BootCamp Solar and Helio RoR Tutorial

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Rm 262 – opposite CCMC lab

June 14, 2017

Introduction

- Runs-On-Request Models of solar corona and solar wind
- Will show you models based on 3 different physical approximations

- What are your backgrounds (ie high school, undergraduate, graduate, post-doc?)

- Menu
  - Some basic principles to keep in mind
  - What the physical system looks like
  - How the models approximate the physics
  - How to request a run
  - What you will get back

Model Inventory

- Our coronal models include
  - Models of the field only
    1. WSA
    2. NLFFF
  - Models of the field and plasma
    1. CORHEL-MASP
    2. CORHEL-MAST
    3. SWMF AWSoM_R
- Our Solar wind models are all field + plasma and <u>require</u> a coronal model feed
  1. ENLIL
  2. CORHEL-MASP
  3. CORHEL-MAST
  4. SWMF AWSoM_R
- ENLIL and AWSoM offer option to include CMEs

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Introduction

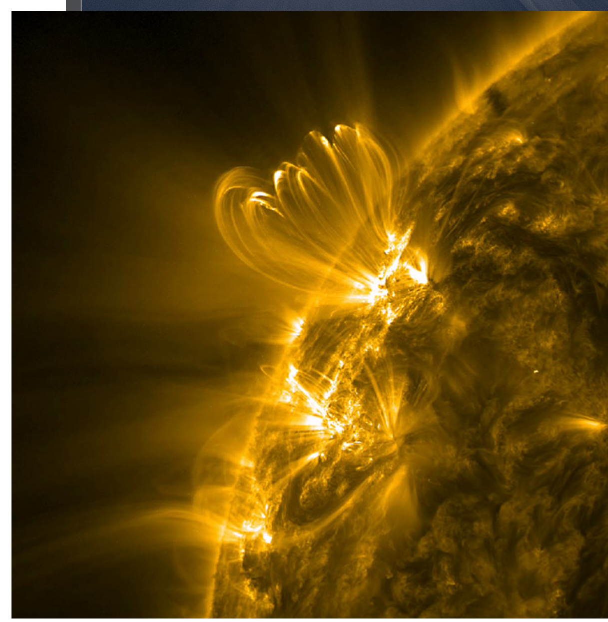
- RoR Models of solar corona and solar wind
  - From ~1 solar radius (r_o) to 2AU
- Desired – Global 3D representation of time dependent evolution of ρ, $\boldsymbol{v}$, p, $\boldsymbol{B}$.
- Magnetic field is generated in the solar interior which we don't include in our models – so we need a representation of the field at the solar 'surface'
- Can only really measure field in the photosphere
- What does this system typically look like?
  - Photosphere to coronal base
  - Inner Corona (1 – 2.5r_o)
  - 2.5r_o through the sonic and super-alfvenic points to ~30 r_o
  - The supersonic wind (eg Parker solution)
    - Slow wind at low latitudes
    - Fast wind at higher latitudes
    - Radial flow and Parker spiral

Some Basic Concepts 1

- Where electrical resistivity is low, ionized plasma and magnetic field are locked together – the ‘frozen-in condition’
- In MHD the Lorentz force decomposes into ‘magnetic tension’ + ‘gradient of magnetic pressure’

Wants to expand Magnetized volume

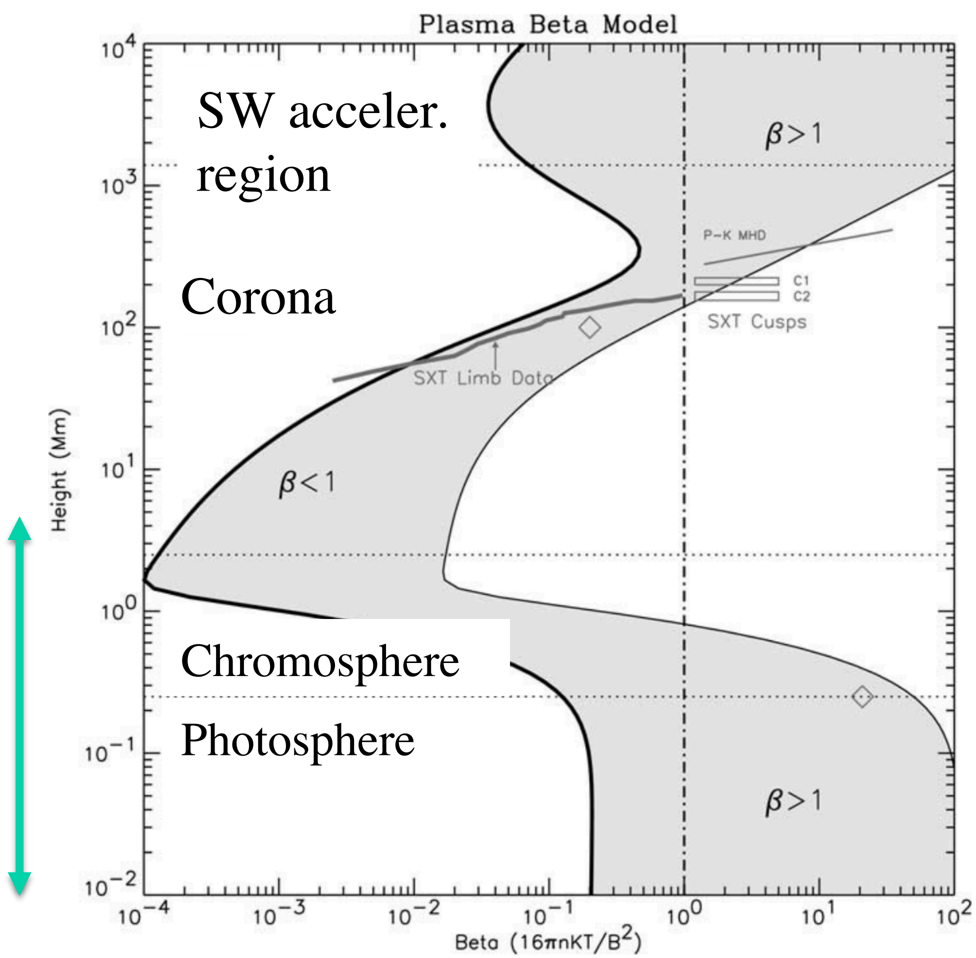
Wants to unbend fieldlines



- Gas pressure ($p = 2nkT$) competes with magnetic pressure ($p_B = B^2/8\pi$)
  - Plasma $\beta = p/p_B$
- Where gas pressure dominates, the wind flow drags the fieldlines with it.
- Where magnetic pressure dominates, closed fieldlines trap the wind in loops close to the sun.

