

MHD MODELING FOR HMI

ZORAN MIKIĆ
JON A. LINKER

SCIENCE APPLICATIONS INTL. CORP.
SAN DIEGO



Presented at the HMI Team Meeting
Stanford University, Palo Alto, May 1–2, 2003

USEFULNESS OF MHD MODELS

- A global evolving solar wind model will be very useful for providing contextual information for HMI observations (e.g., source regions, location and geometry of CIRs and solar wind streams, magnetic field polarity, magnetic field topology in CMEs)
- The coronal + heliospheric model is useful in particular for connecting *in situ* measurements with solar source regions and coronal phenomena
- The heliospheric model is useful for tracking CME propagation through the interplanetary medium
- New opportunity: coronal models including vector field measurements

MHD EQUATIONS (POLYTROPIC MODEL)

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \frac{1}{c} \mathbf{J} \times \mathbf{B} - \nabla p + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}) = -(\gamma - 1)p \nabla \cdot \mathbf{v}$$

$\gamma = 1.05$ for coronal solution;

$\gamma = 1.5$ for heliospheric solution

MHD EQUATIONS (IMPROVED ENERGY EQUATION MODEL)

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \frac{1}{c} \mathbf{J} \times \mathbf{B} - \nabla p - \nabla p_w + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}) = (\gamma - 1) \left(-p \nabla \cdot \mathbf{v} - \nabla \cdot \mathbf{q} - n_e n_p Q(T) + H \right)$$

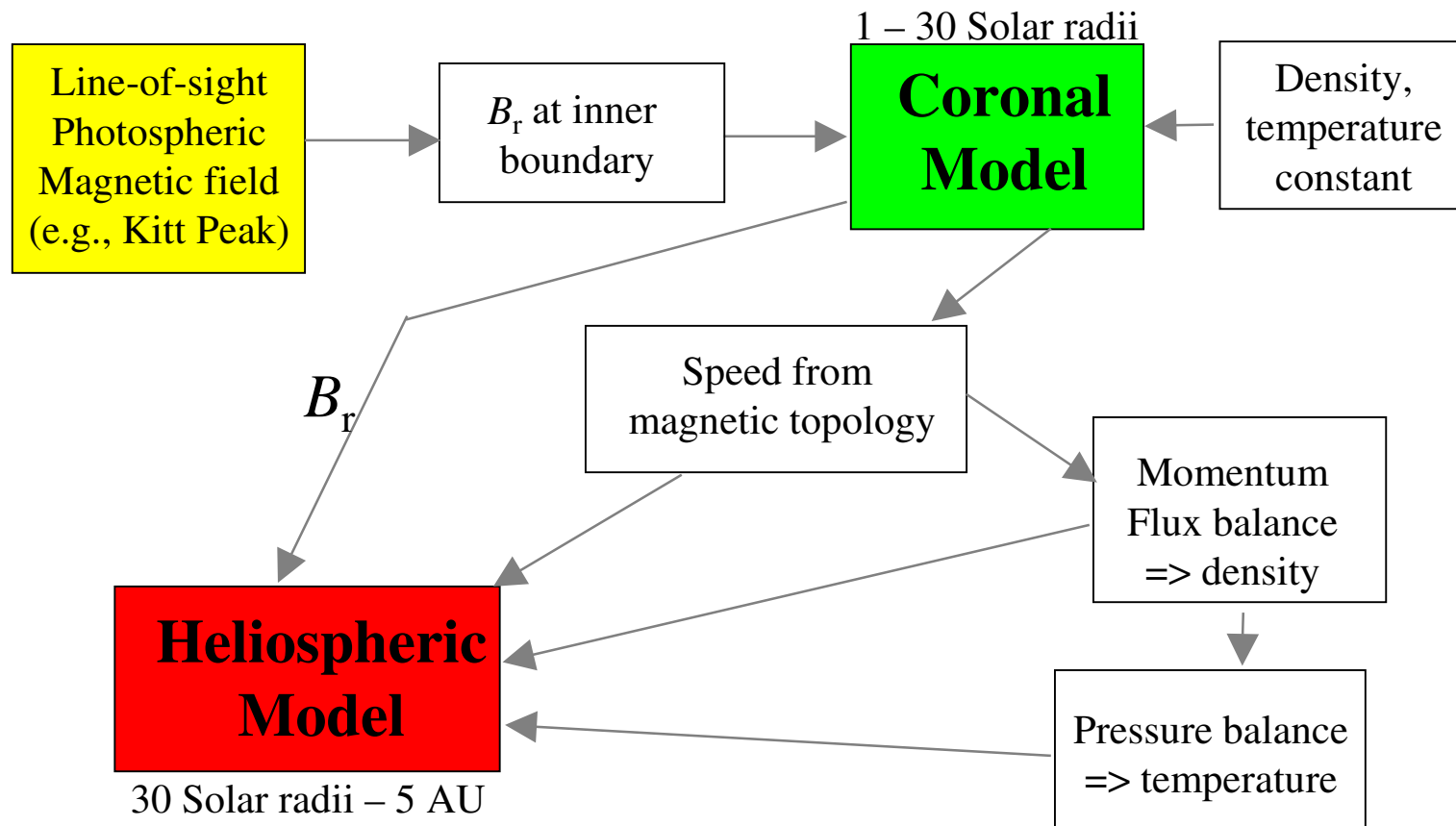
$$\gamma = 5/3$$

$$\mathbf{q} = -\kappa_{\parallel} \hat{\mathbf{b}} \hat{\mathbf{b}} \cdot \nabla T \quad (\text{Close to the Sun, } r \lesssim 10R_S)$$

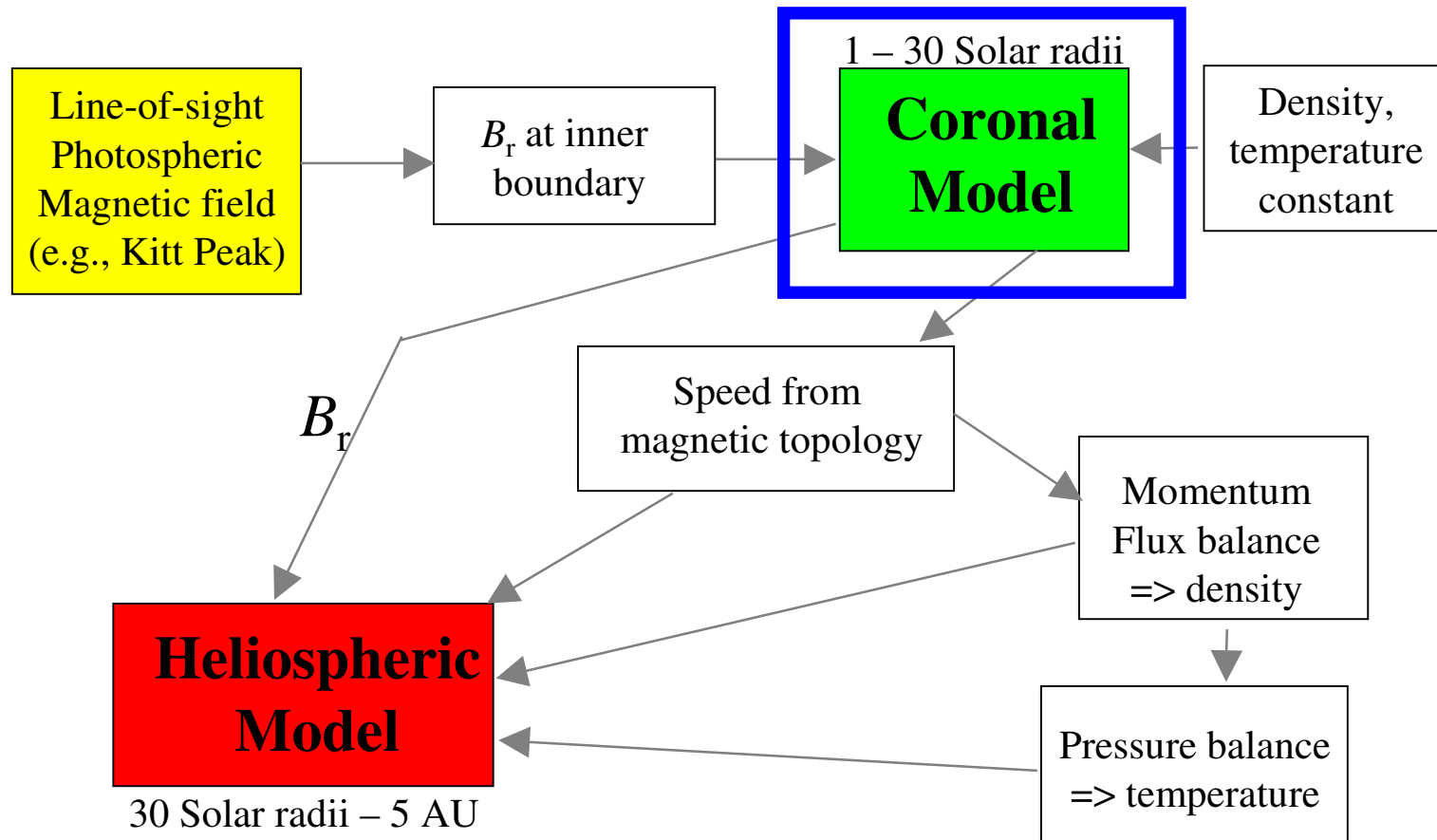
$$\mathbf{q} = 2\alpha n_e T \hat{\mathbf{b}} \hat{\mathbf{b}} \cdot \mathbf{v} / (\gamma - 1) \quad (\text{Far from the Sun, } r \gtrsim 10R_S)$$

+ WKB equations for Alfvén wave pressure p_w evolution

MHD Model of the Corona and Inner Heliosphere: Overview



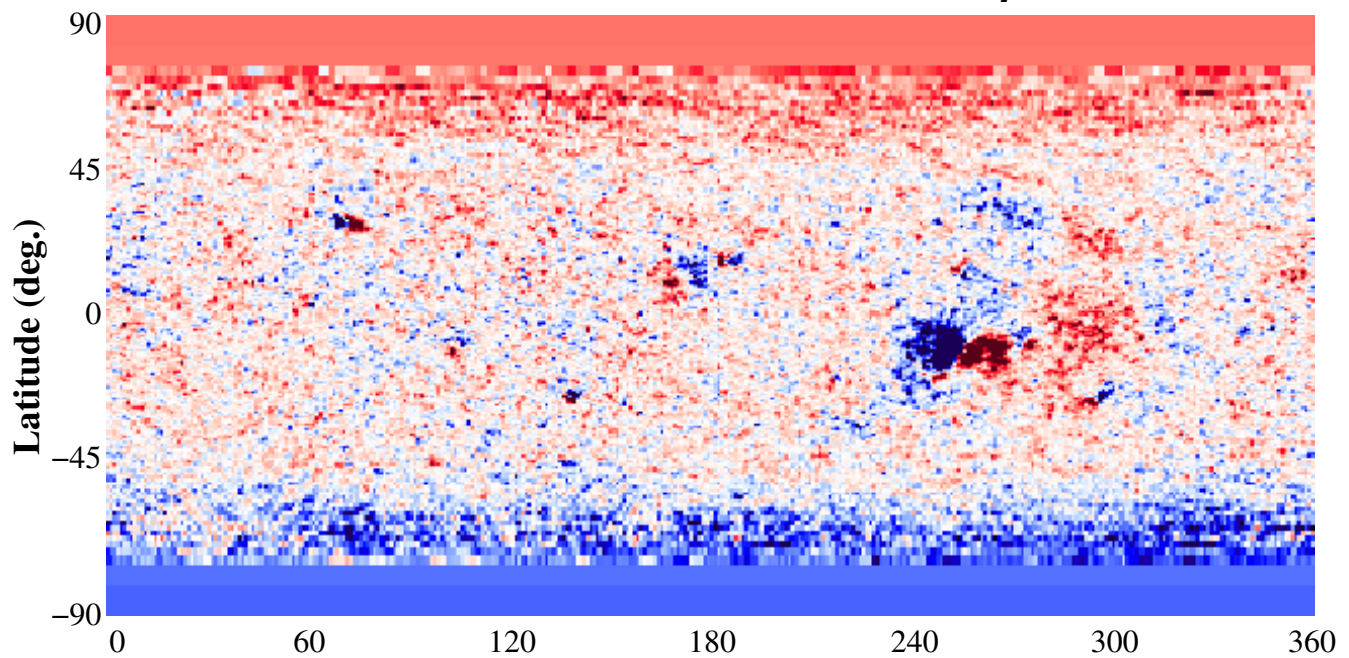
MHD Model of the Corona and Inner Heliosphere: Overview



