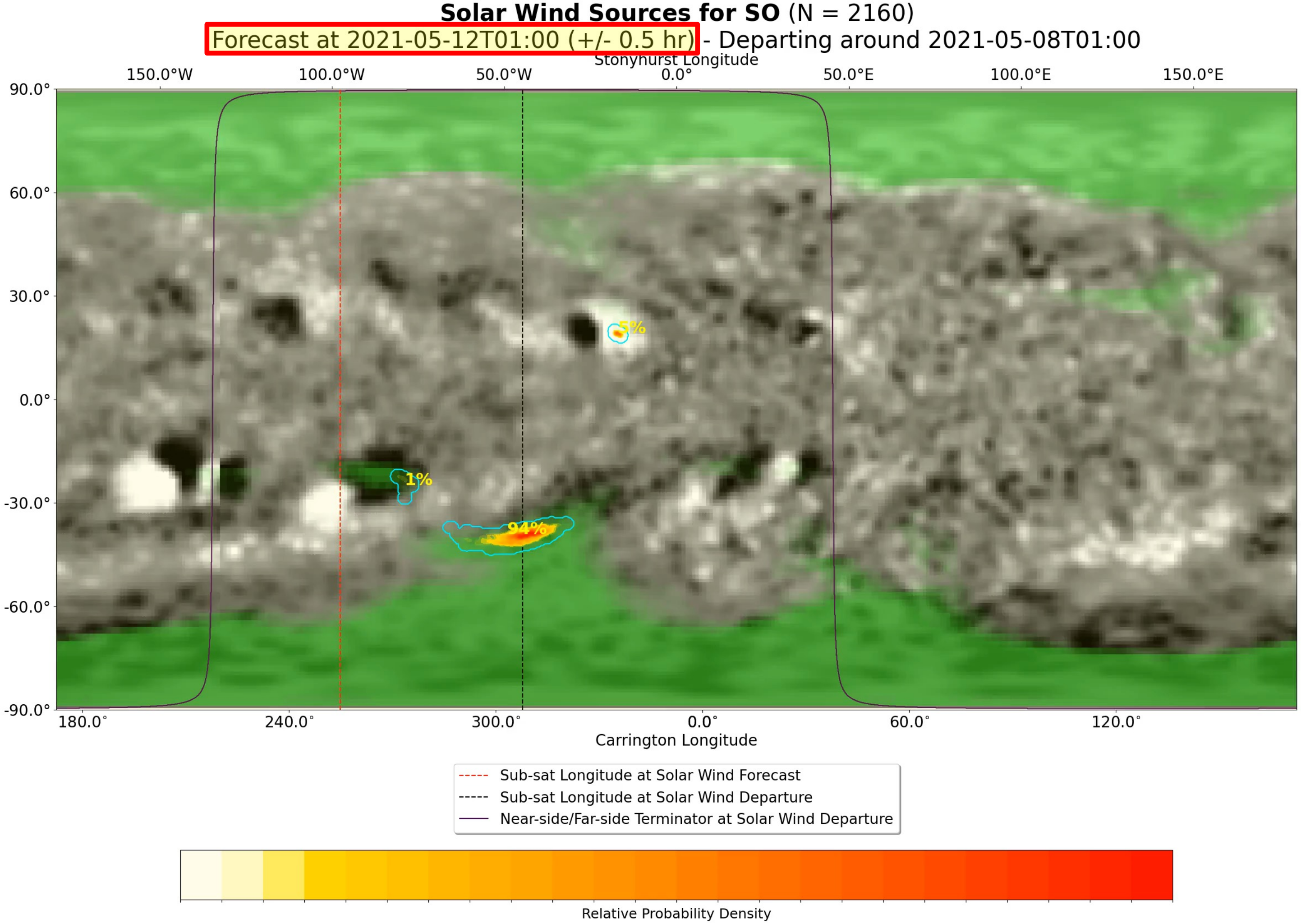


The Solar Wind and the Interplanetary Magnetic Field (Formation of the Parker Spiral)



Forecasting the Solar Wind Connectivity for Solar Orbiter

4-Day Advanced Forecasts



Summary

Modeling the corona and solar wind is very challenging!

Most coronal & solar wind models are highly dependent on photospheric magnetic field observations

- ***Photospheric magnetic field maps are highly uncertain!***
- ***Use ensemble of photospheric magnetic field maps to help represent model uncertainly.***
- ***Determining realistic ensemble is difficult!***

Discussed multiple methods for quantitatively constraining & validating coronal and solar wind models

- **In situ spacecraft observations - multipoint comparison is better.**
- **Coronal holes.**
- **Coronal structure/topology.**

Knowing BOTH model and observational uncertainties critical to constraining models well.