Some Basic Concepts 2

Plasma β above an active region



Flows drag field

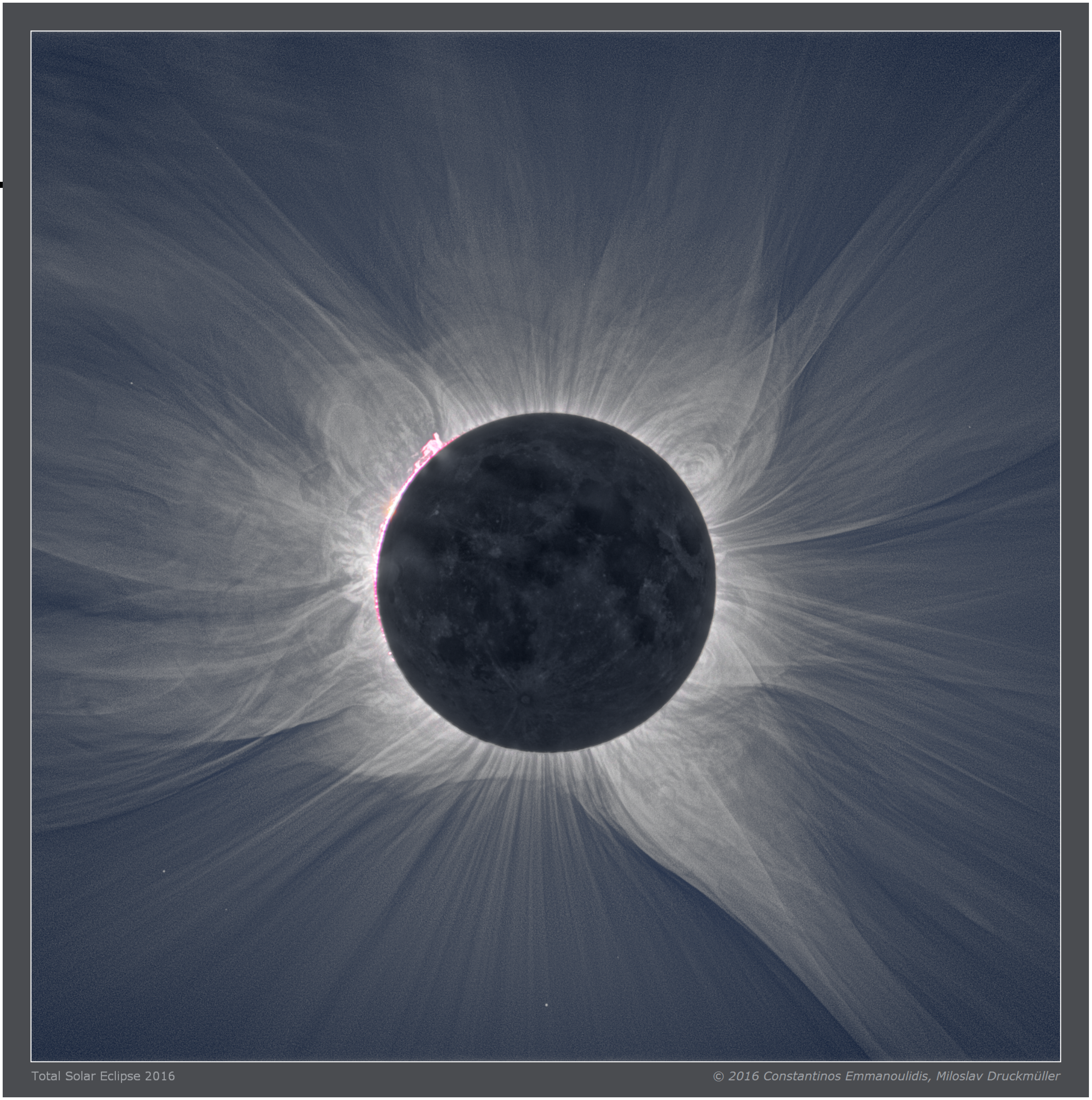
Field controls plasma

Flows drag field

Corona

$(1 - 2.5 r_o)$

Eclipse
2016
Indonesia



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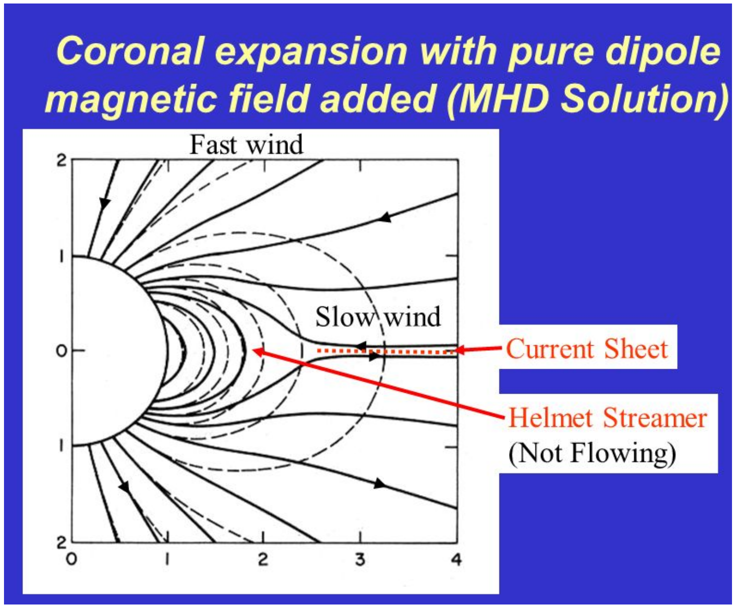

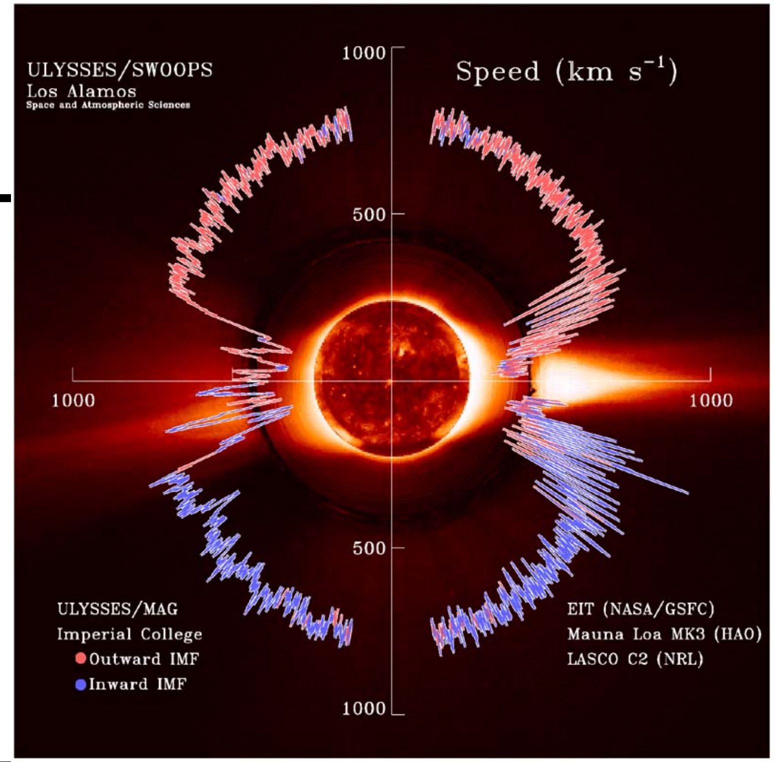

- Solar Wind Feature
    - Heliospheric Current sheet
    - Parker Spiral
    - Slow wind / Fast wind

Assumptions behind Ideal MHD

- Quasi-neutrality
  - Plasma is locally neutral (on the macroscopic length scales we consider)
- Plasma motions are much slower than the speed of light
  - $v << c$
- Electron and ion velocity distributions are close to Maxwellian
- The electrical resistivity is so small that we assume it is zero

Equations of Ideal MHD

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Conservation of mass

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

Conservation of momentum / force balance

$$\rho(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{v} = \boldsymbol{J} \times \boldsymbol{B} - \boldsymbol{\nabla} p + \rho \boldsymbol{g}$$

Magnetic force

Conservation of energy

$$(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \boldsymbol{\nabla})\rho e = -\nabla \cdot (p v) - \boldsymbol{\nabla} \cdot \boldsymbol{q} + H - R$$

Equation of state (how the gas can store energy internally)

$$e = \frac{3}{2} p = 2\rho k_b T / m_p$$

Induction equation

$$\frac{\partial}{\partial t}\boldsymbol{B} = \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B})$$

From Ohms law – currents appear where the field changes quickly

$$\boldsymbol{J} = \boldsymbol{\nabla} \times \boldsymbol{B}$$

Fieldlines must close !