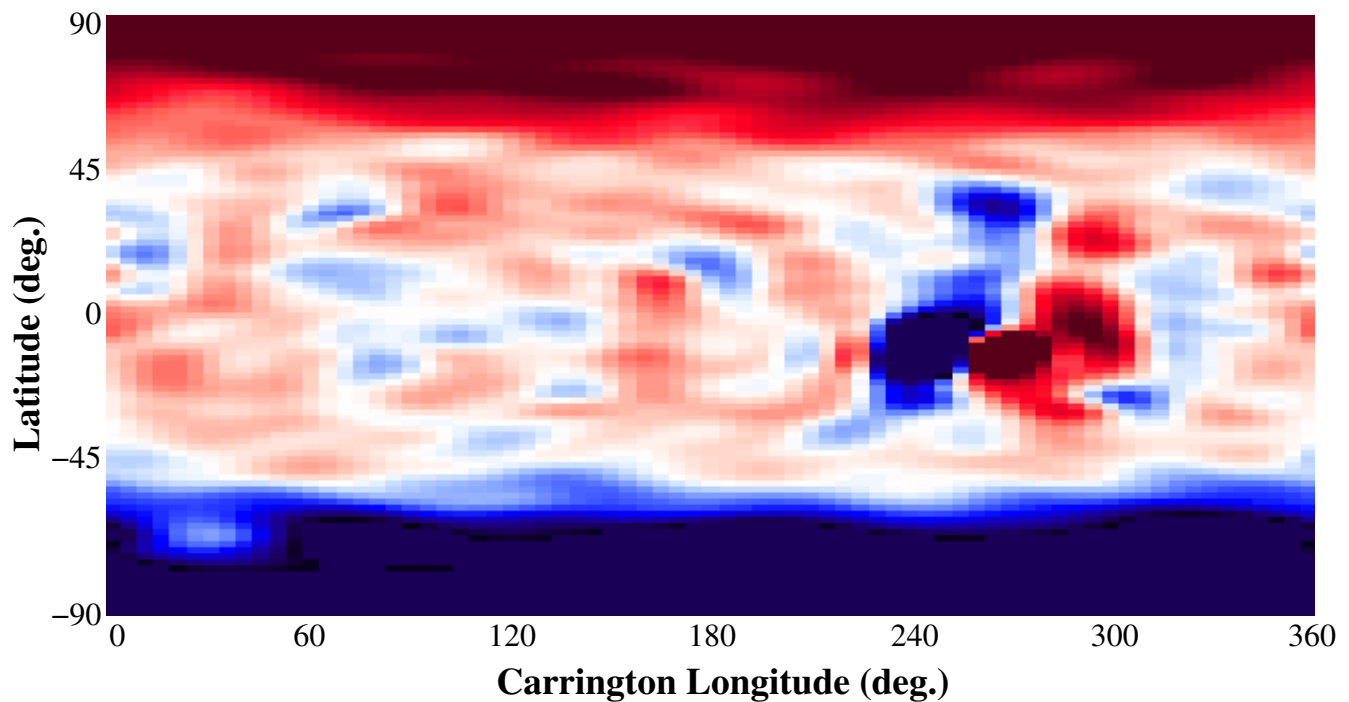
Whole Sun Month

Aug. 10 – Sep. 8, 1996

Kitt Peak Synoptic Chart, B_r



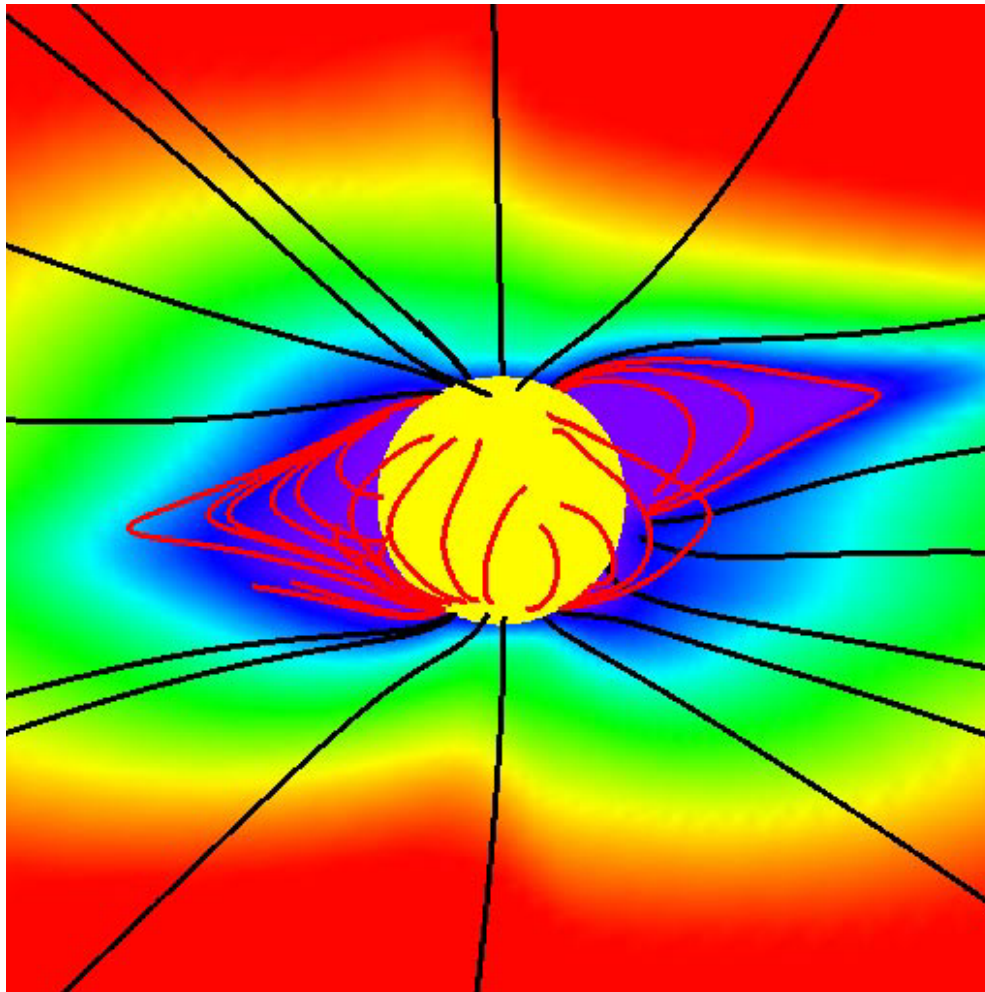
Smoothed Magnetic Field (used in MHD model)



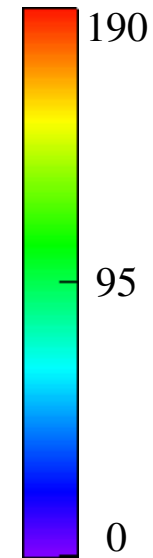
Whole Sun Month

Aug. 10 – Sep. 8, 1996

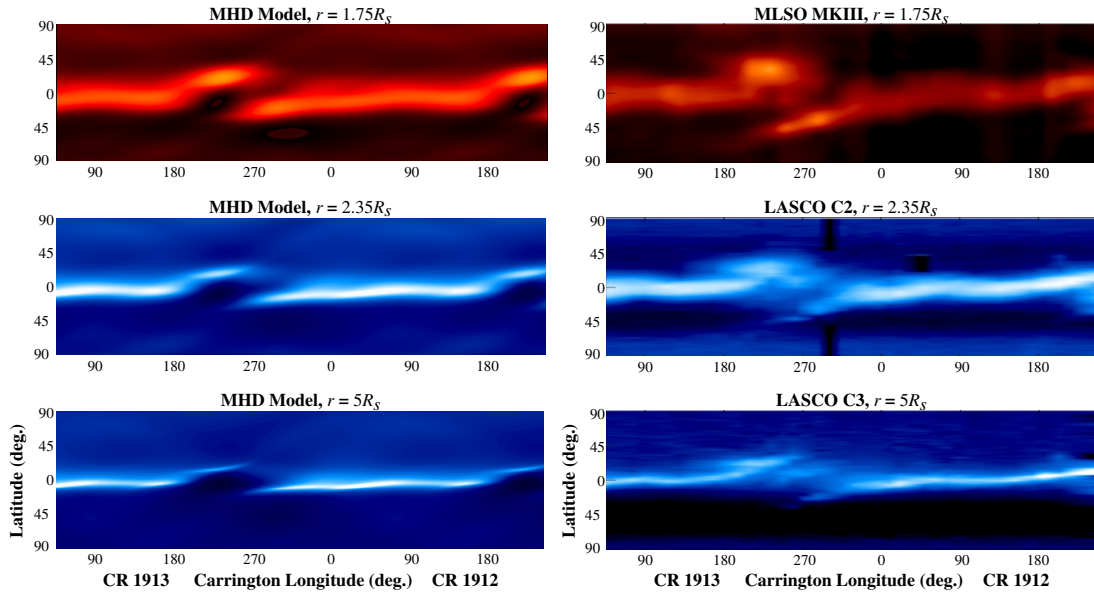
Radial Velocity
Open and **Closed** Field Lines



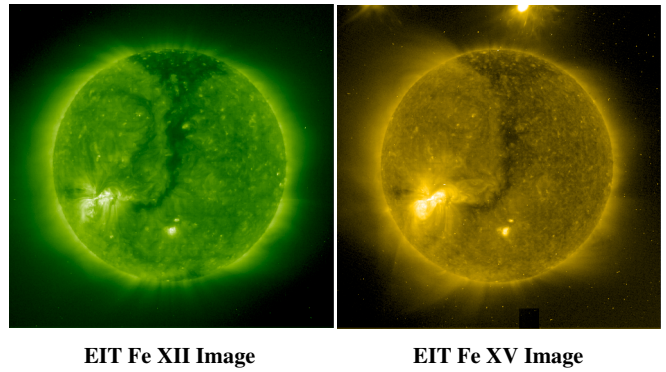
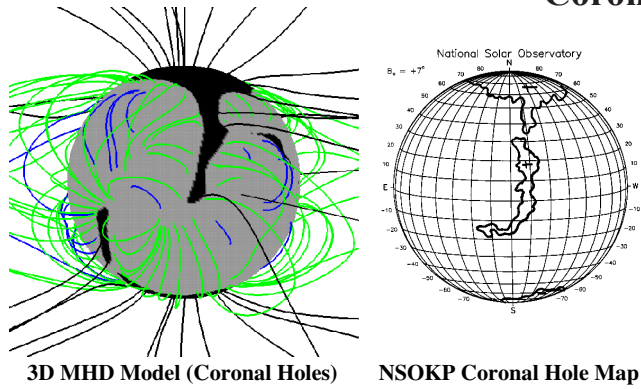
Radial Velocity (km/s)