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

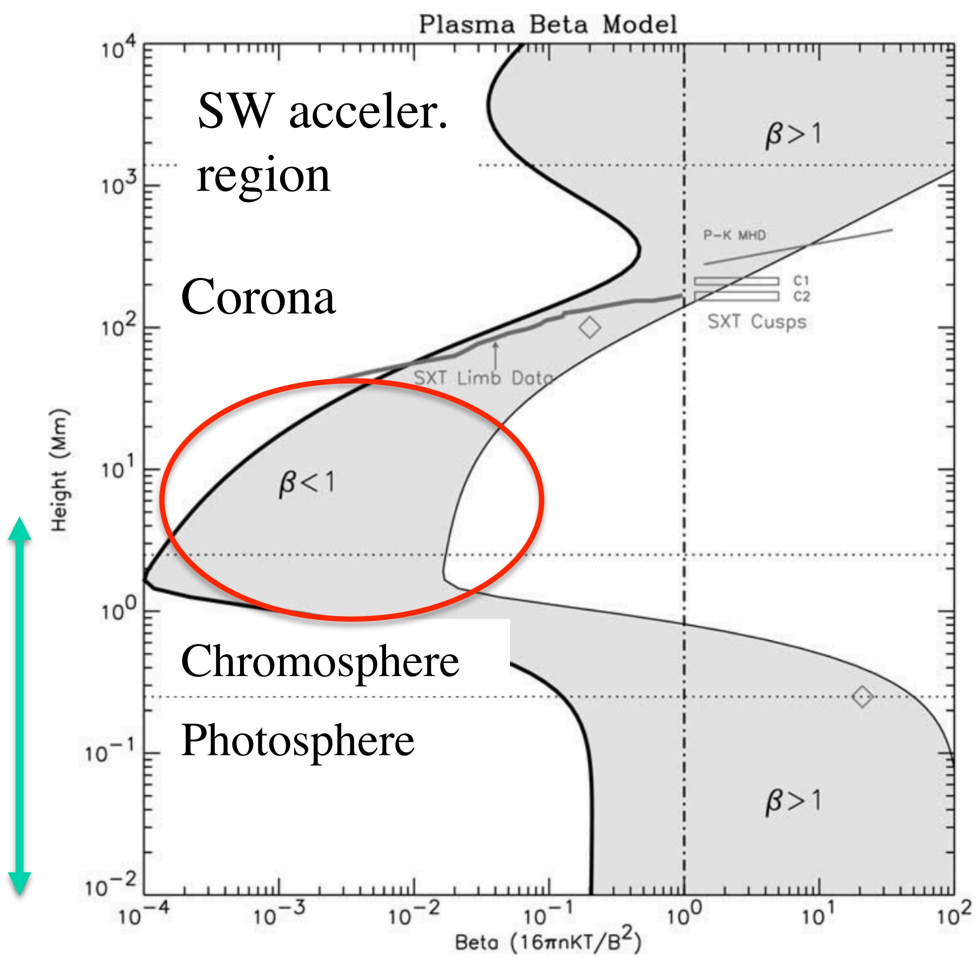
MHD Codes

- The most complete physical treatment that our models offer
- ENLIL, MAS(in CORHEL), AWSoM

- MHD codes are expensive to run
- Algorithms are complex and therefore fragile
- Results must be reviewed carefully for physical sense

Some Basic Concepts 2

Plasma β above an active region



Flows drag field

Field controls plasma

Flows drag field

Equations of Ideal MHD
Time independent – limit of $\beta = 0$

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Conservation of mass

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

Conservation of momentum / force balance

$$\cancel{\rho(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{v}} = \underbrace{\boldsymbol{J} \times \boldsymbol{B}}_{\text{Magnetic force}} = 0 \cancel{- \boldsymbol{\nabla} p + \rho \boldsymbol{g}}$$

Conservation of energy

$$\cancel{(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \boldsymbol{\nabla})\rho e = - \nabla \cdot (p\boldsymbol{v}) - \boldsymbol{\nabla} \cdot \boldsymbol{q} + H - R}$$

Equation of state (how the gas can store energy internally)

$$\cancel{e = \frac{3}{2} p = 2 \rho k_b T / m_p}$$

Faraday's equation / induction equation

$$\cancel{\frac{\partial}{\partial t}\boldsymbol{B} = \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B})}$$

From Ohms law – currents appear where the field changes quickly

Fieldlines must close !

$$\boxed{\begin{aligned} \boldsymbol{J} &= \boldsymbol{\nabla} \times \boldsymbol{B} \\ \nabla \cdot \boldsymbol{B} &= 0 \end{aligned}}$$

Can ignore the plasma dynamics

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Simpler Models

- Time independent, low β approximation.
- Magnetic forces overwhelm pressure and gravity in cross-field direction

$$\boldsymbol{J} \times \boldsymbol{B} = 0$$

$$\Rightarrow \quad \boldsymbol{J} \parallel \boldsymbol{B} \quad \text{or} \quad \boldsymbol{J} = 0 \quad \text{or} \quad \boldsymbol{B} = 0$$

Non Linear Force free

Potential field

Boring!

Potential Field Source Surface PFSS

$$\boldsymbol{J} = \nabla \times \boldsymbol{B} = 0$$

$$\Rightarrow \quad \boldsymbol{B} = \nabla\phi$$

$$\Rightarrow \quad \nabla \cdot \boldsymbol{B} = \boxed{\nabla^2\phi = 0}$$ Potential field

- Has analytic solution!
- Solution determined entirely by surface magnetogram
- Outer boundary condition – field radial at $2.5r_o$

- Inexpensive
- Very Robust
- Poorest physical approximation

NLFF

- Non zero currents allowed, but only parallel to fieldlines

$$\Rightarrow \; (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = 0$$

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

- Relatively Inexpensive
- Robust
- More realistic than potential
    - Allows for magnetic free energy
- Not as realistic as MHD

Solar and Helio RoR Summary

- Available Models
  - WSA/ENLIL
  - CORHEL (MASP, MAST)
  - SWMF AWSoM
  - Non Linear Force Free Field (NLFFF)

- 3 Different approximations for treatment of corona
  1. No current in low inner corona – WSA

$$\nabla^2\phi = 0$$

  2. Only field aligned currents in inner corona – NLFFF

$$\boldsymbol{J} \times \boldsymbol{B} = (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = 0$$

Solar and Helio RoR Summary

- Potential field models
  - Poorest approximation
  - Time independent
  - Cheapest
  - Most Robust
  - Useful for developing a sense of the global field structure
- NLFF
  - more accurate approximation
  - Still time independent
  - Slightly more expensive
  - Still very robust
  - Useful for studying Active Region free energy buildup and stability
- MHD
  - Best approximation above kinetic scales
  - Time dependent
  - Expensive
  - Very temperamental
  - Useful for everything

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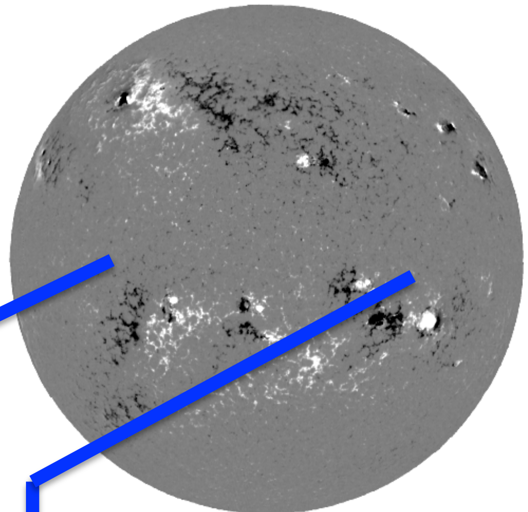
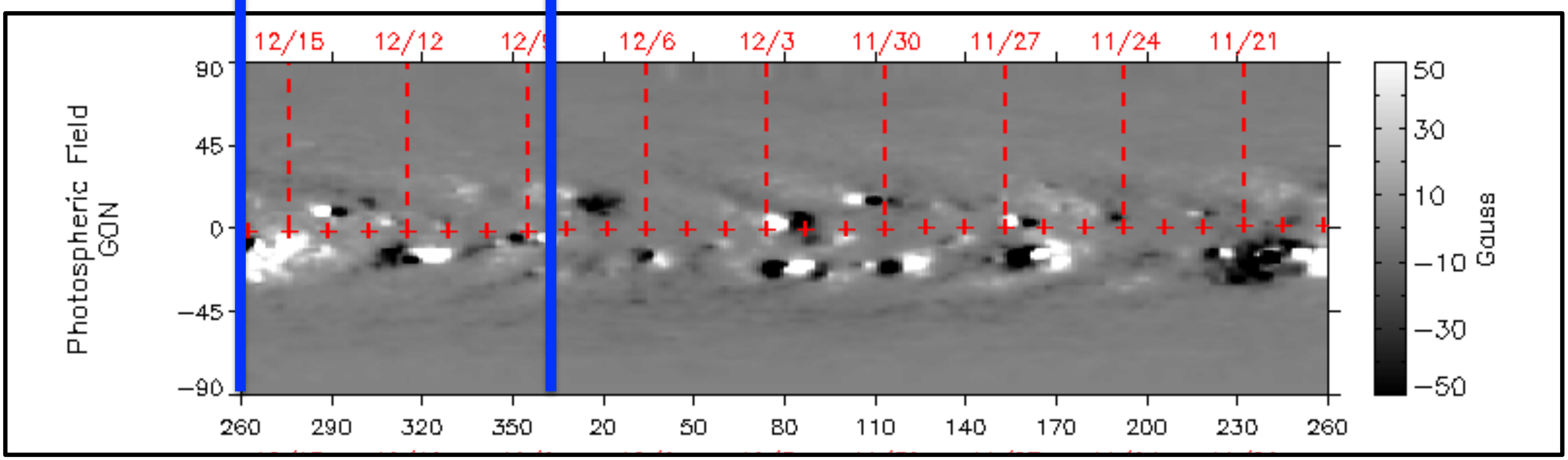
Synoptic Magnetograms

Full Disk Photospheric Magnetogram



- Daily synoptic maps hourly from GONG
- Full rotation ‘science quality’ maps posted within about 2 months



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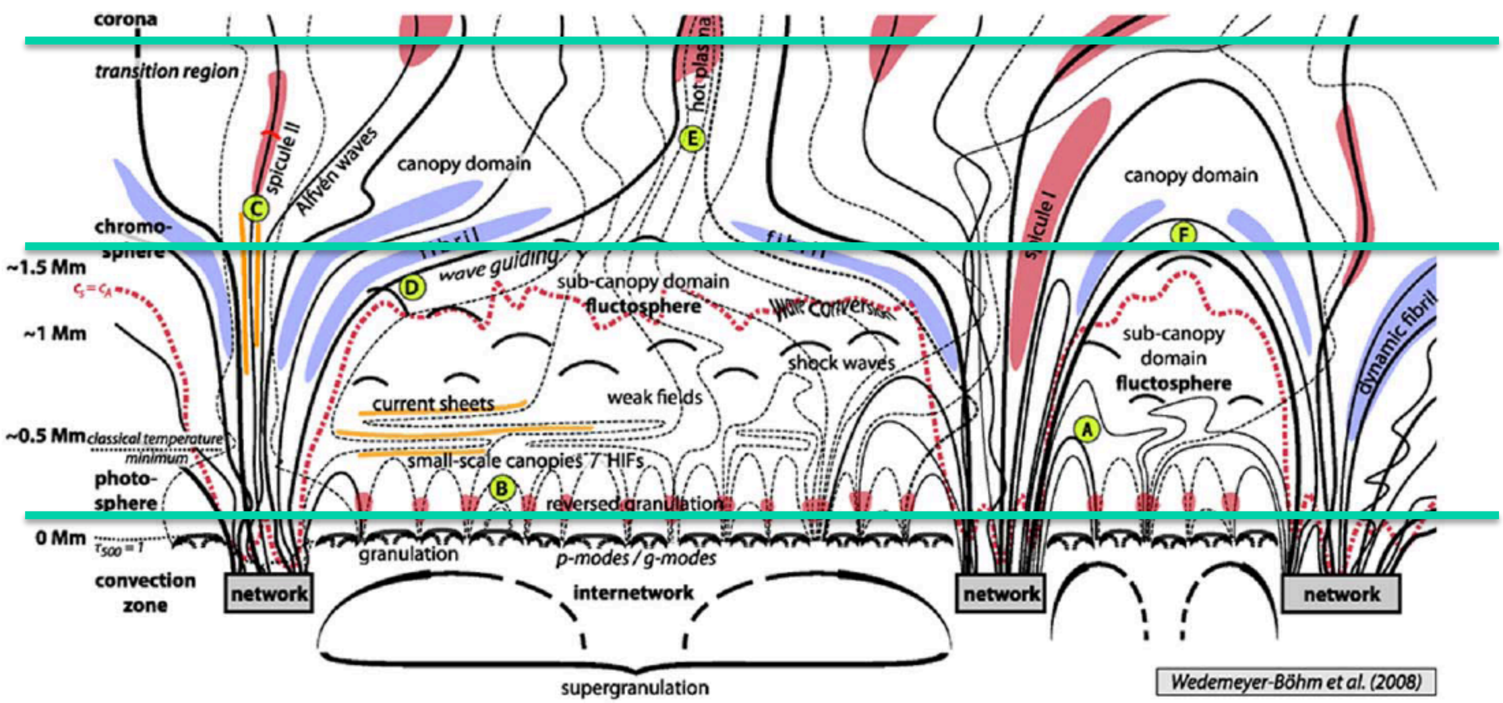
Magnetogram Height and Model Inner Boundary



Coronal model base

Chromospheric magnetograms

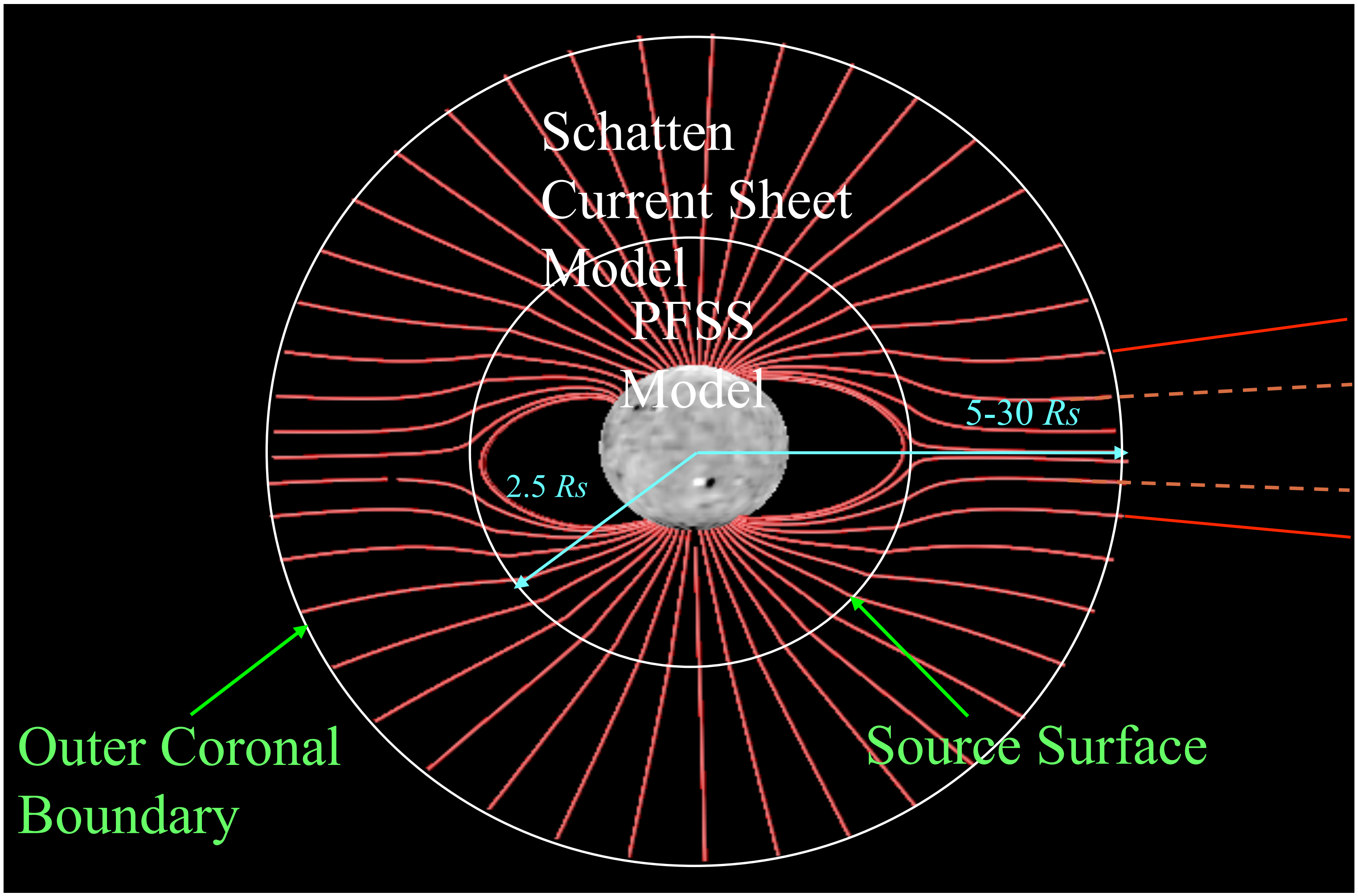
Photospheric magnetograms

30 Mm

GONG Pixel size

Aspect ratio distorted – Height enhanced by factor of 10

Wang-Sheeley-Arge (WSA) Model



Solar Wind Model (e.g., WSA 1D Kinematic model, ENLIL, CORHEL, SWMF) (5-30*Rs* to 1AU)