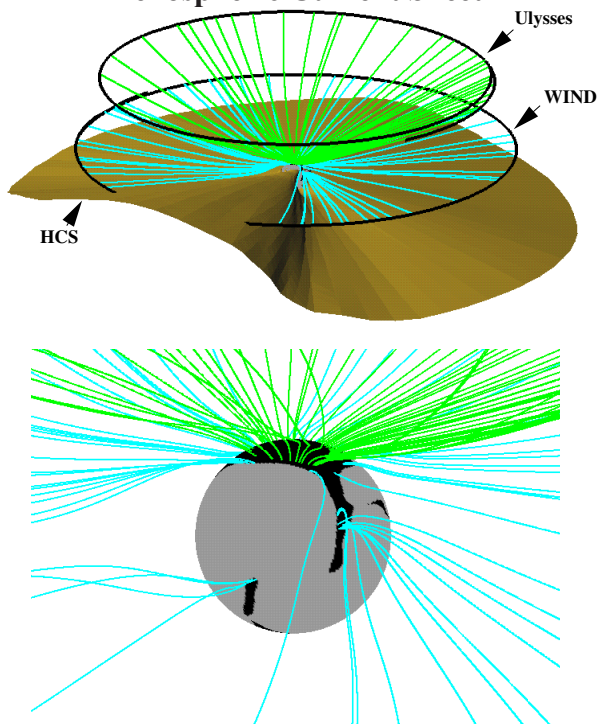
MHD Modeling of the Solar Corona During Whole Sun Month



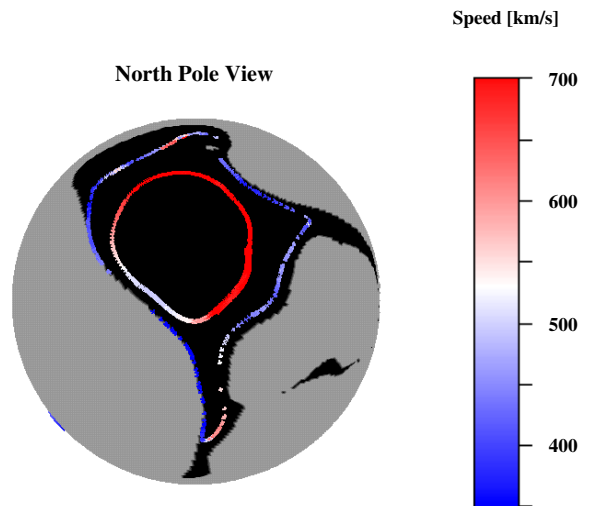
Coronal Holes



Magnetic Field Lines and Heliospheric Current Sheet

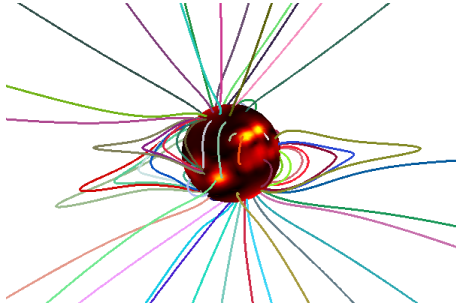


Sources of Solar Wind at the Sun Measured at Ulysses

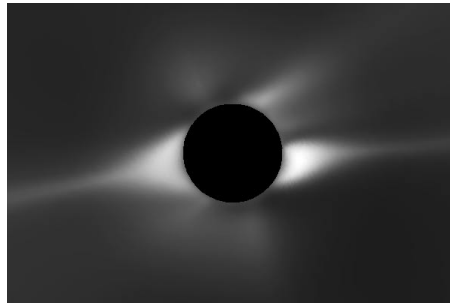


Eclipse Comparisons

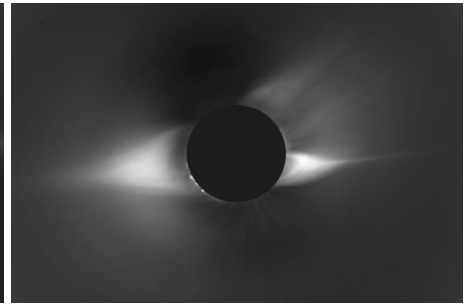
Field Lines
(MHD Model)



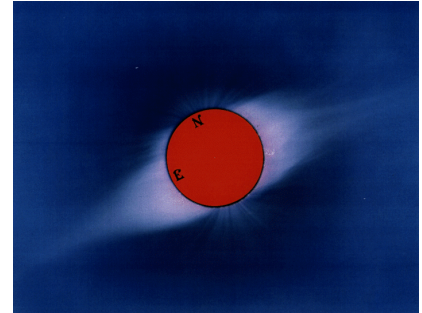
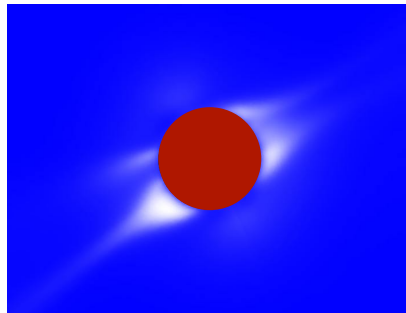
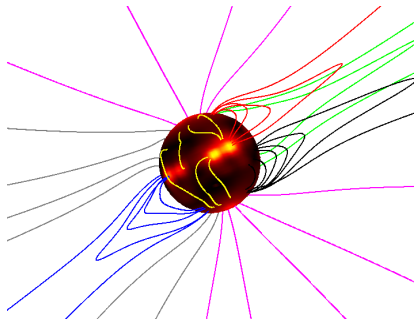
Polarization Brightness
(MHD Model)



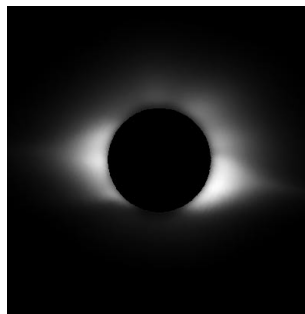
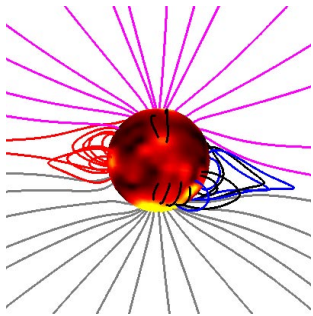
Eclipse Image



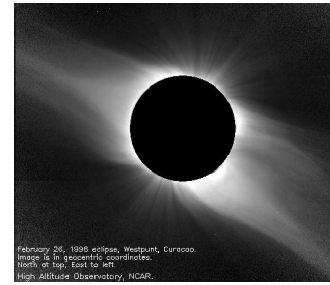
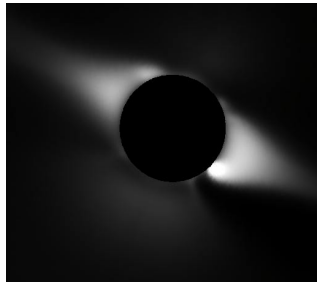
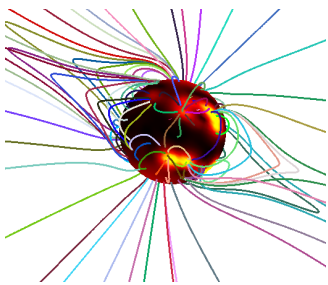
November 3, 1994



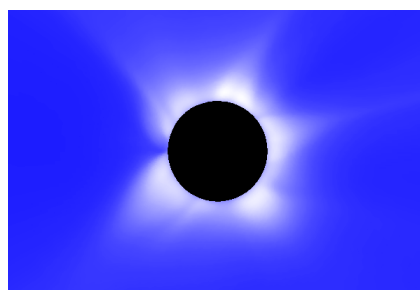
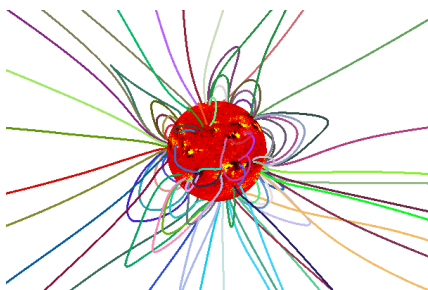
October 24, 1995