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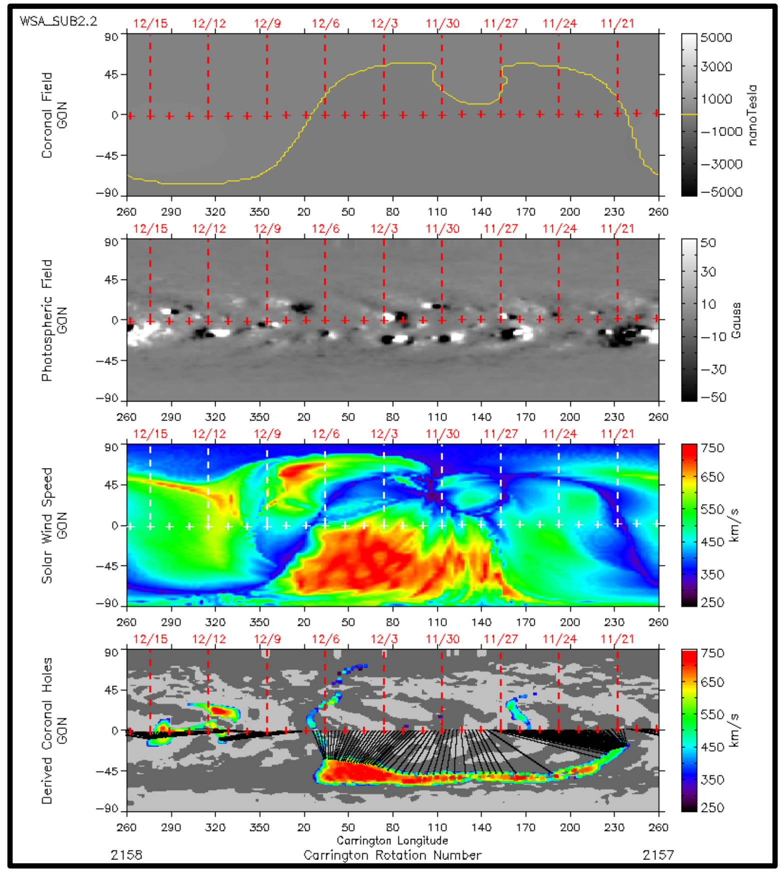
Wang-Sheeley-Arge (WSA) Model

- PFSS from surface to $2.5r_o$
- Pseudo-potential solution from $2.5r_o$ to $21.5r_o$
  - Solves separate potential problems for regions of +ve and –ve radial flux
  - Introduces a current sheet at boundary plane
- At $21.5r_o$ defines a local wind speed using an empirical formula based on
  - Rate of expansion of flux tubes
  - Proximity of fieldline footpoint to the nearest coronal hole boundary



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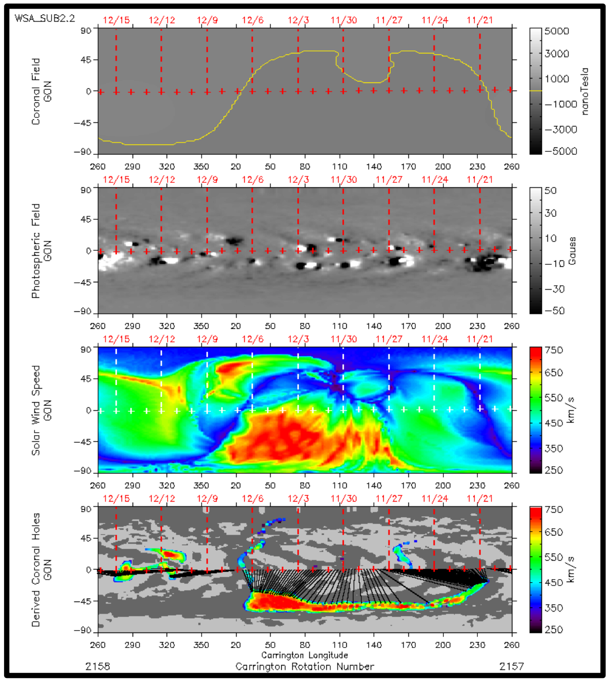
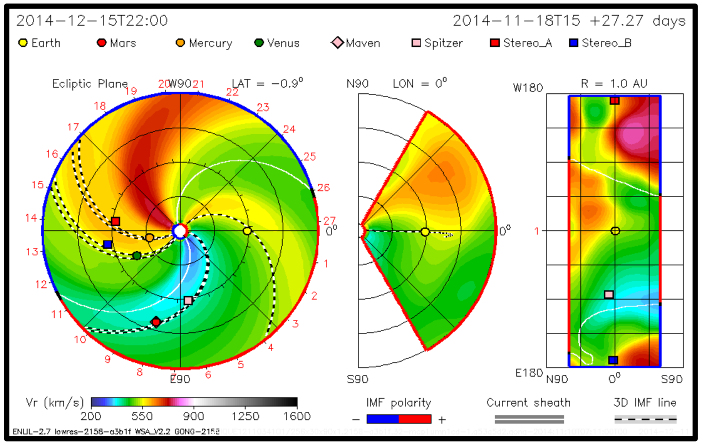
Some Basic Concepts 3

- In MHD, parcels of plasma talk to each other through sound and alfven waves.
- Sound waves cannot propagate upstream in a supersonic flow.
- Beyond the sonic point (~ 5 - 10 Solar radii) and the super-alfvenic point (~10-20 Solar radii), information travels outward only.
  - Equilibrium MHD solutions in the corona must allow waves to slosh back and forth between the surface and the super-alfvenic point – Slower to complete!
  - Beyond the super-alfvenic point the solution is determined by information propagating outward only – Faster to complete!
- Solar wind codes set their inner boundary at 21.5 or 30 r_o which greatly simplifies their inner boundary condition

ENLIL (Odstrcil) Ambient Modeling

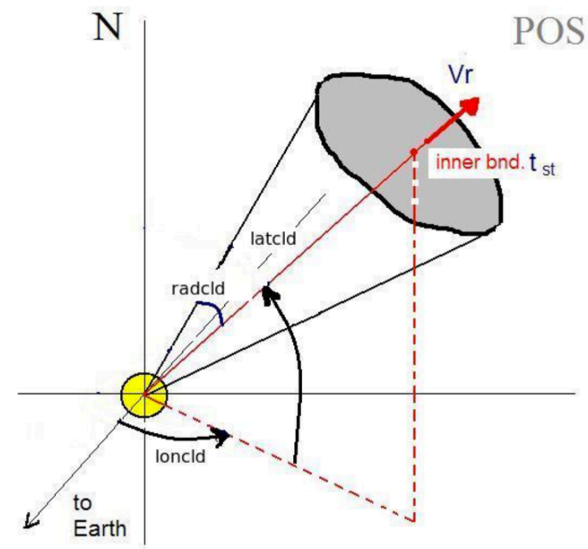
- WSA/ENLIL
- WSA provides model of the coronal field inside 0.1AU and the solar wind flow speed on the sphere at 0.1AU ($21.5r_o$)
  - Input is low resolution time independent synoptic (diachronic) LOS photospheric magnetograms
- ENLIL uses MHD to model from 0.1AU outward
- ENLIL takes the WSA solution at 0.1AU, and adds,
  - – Mass density – uniform mass flux at 0.1AU
  - – Temperature – uniform pressure at 0.1AU
  - – Longitudinal component of B

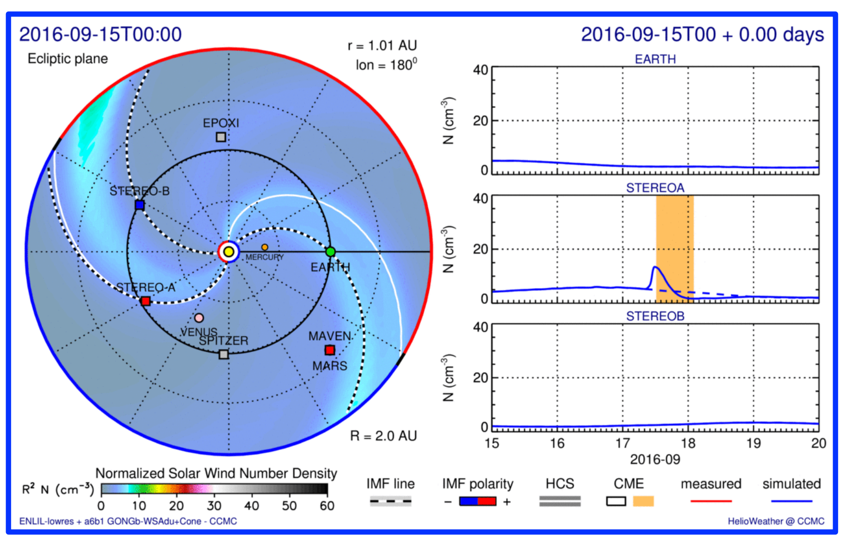




ENLIL (Odstrcil)
Ambient + Cone Model CME

- Adds a CME by inserting a blob of mass emerging through the inner boundary
- The cone model is based on the idea that close to the Sun CME propagates with constant angular and radial velocity, and so has the shape of a cone.
- No internal CME field





CORHEL (PredSci)

- MAS – 3D Mhd Around a Sphere
- Ambient corona/SW
  - Two flavors
    - Polytropic equation of state (MASP)
    - Full energy equation (MAST)
- Two Solution Domains
  - Corona (inside $30r_o$)
    - 3 code options - MASP, MAST, WSA
  - Inner Heliosphere
    - 3 code options – MASP, MAST, ENLIL
- Magnetogram sources - NSO, MWO, GONG, WSO, MDI, HMI

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SWMF AWSoM_R (U. Mich.)

- Alfven Wave Solar Atmosphere Model
- Include Solar Corona (1 to 24 r_o) and Inner Heliosphere (>20r_o) components of SWMF
- 3D MHD on a block adaptive mesh
- Separate electron and ion temperature equations
- Heating by dissipation of alfven waves
- Initialized with a Parker wind solution and PFSS field solution consistent with the selected GONG synoptic magnetogram

SWMF AWSoM_R (U. Mich.)

- For CME cases inserts an unstable Gibson-Low flux rope in corona
- Use StereoCat to determine the CME parameters
- EEGGL system GUI handles user definition of flux rope parameters
- Detailed info on how to use at ccmc.gsfc.nasa.gov/RoR_WWW/presentations/EEGGL_instructions.pdf

- Insert graphic from EEGGL here!!!

NLFFF

- Time independent, low β approximation.
- Magnetic forces overwhelm pressure and gravity in cross-field direction

$$\cancel{\rho(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v}} = \boldsymbol{J}\times\boldsymbol{B} - \cancel{\boldsymbol{\nabla}p+\rho g}$$

$$\boldsymbol{J} = \nabla \times \boldsymbol{B}$$

$$\left.\begin{aligned} &\Rightarrow (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = 0 \\ &\nabla \cdot \boldsymbol{B} = 0 \end{aligned}\right\}$$

Solves these equations consistently with provided vector magnetograms

NLFFF

- NLFFF code solves these equations to extrapolate the magnetic field from the photosphere into the corona
- Code uses a relaxation approach
  - Varies the field to minimize the functional

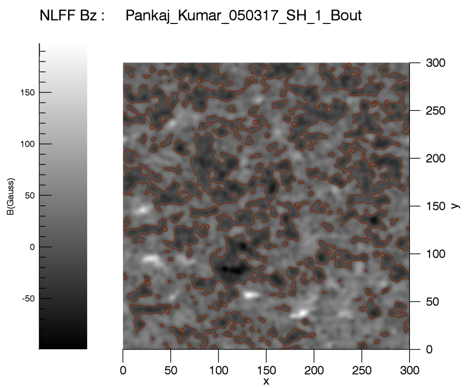
$$L = \int_V w(x, y, z) \left[B^{-2} |(\nabla \times \mathbf{B}) \times \mathbf{B}|^2 + |\nabla \cdot \mathbf{B}|^2 \right] \mathrm{d}^3 x$$

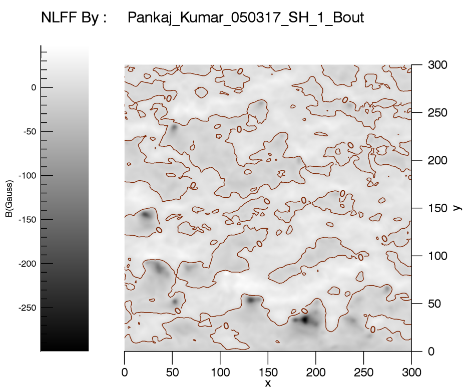
- Must also enforce surface constraints
  - Total force and torque on photospheric boundary must be 0
  - Photosphere ($\beta \sim 1$) is not force free so solution field will vary from the observed vector field.
  - Done by adding surface integral components to L

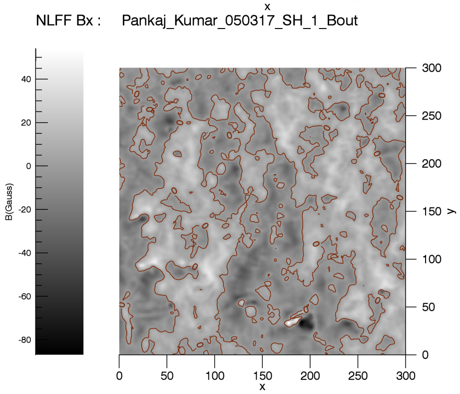
NLFFF Usage

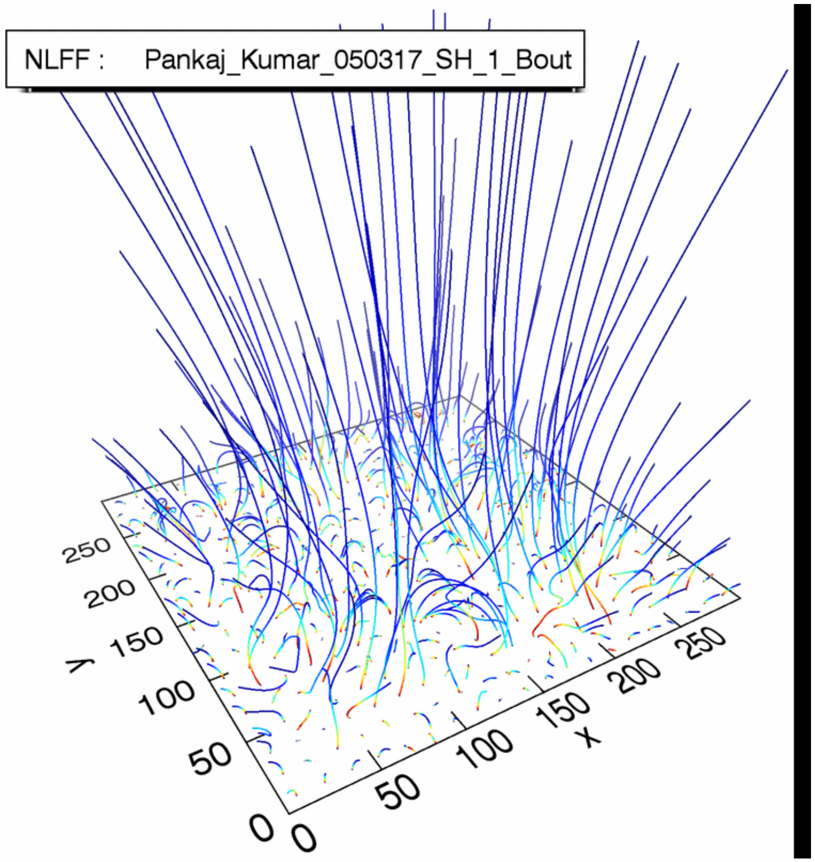
- Code will support 3 modes
  1. Active region size FOV – cartesian grid
     - Custom page at SDO JSoC to provide vector data
     - Useful for AR structure and energy build up studies
  2. Multi-active region size FOV – spherical coords
     - Not available yet
     - Useful for studying interactions between Ars
     - Destabilization of large scale filament structures
  3. Global – spherical coords
     - Not available yet