March 9, 1997

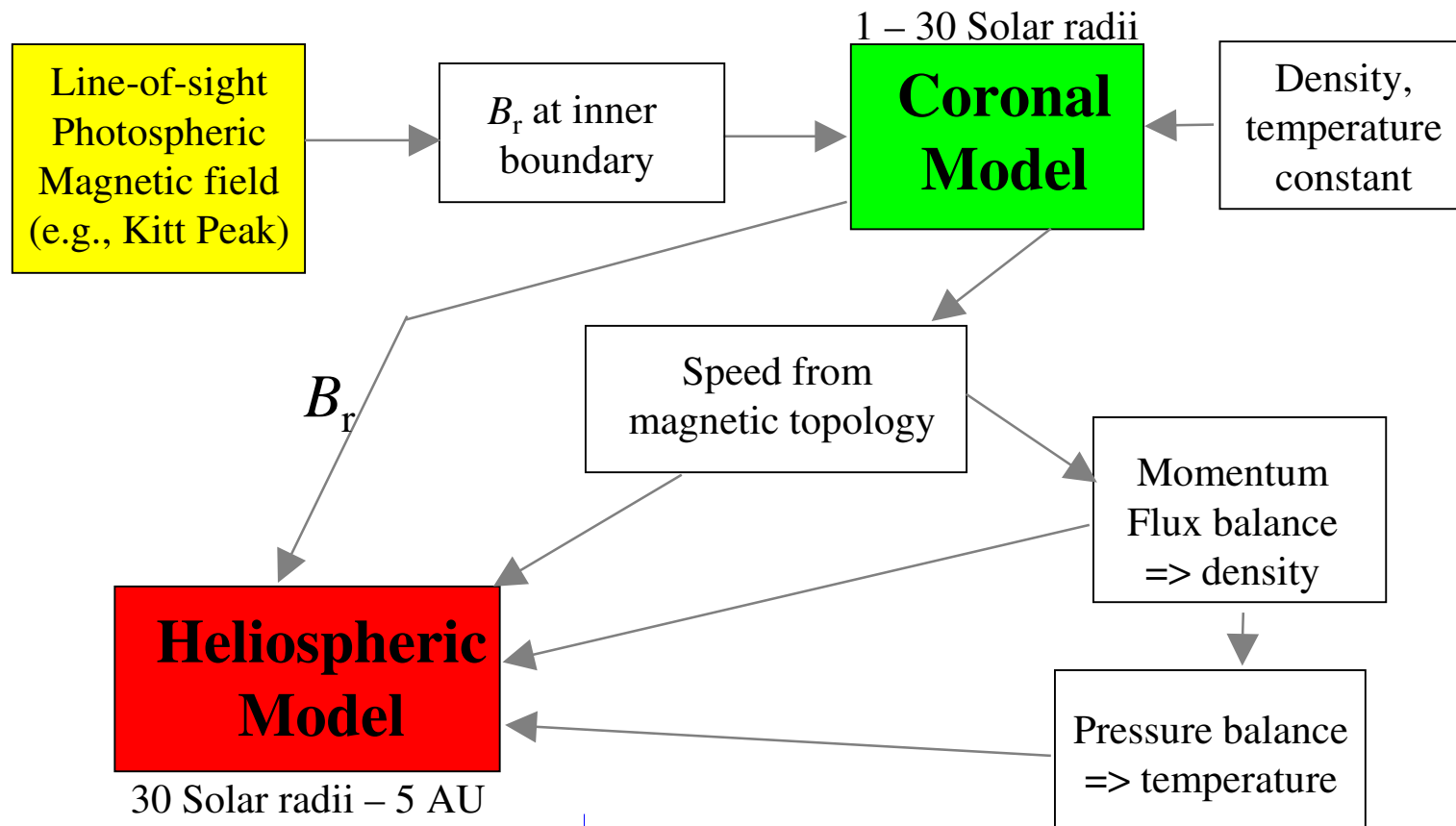


February 26, 1998

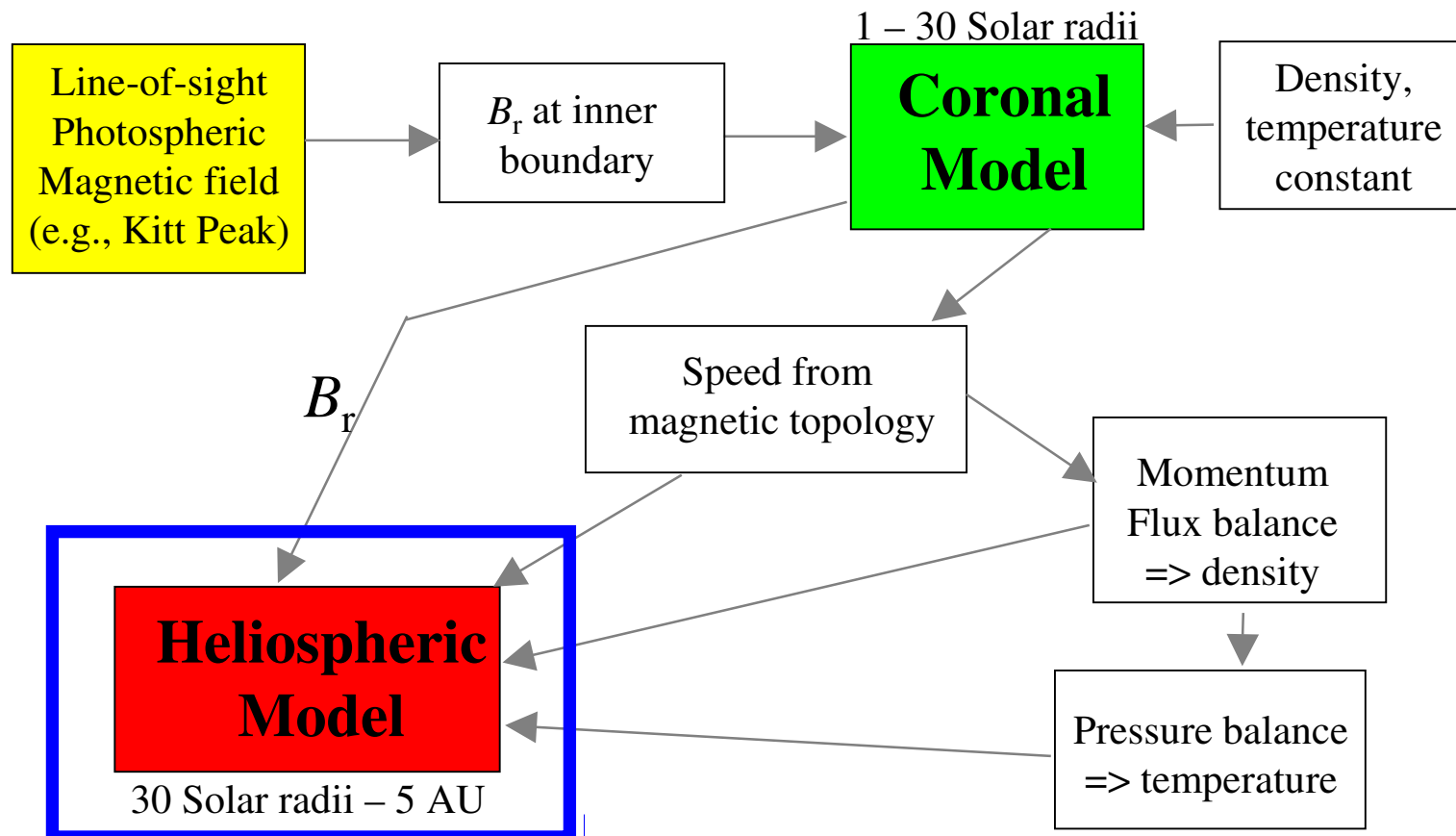


August 11, 1999

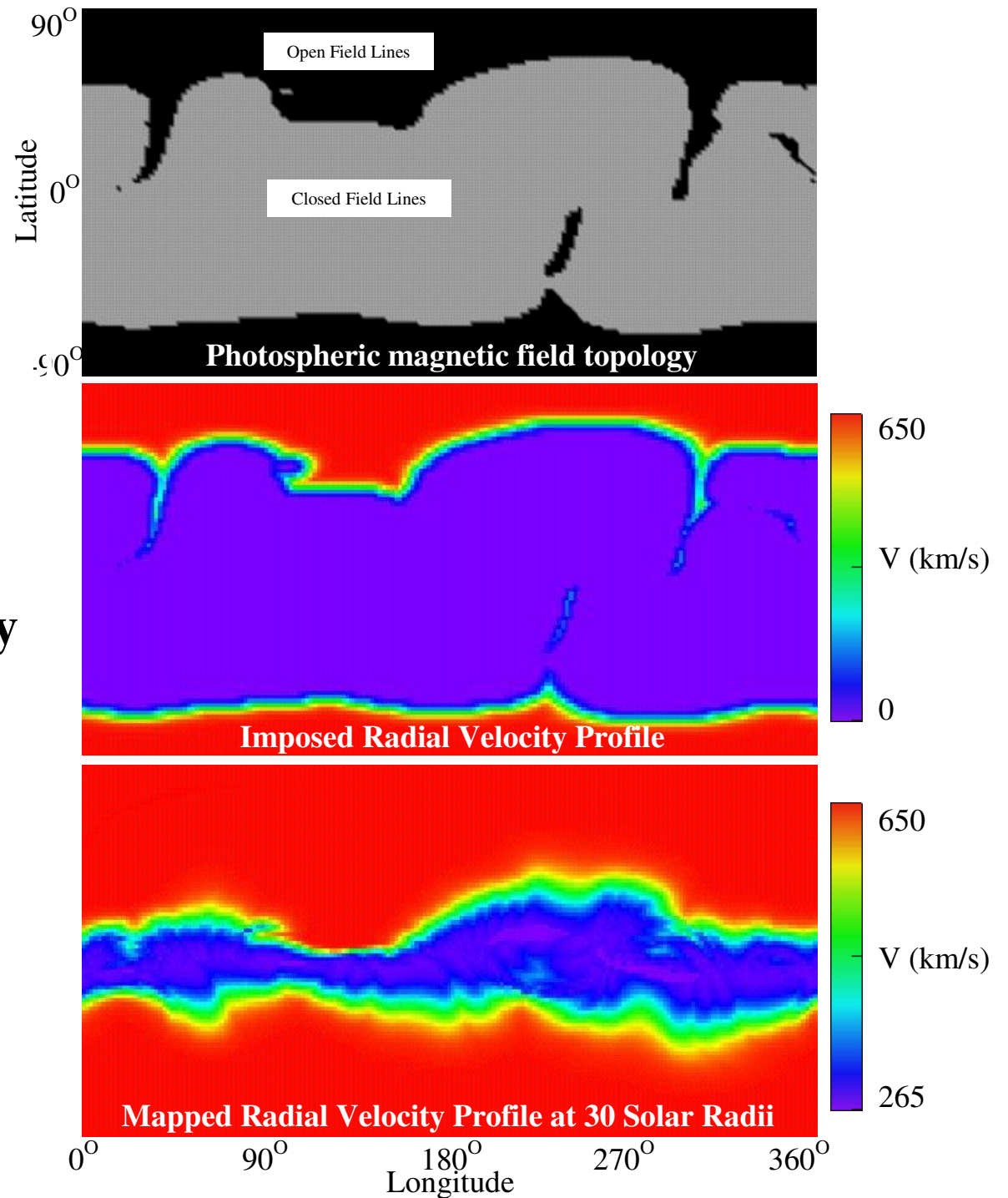
MHD Model of the Corona and Inner Heliosphere: Overview



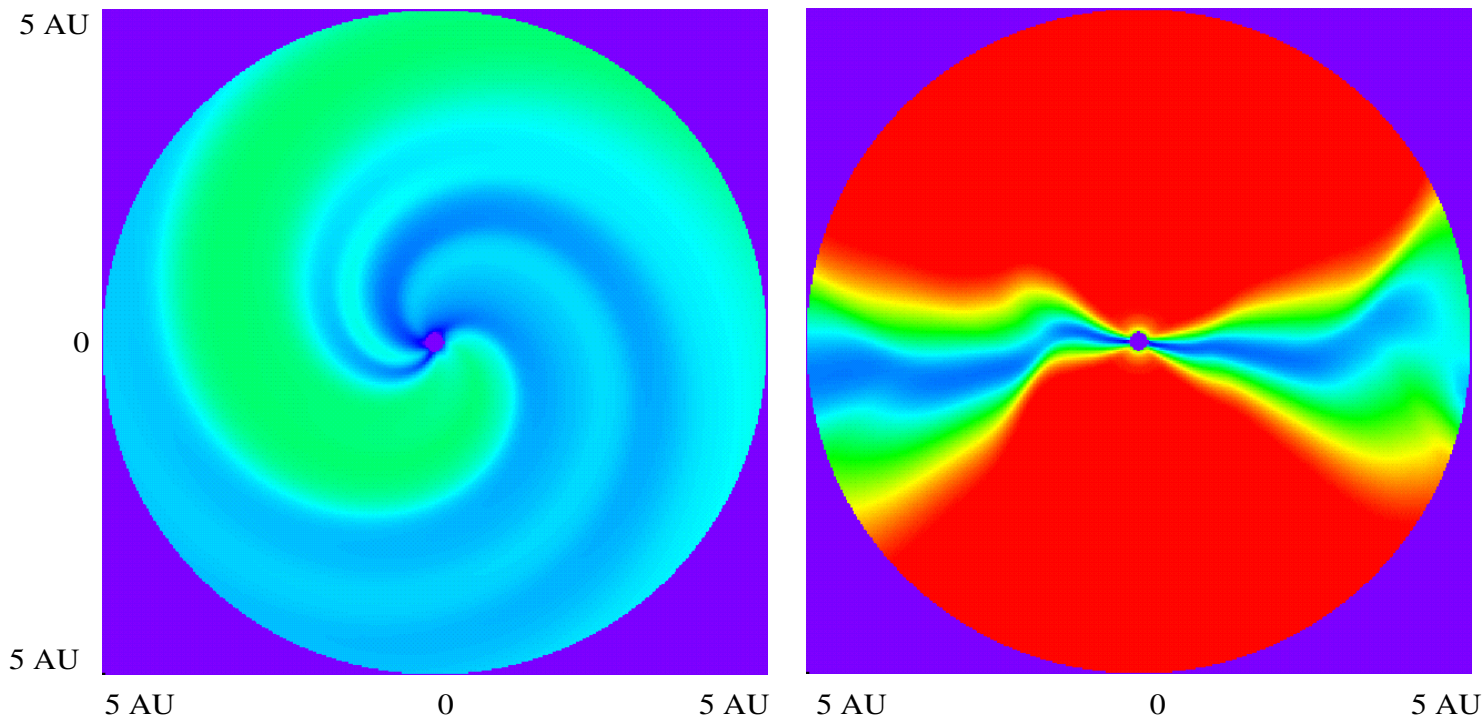
MHD Model of the Corona and Inner Heliosphere: Overview



MHD Model of the Corona and Inner Heliosphere: Heliospheric Boundary Conditions at Solar Minimum

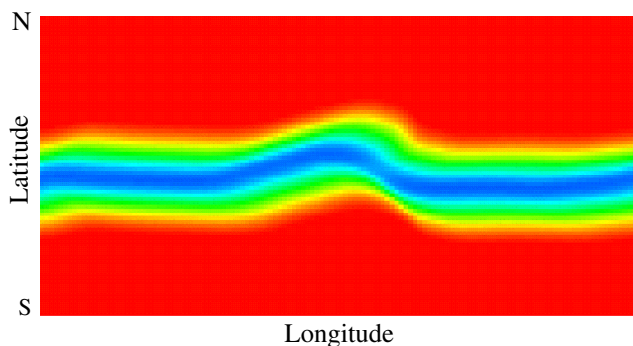


Solar Wind Velocity in the Heliosphere During Whole Sun Month (August–September 1996)

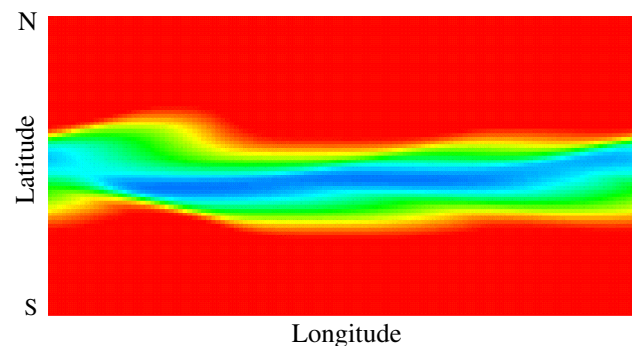


Radial Velocity in Equatorial Plane

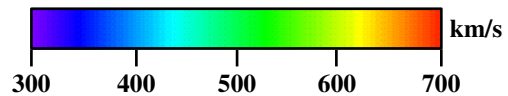
Radial Velocity in Meridional Plane



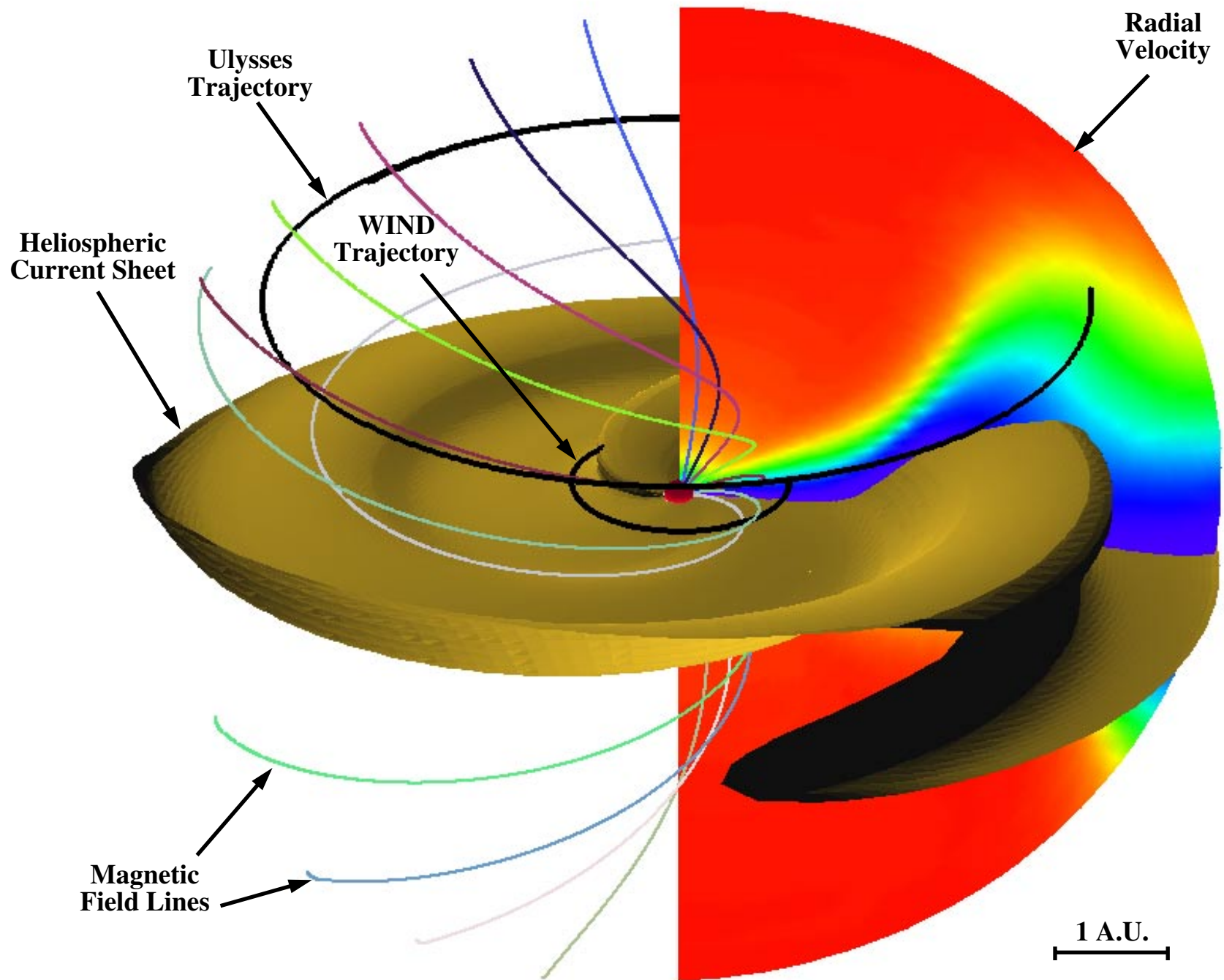
Radial Velocity at $r = 1$ AU

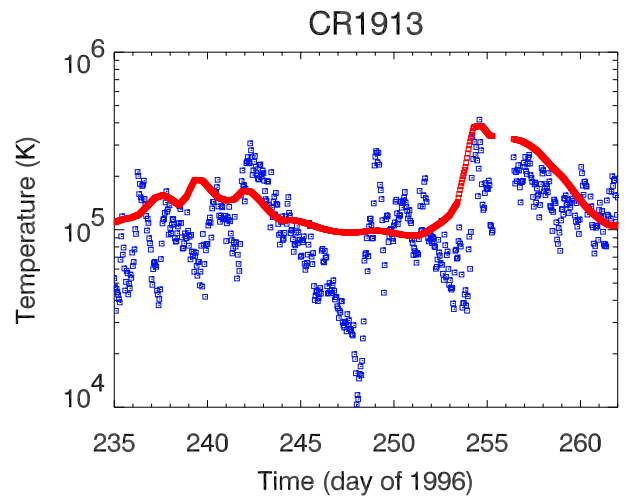
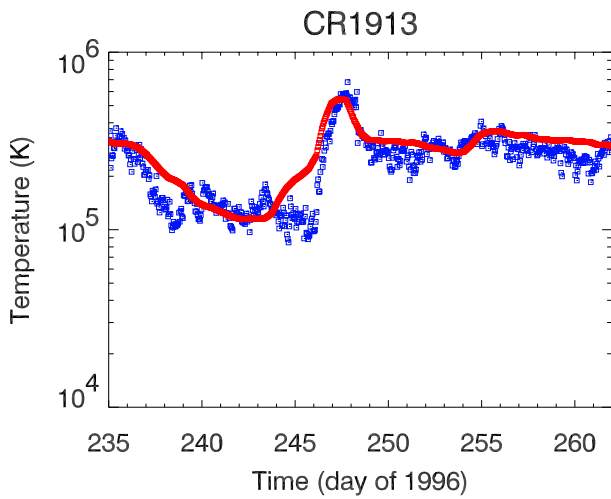
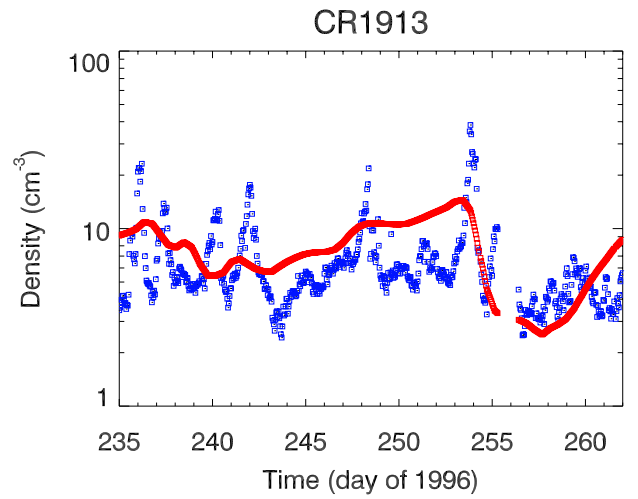
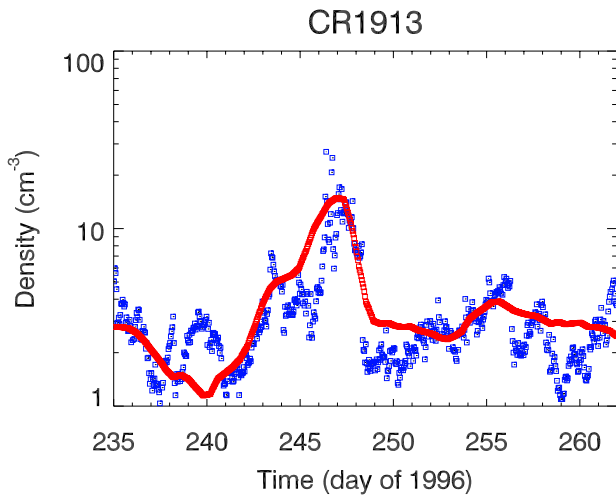
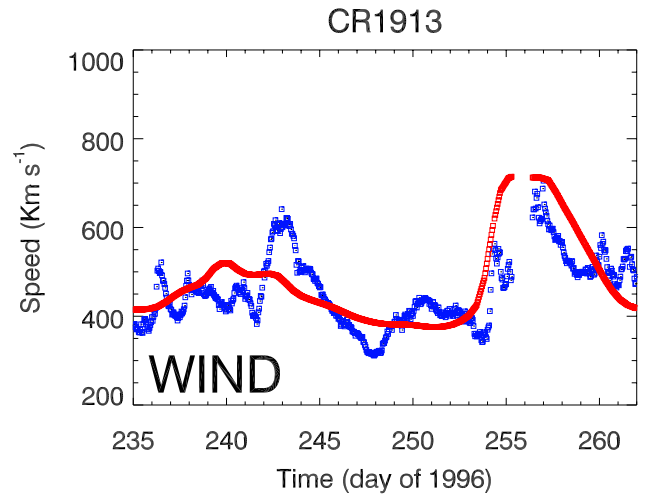
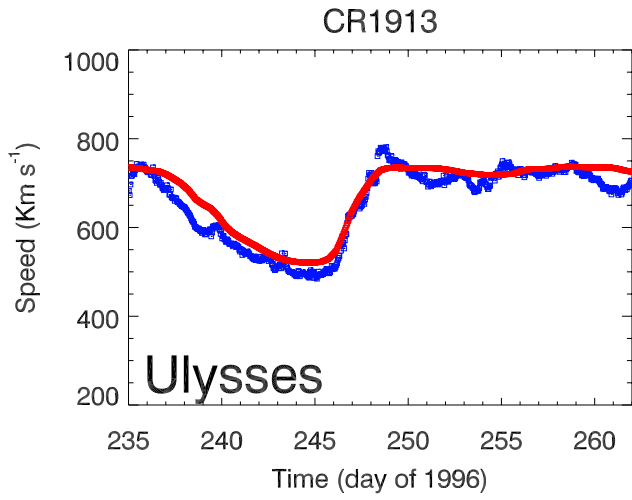