NLFFF Usage

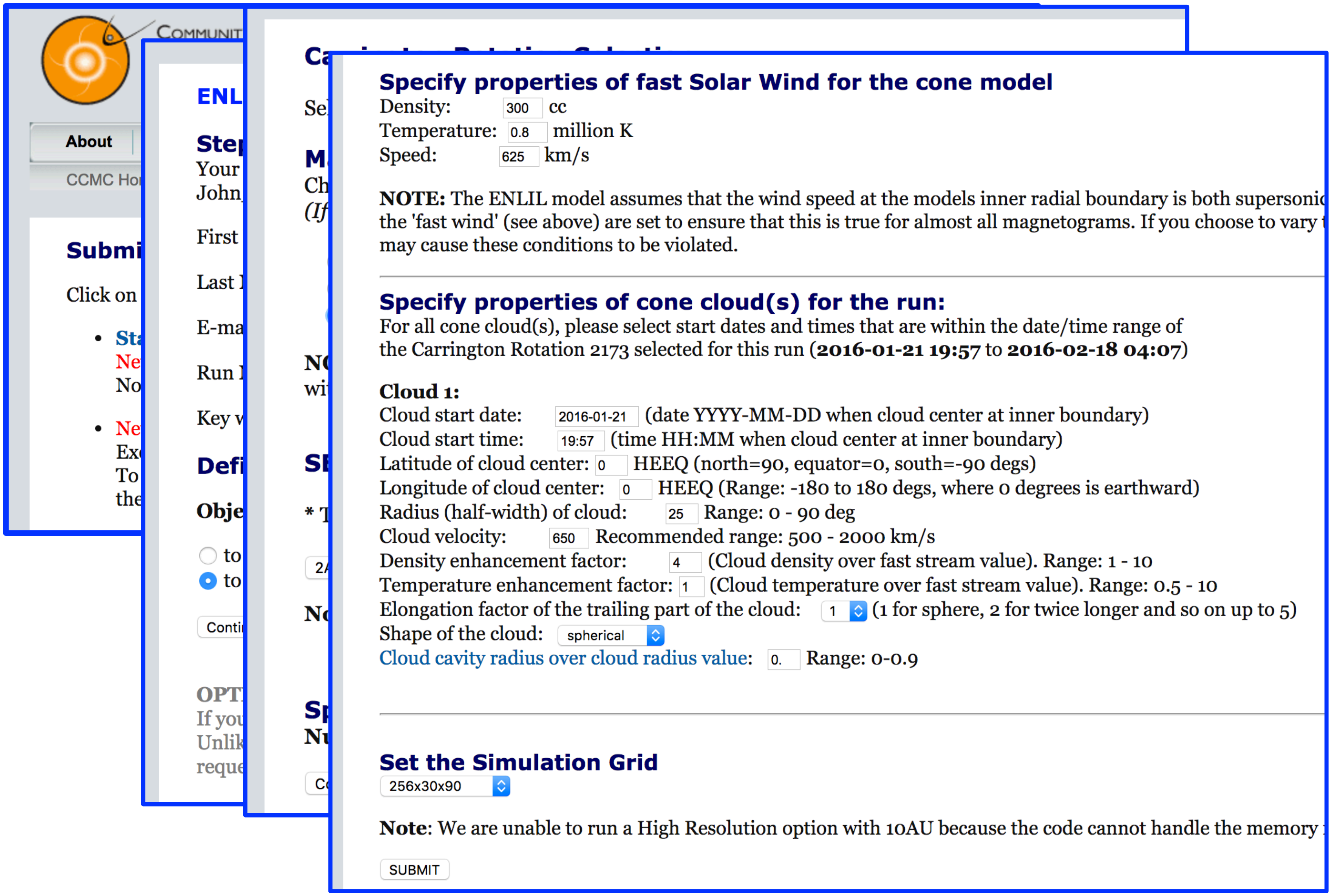

NLFF Bz : Pankaj_Kumar_050317_SH_1_Bout
B(Gauss)
x
y


NLFF By : Pankaj_Kumar_050317_SH_1_Bout
B(Gauss)
x
y


NLFF Bx : Pankaj_Kumar_050317_SH_1_Bout
B(Gauss)
x
y

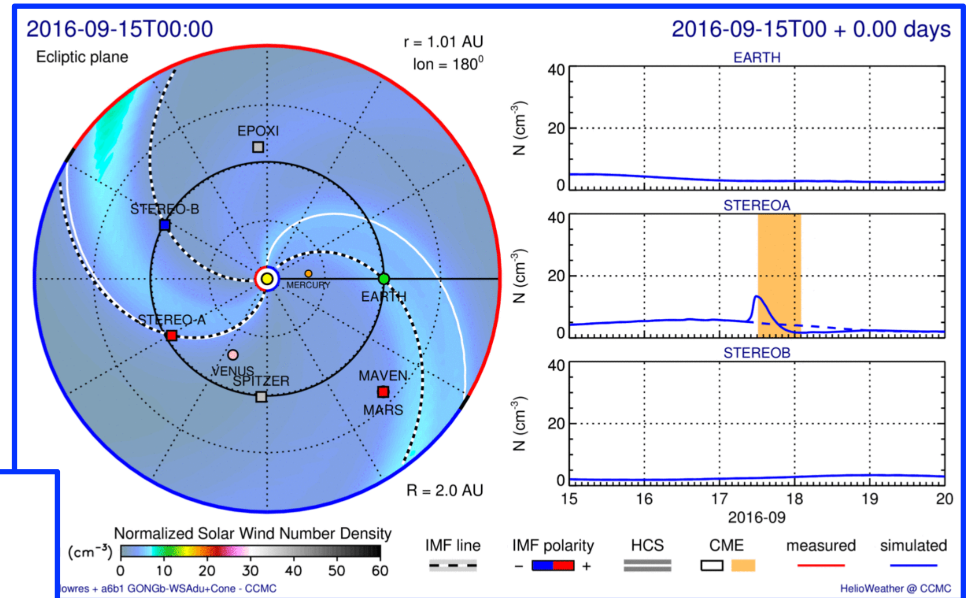

NLFF : Pankaj_Kumar_050317_SH_1_Bout
x
y

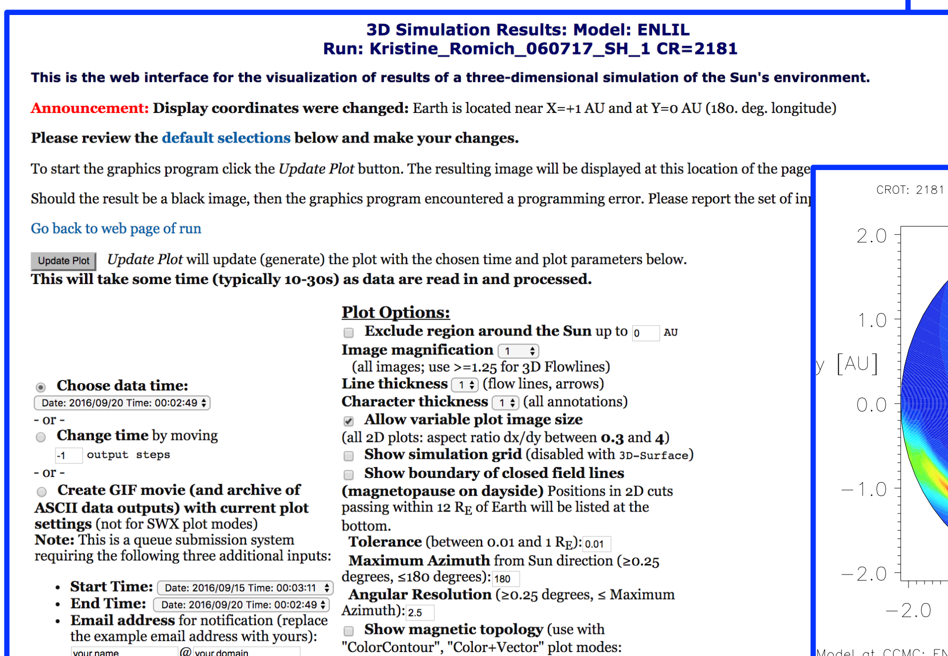
Submission Process
ENLIL Ambient + Cone CME



Viewing Results

- Email with url to results
- Quick Look Graphics
- 3D Viz tool




3D Simulation Results: Model: ENLIL
Run: Kristine_Romich_060717_SH_1 CR=2181

This is the web interface for the visualization of results of a three-dimensional simulation of the Sun's environment.

Announcement: **Display coordinates were changed:** Earth is located near X=+1 AU and at Y=0 AU (180. deg. longitude)

Please review the default selections below and make your changes.

To start the graphics program click the *Update Plot* button. The resulting image will be displayed at this location of the page

Should the result be a black image, then the graphics program encountered a programming error. Please report the set of in

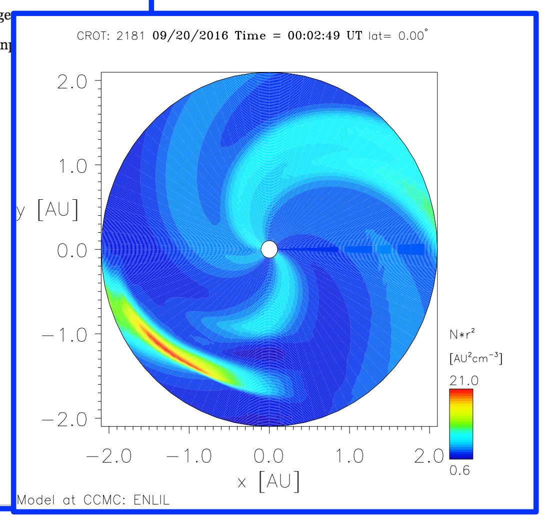
Go back to web page of run

Update Plot *Update Plot* will update (generate) the plot with the chosen time and plot parameters below.
This will take some time (typically 10-30s) as data are read in and processed.