Radial Velocity at $r = 4.2$ AU



The Heliosphere During Whole Sun Month August – September 1996





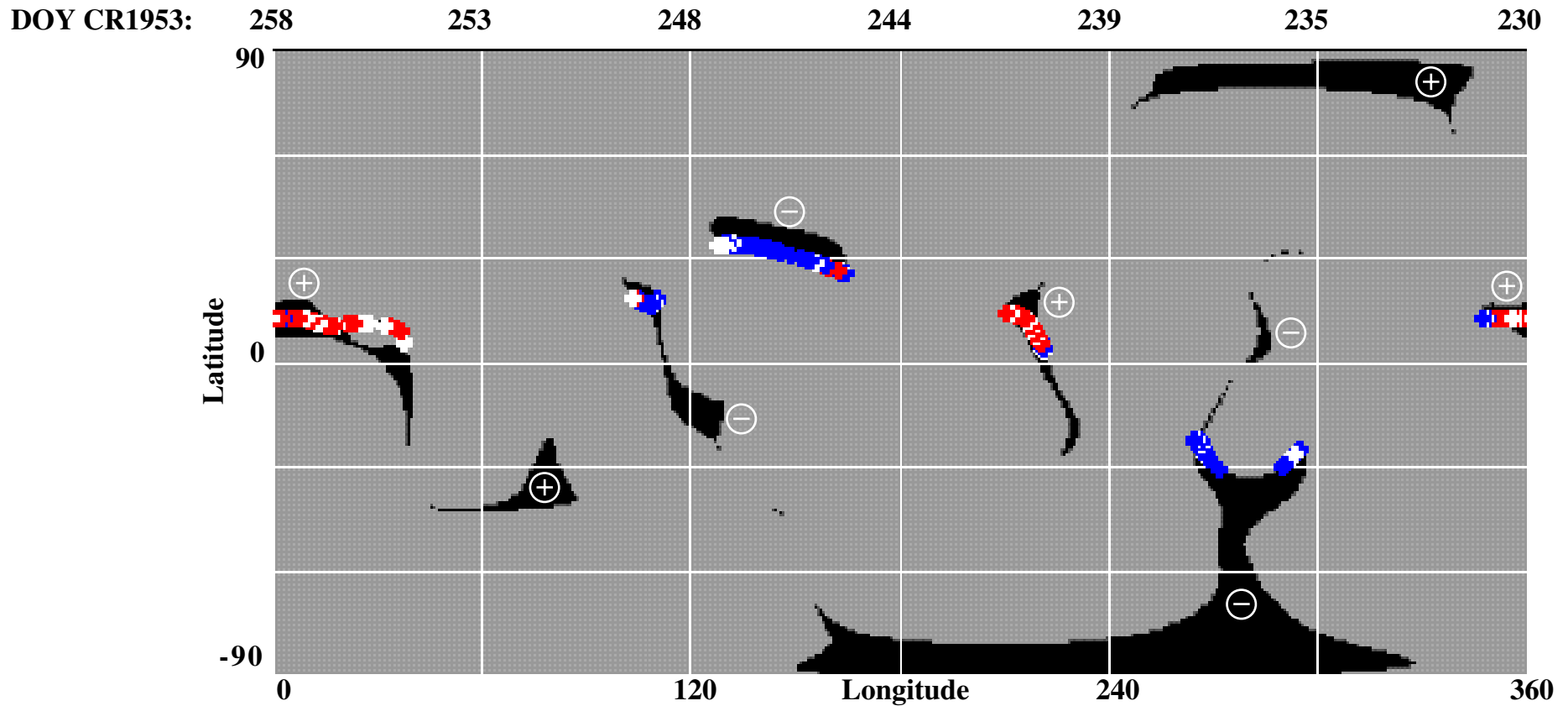
Solar Wind Source Regions

Determined from a 3D MHD Calculation

Compared with ACE Measurements

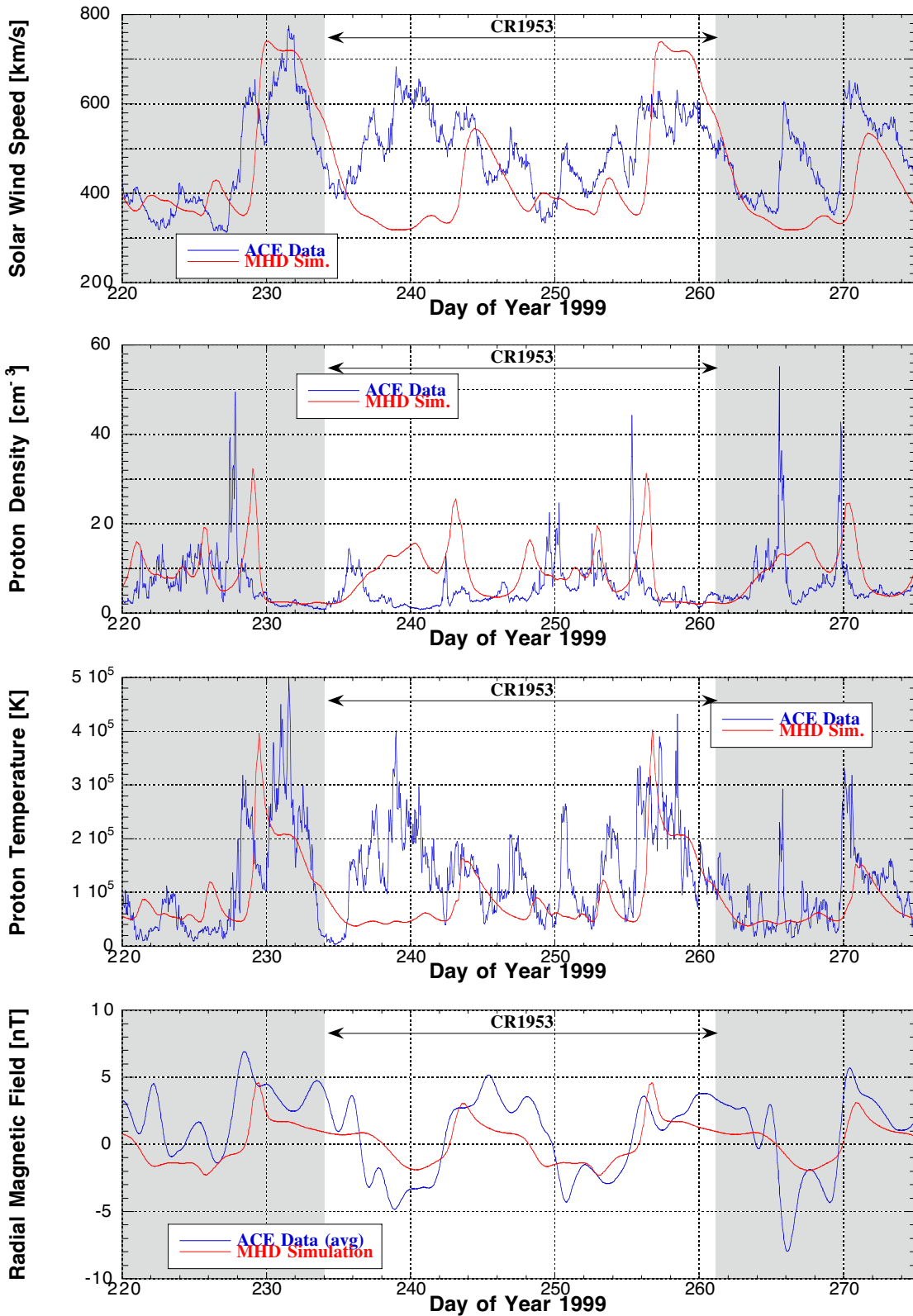
Whole Sun Month 3 (Aug. 18 - Sep. 14, 1999)

Magnetic Field Direction



Out of Sun: $|P - B| < 45^\circ$ Into Sun: $|P - B - 180^\circ| < 45^\circ$

WSM3 Comparison Between ACE Measurements* and an MHD Simulation



*No account has been taken of CMEs

AN EVOLVING SOLAR WIND MODEL

- We can run a time-dependent coronal model with continuous updates of the photospheric magnetic field driven by observations
- We can use daily or more frequent updates (determined primarily by resources)
- The boundary magnetic field B_{r_0} in the model is updated using an electric field at the boundary
- The coronal solution and solar wind respond to the boundary condition changes
- A “quasi-real-time” model can be developed if a massively parallel computer is used (e.g., a Beowulf cluster with 32 processors) for a medium-resolution run [$\sim O(100^3)$ mesh points]

EVOLVING BOUNDARY CONDITIONS

- The boundary magnetic field B_{r_0} (at $r = R_0$) is updated using an electric field at the boundary:

$$\mathbf{E}_{t_0} = \nabla_t \times \Psi \hat{\mathbf{r}} + \nabla_t \Phi ,$$

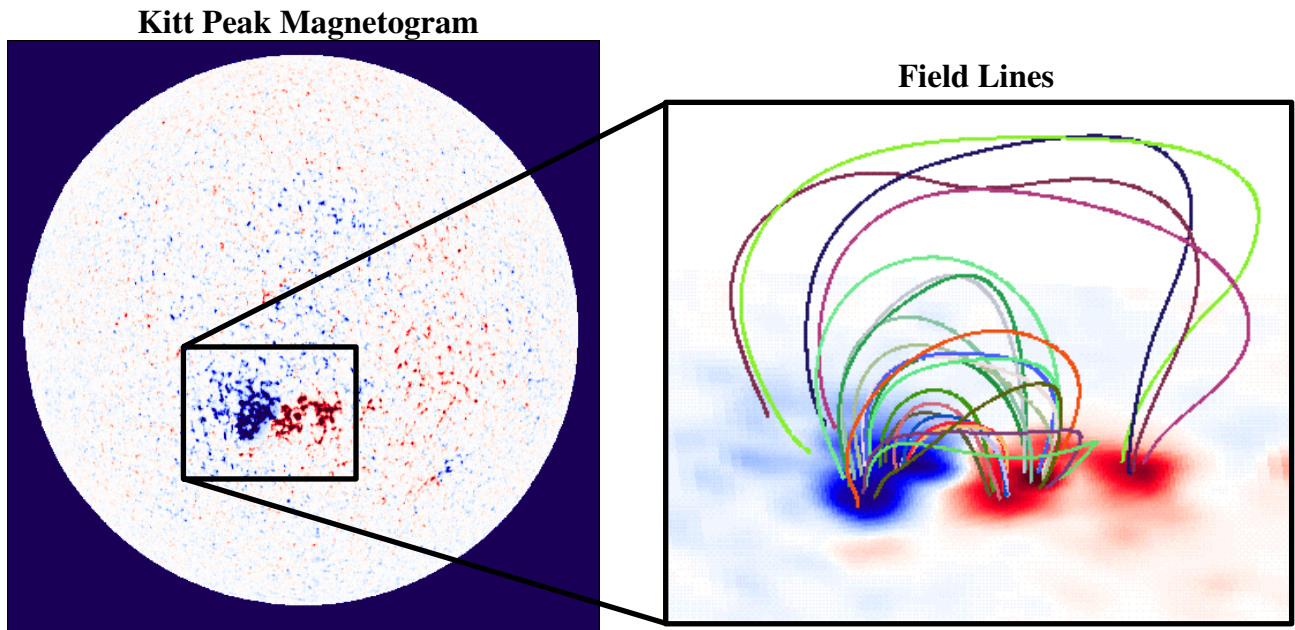
where $\Psi(\theta, \phi)$ controls the normal magnetic field B_{r_0} , and $\Phi(\theta, \phi)$ controls the transverse magnetic field

- Ψ is determined from:

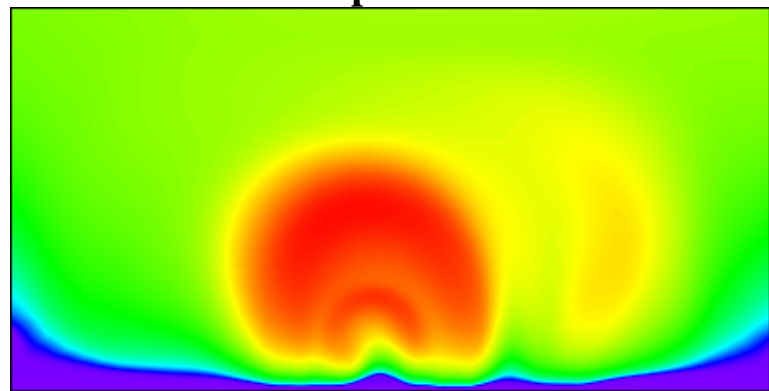
$$c \nabla_t^2 \Psi = \frac{\partial B_{r_0}}{\partial t}$$

- Φ can be determined from a circuit model to match the normal component of the electric current J_r (deduced from measurements of the transverse field):

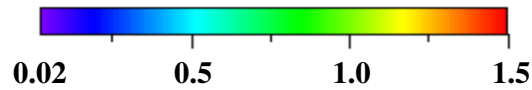
$$\frac{\partial \Phi}{\partial t} \propto (J_r - J_{r_0})$$



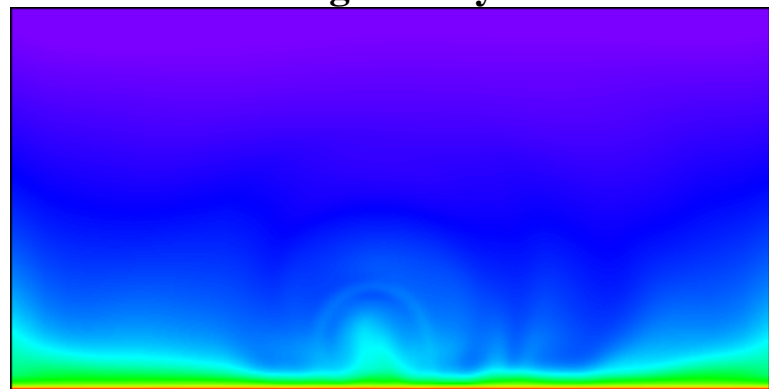
Coronal Cross Sections
Temperature



Temperature [10^6 K]



Log Density



Log Density [cm^{-3}]

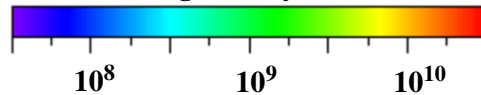
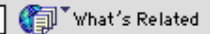


Figure 1. Modeling the magnetic and thermal structure of an active region on August 29, 1996. A Kitt Peak magnetogram is used to specify the normal component of the magnetic field. A twist is applied to the field, and the steady state is calculated for a given coronal heating distribution. The temperature and density structure shows that the transition region height varies in different parts of the active region.

STANDARD DATA PRODUCTS

- We are developing WWW site with data for 2.5 solar cycles (~ 350 Carrington rotations, CR 1625 – present)
- Coronal hole maps with magnetic field polarity
- Field line connectivity (spacecraft to source regions on the Sun)
- Plasma parameters: \mathbf{B} , \mathbf{v} , T , n
 - plots vs. latitude, longitude, radius
 - meridional and equatorial cuts
- Limb pB images at Earth and spacecraft views, movies of pB
- Synoptic maps of pB at various radii
- 3D images of the heliospheric current sheet and field lines (VRML)
- Raw data: $\mathbf{B}(\mathbf{x},t)$, $\mathbf{v}(\mathbf{x},t)$, $T(\mathbf{x},t)$, $n(\mathbf{x},t)$
- Future products: Interactive tools (e.g., field line tracing on demand)

Location: <http://sheba.saic.com/~uk2/mhdweb/mhdweb.html>[Google Search](#) [ISSAIC](#) [SETS Logon](#) [Haven Web Mail](#) [Wells Fargo](#) [E*TRADE](#) [Yahoo! Finance](#) [Calendar](#)

Modeling the Sun and Inner Heliosphere

Welcome to SAIC's MHD modeling website. These pages are currently undergoing significant development and some of the links may not work. Eventually, these pages will replace our standard website, at <http://haven.saic.com>. However, for now, these pages should be considered experimental. In fact, please read [the disclaimer](#) before proceeding. Nevertheless, please feel free to use the tools provided here if you find them useful. We would be grateful for any suggestions for improving this interface and/or adding tools for interacting with our simulation results.

We have modeled the structure of the solar coronal environment for the entire year of 2000. These are summarized in a series of simulations running from Carrington rotation 1957 (begins 12/05/2000) to Carrington rotation 1971 (ends 01/17/2001). In the upcoming months, we will be adding more rotations to this database, ultimately covering the entire range from Carrington 1625 (02/19/1975) to the present - an interval of more than 25 years.

Please choose from one of the following available options:

- [Overview plots \(plasma and magnetic field parameters\) from Coronal and Heliospheric MHD simulations](#)
- [The Heliospheric Current Sheet](#)
- [Computed Coronal Hole Boundaries \(color-coded with magnetic polarity\)](#)
- [Simulated disc images of Polarized Brightness \(as seen from Earth\)](#)
- [Movies of Polarized Brightness \(as seen from Earth\)](#)
- [Simulated Synoptic maps of Polarized Brightness \(as seen from Earth\) at selected heights](#)
- [Trajectories of Earth-Based and Ulysses Spacecraft mapped back to the solar surface](#)
- VRML worlds of the coronal and heliospheric magnetic fields (requires a VRML plug-in such as Cosmoplayer)
- [A collection of \(hopefully\) useful conversion utilities](#)

Please send suggestions for improving this site to: webmaster@sun.saic.com.

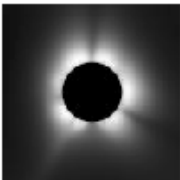


Netscape:

Back Forward Reload Home Search Netscape Images Print Security Shop Stop

Location: What's Related

Google Search ISSAIC SETS Logon Haven Web Mail Wells Fargo E*TRADE Yahoo! Finance Calendar



Polarized Brightness Disc Images

On these pages, we generate simulated polarized brightness (pB) disc images. All images displayed with solar north being vertically upward and are corrected for the relative tilt of the solar rotation axis to the ecliptic plane. Since there are a number of 'free' parameters that are applied in the construction of these images, by processing them in this automatic way, it is possible that features may be unnecessarily masked or emphasized. Please contact us if you would like specific filters, etc, applied.

Please select one of the following options. You can choose which Carrington rotation you want to look at and the Carrington longitude at central meridian (i.e., corresponding to a particular instant in time).

Carrington Rotation:

Carrington Longitude:

Please send suggestions for improving this site to: webmaster@sun.saic.com.

Location: <http://sheba.saic.com/~uk2/mhdweb/hcs/hcs.html>

What's Related

[Google Search](#) [ISSAIC](#) [SETS Logon](#) [Haven Web Mail](#) [Wells Fargo](#) [E*TRADE](#) [Yahoo! Finance](#) [Calendar](#)

Computed Heliospheric Current Sheet

The heliospheric current sheet (HCS) is computed from the heliospheric solution (30Rs - 5AU). It is the iso-surface of $B_r=0$.

Please select one of the following options. You can choose which Carrington rotation you want to look at and whether you want to plot the data or download an HDF file. Alternatively, you can view the [HCS photoalbum](#), which summarizes all rotations on a single page.

Carrington Rotation: Action Plot the Data
 Download the Data (this feature is currently not implemented)

Please send suggestions for improving this site to: webmaster@sun.saic.com.

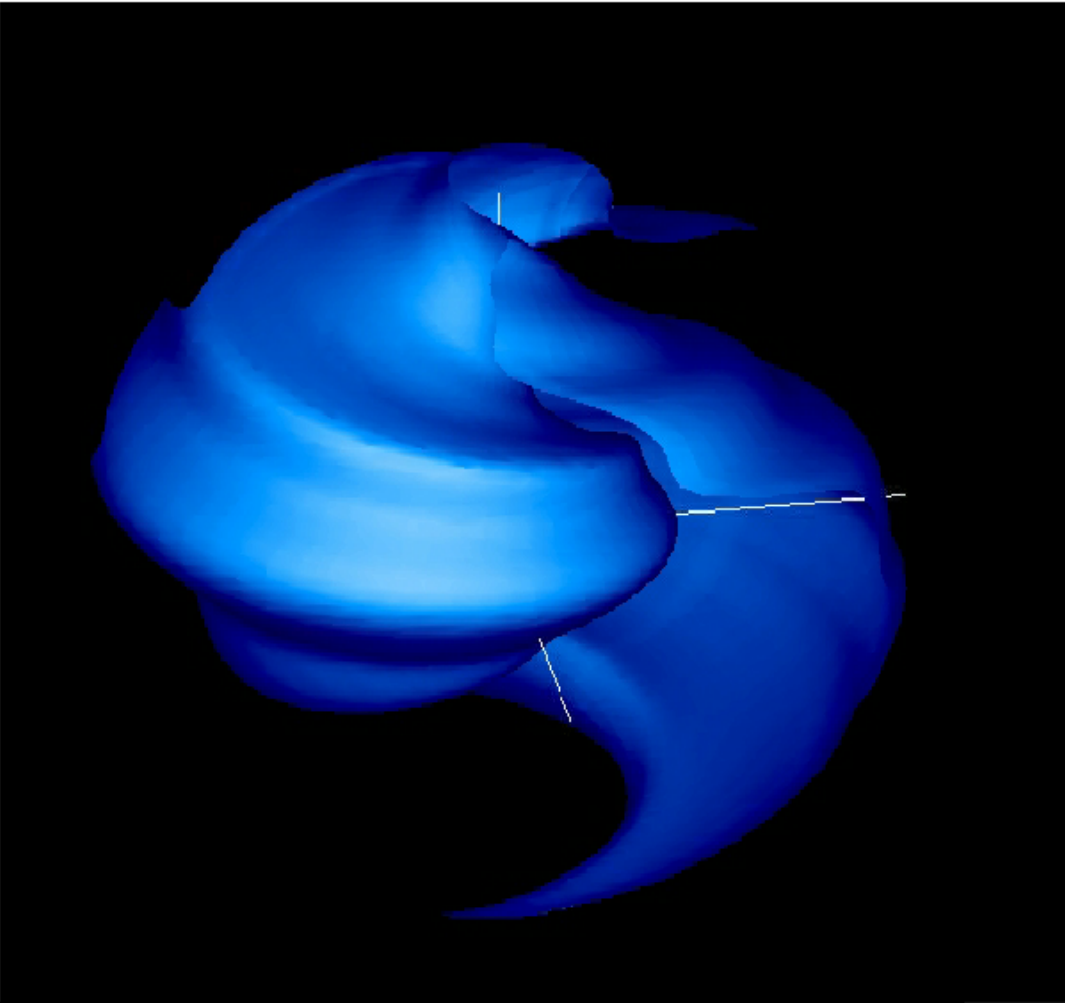
Netscape:

Back Forward Reload Home Search Netscape Images Print Security Shop Stop

Location: <http://sheba.saic.com/cgi-bin/hcs.cgi?cr=1957&ptype=plot&SUBMIT=Submit> What's Related

Google Search ISSAIC SETS Logon Haven Web Mail Wells Fargo E*TRADE Yahoo! Finance Calendar

Carrington Rotation: 1957



The image displays a 3D visualization of a Carrington rotation, a phenomenon in solar physics. The visualization is a complex, blue, multi-lobed structure against a black background. The structure has a central core and several curved, wing-like extensions. A mouse cursor is visible on the right side of the image.