Choose data time:
Date: 2016/09/20 Time: 00:02:49
\- or -
Change time by moving
-1 output steps
\- or -
Create GIF movie (and archive of ASCII data outputs) with current plot settings (not for SWX plot modes)
Note: This is a queue submission system requiring the following three additional inputs:

- **Start Time:** Date: 2016/09/15 Time: 00:03:11
- **End Time:** Date: 2016/09/20 Time: 00:02:49
- **Email address** for notification (replace the example email address with yours):
your.name @ your.domain

Plot Options:
Exclude region around the Sun up to 0 AU
Image magnification 1
(all images; use >=1.25 for 3D Flowlines)
Line thickness 1 (flow lines, arrows)
Character thickness 1 (all annotations)
Allow variable plot image size
(all 2D plots: aspect ratio dx/dy between **0.3** and **4**)
Show simulation grid (disabled with 3D-Surface)
Show boundary of closed field lines (magnetopause on dayside) Positions in 2D cuts passing within 12 R_E of Earth will be listed at the bottom.
Tolerance (between 0.01 and 1 R_E): 0.01
Maximum Azimuth from Sun direction (≥0.25 degrees, ≤180 degrees): 180
Angular Resolution (≥0.25 degrees, ≤ Maximum Azimuth): 2.5
Show magnetic topology (use with "ColorContour", "Color+Vector" plot modes:



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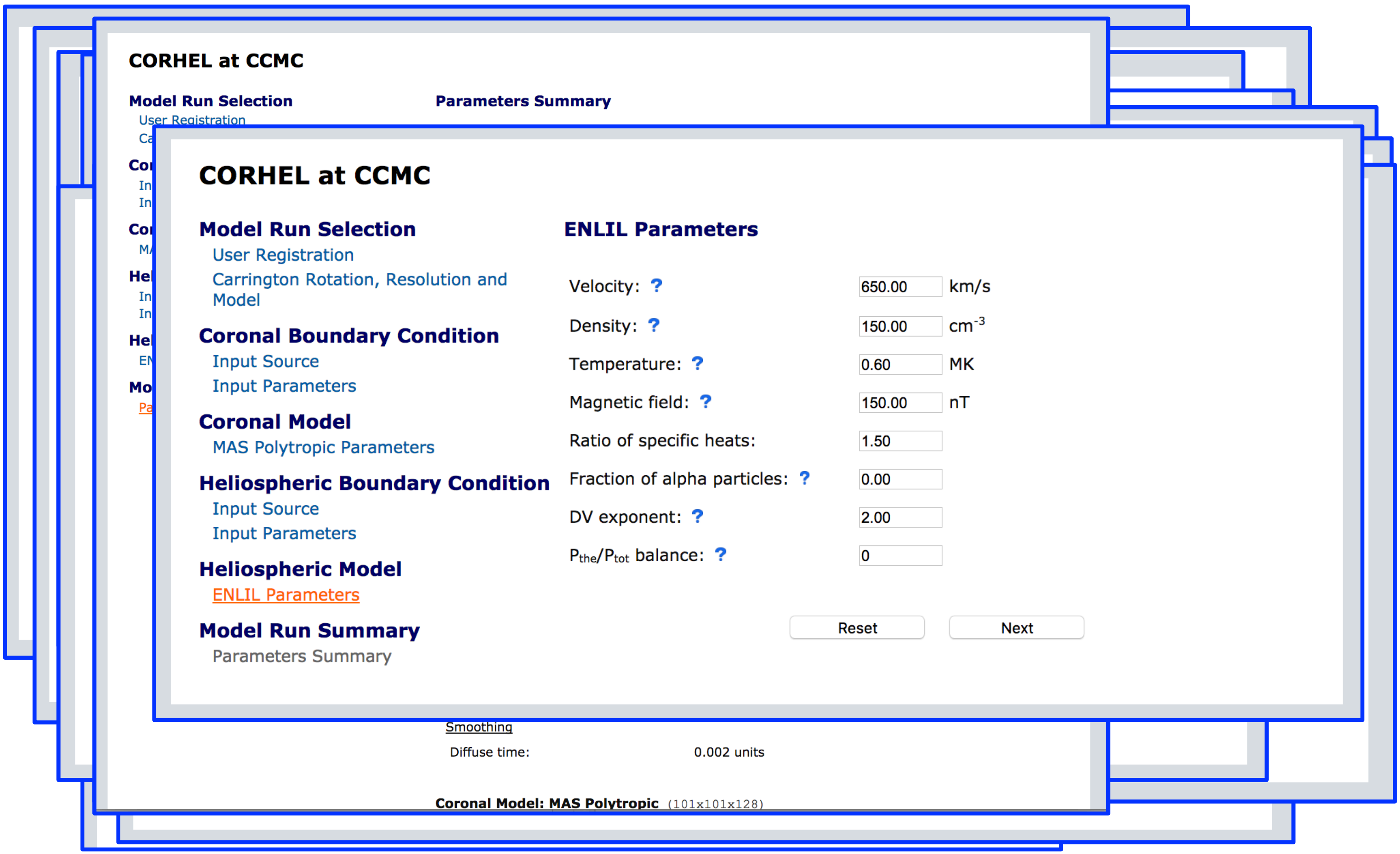
CORHEL Submission

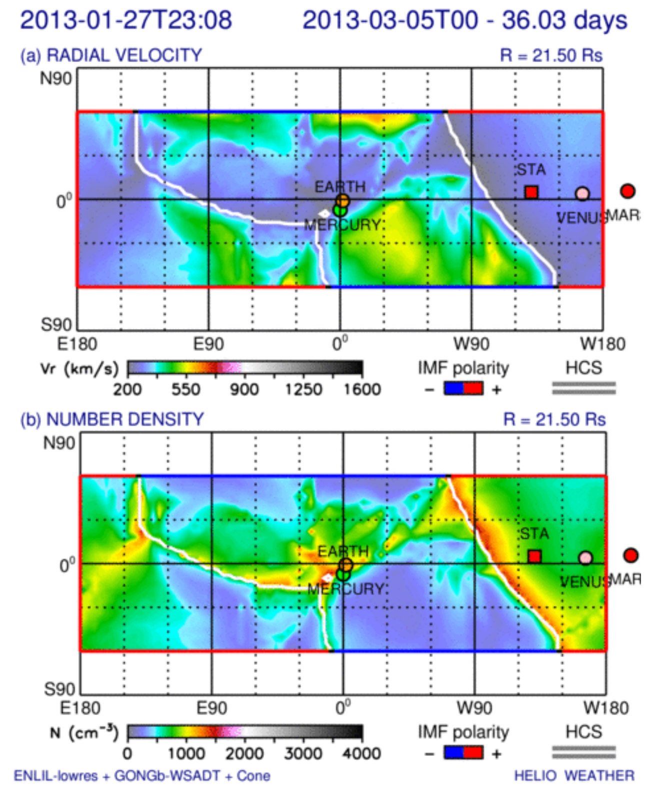


Impending Updates

- Time dependent magnetograms
- Coupling wind models wind models of particle acceleration at ICME shock fronts
- CGEM – Time evolving NLFF solutions driven by HMI vector data and surface flows
- QSL – Squashing factor field topology analysis tool

Time Dependent Magnetogram Drivers

- Old approach – ambient corona determined from a static global photospheric field
- New approaches provide time evolving global photospheric field
  - Approach 1 – Time Interpolating hourly gong synoptic magnetograms - Odstrcil
  - Approach 2 – ADAPT (Arge and Henney) Time Interpolated Magnetograms
    - Adds evolution of far side field, differential rotation, meridional flows, flux emergence, Ars detected by helioseismology



- Benefits
  - More accurate temporal evolution of solar wind
  - Enables continuity of model runs longer than 27.27 days
  - Better treatment of impact of CMEs on ambient wind
  - ADAPT provides ensemble of far side field evolution