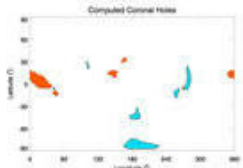
Location: <http://sheba.saic.com/~uk2/mhdweb/ch/images/jpeg/>

What's Related

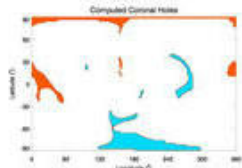
Google Search ISSAIC SETS Logon Haven Web Mail Wells Fargo E*TRADE Yahoo! Finance Calendar

jpeg

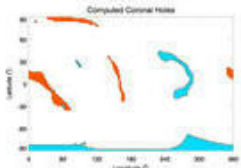
[Up](#)



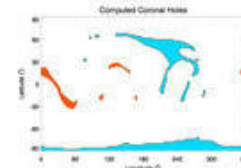
[ch 1957](#)



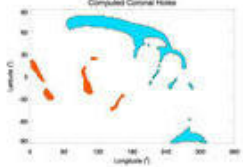
[ch 1958](#)



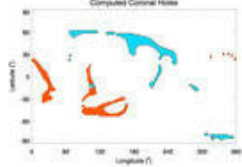
[ch 1959](#)



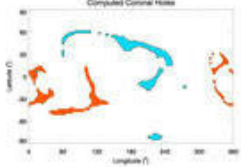
[ch 1960](#)



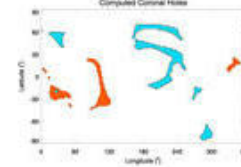
[ch 1961](#)



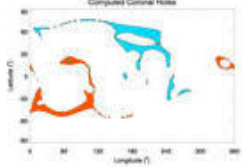
[ch 1962](#)



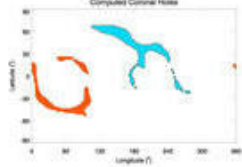
[ch 1963](#)



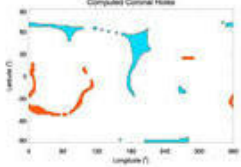
[ch 1964](#)



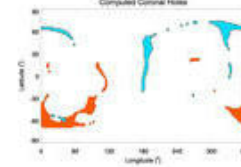
[ch 1965](#)



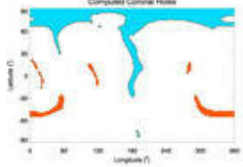
[ch 1966](#)



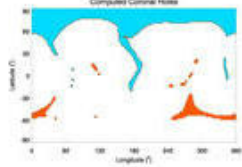
[ch 1967](#)



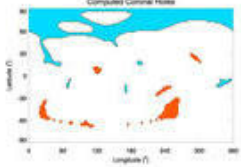
[ch 1968](#)



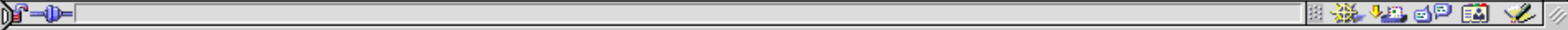
[ch 1969](#)

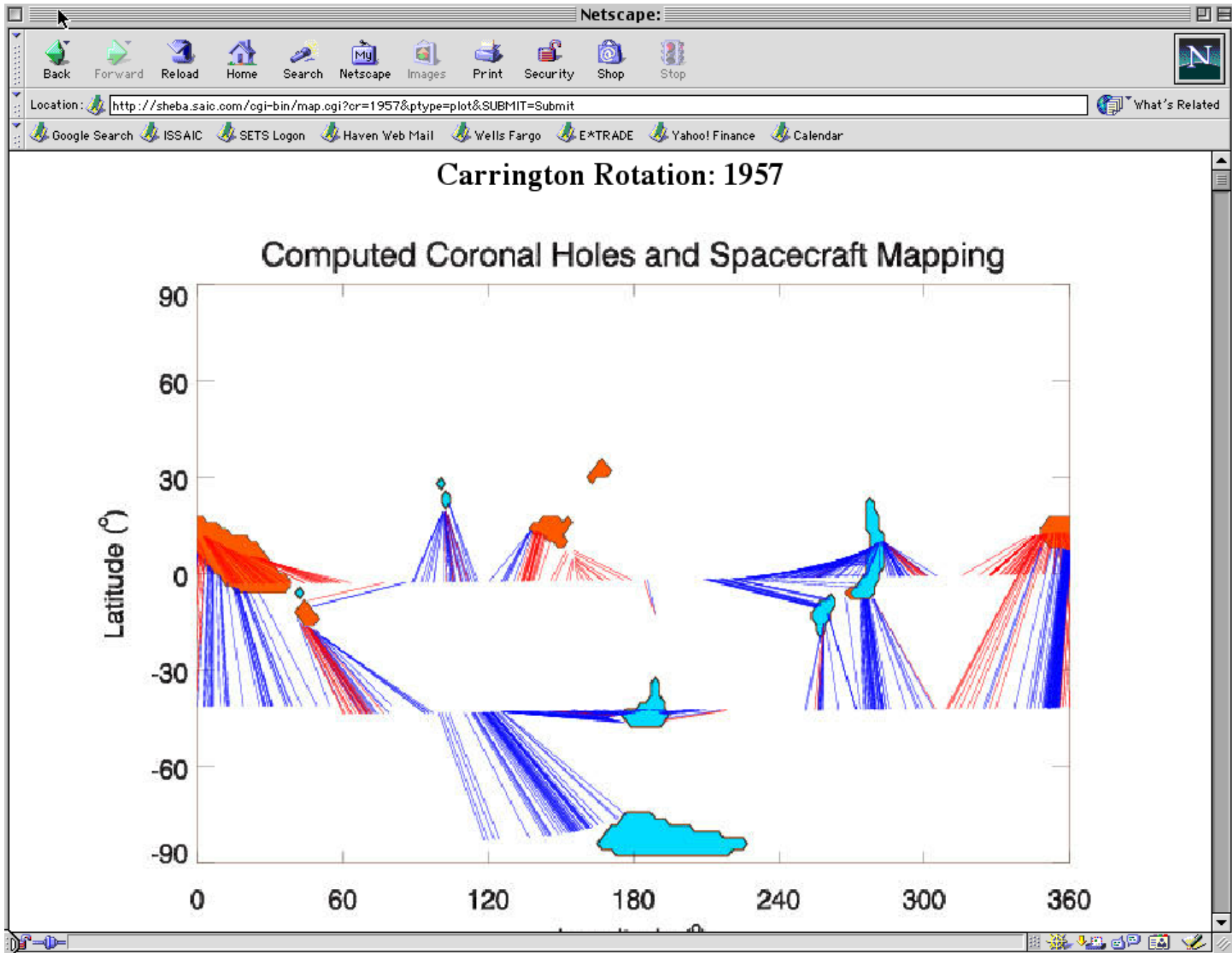


[ch 1970](#)

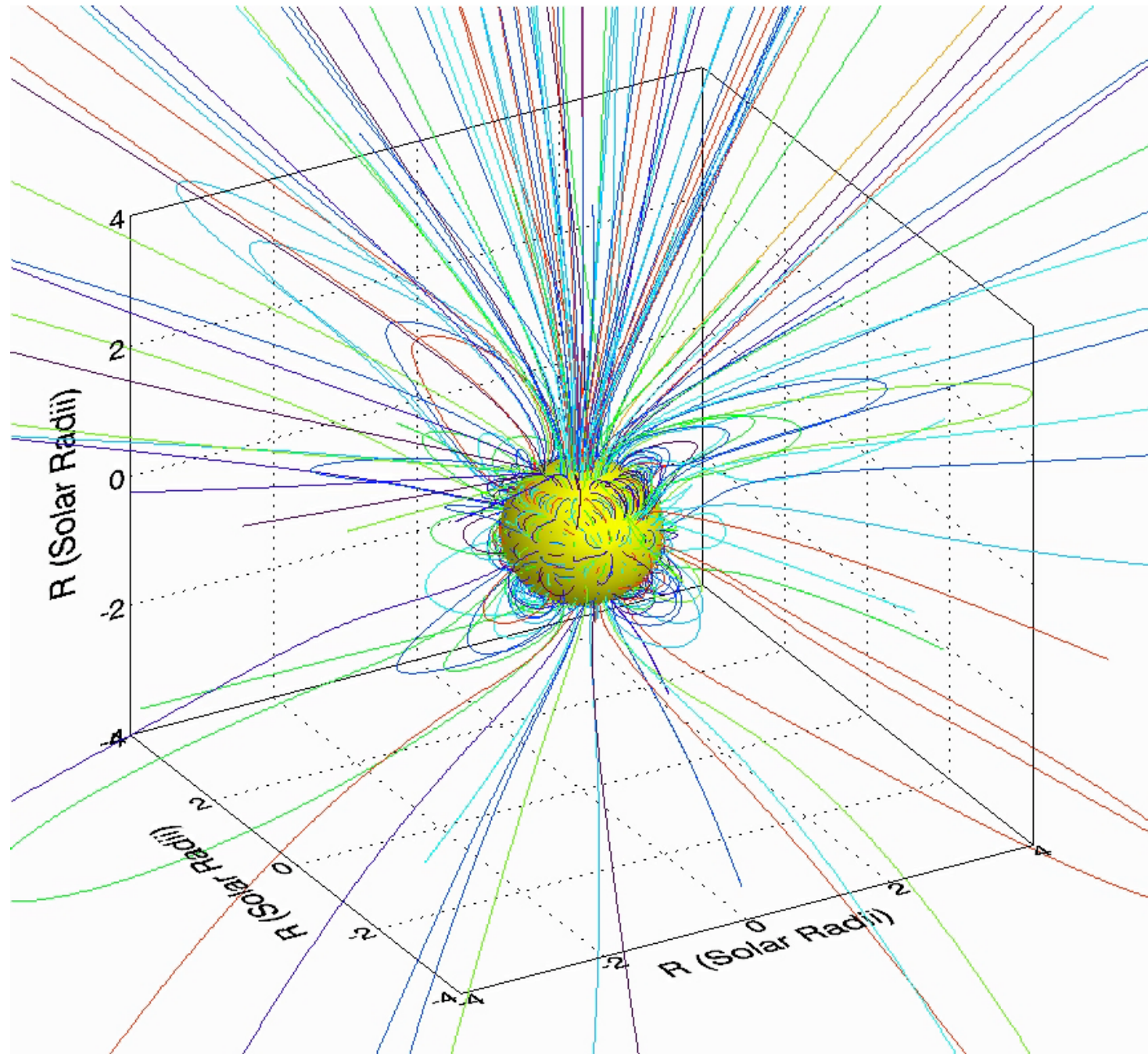


[ch 1971](#)





VRML of Coronal Field Lines (CR 1971, Dec. 12, 2000 – Jan. 17, 2001)



VRML of Heliospheric Field Lines (CR 1971, Dec. 12, 2000 – Jan. 17, 2001)

