PROGRESS Space Weather Summer School
26-28 July 2017

From the Sun to L1
Propagation of the solar wind

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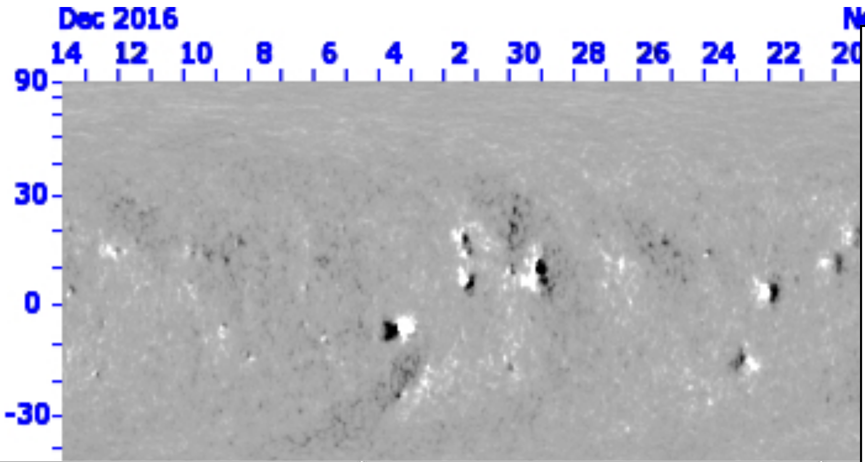
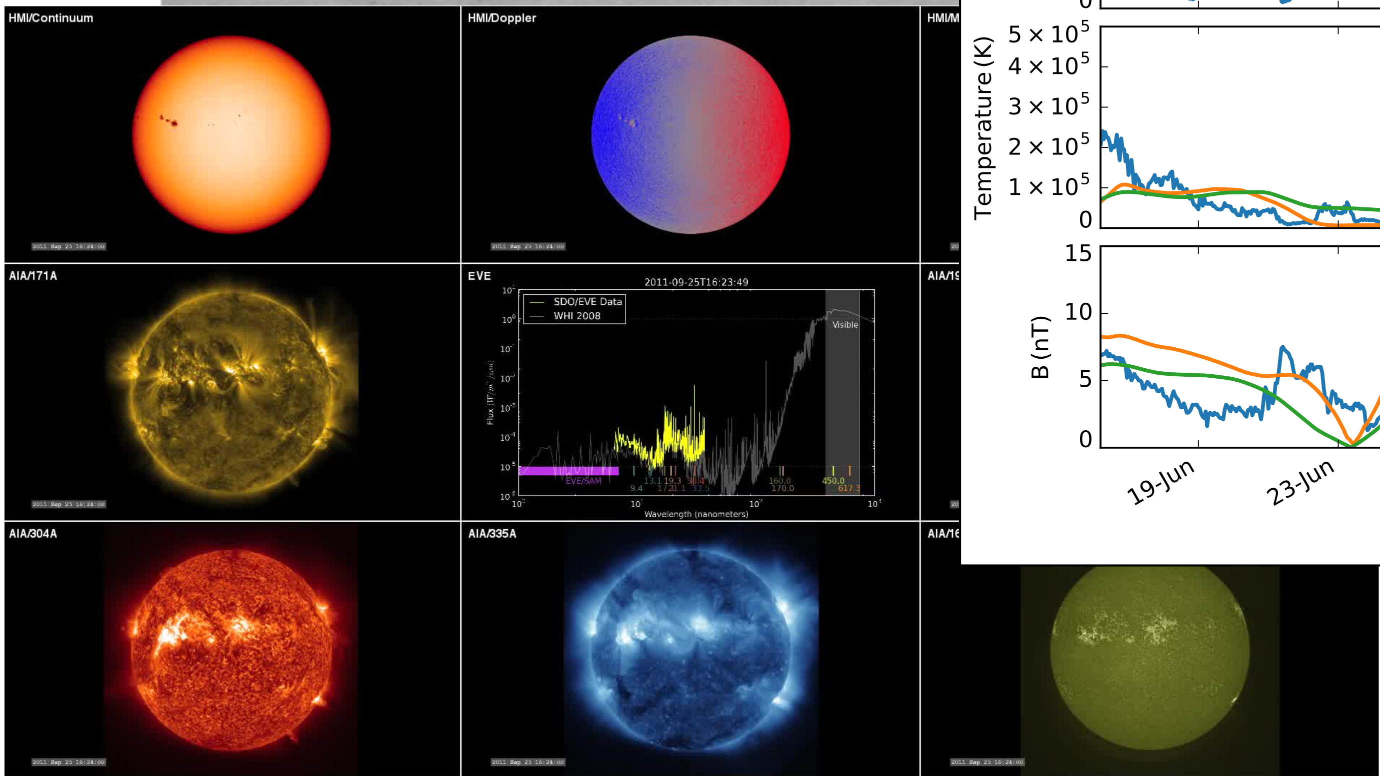
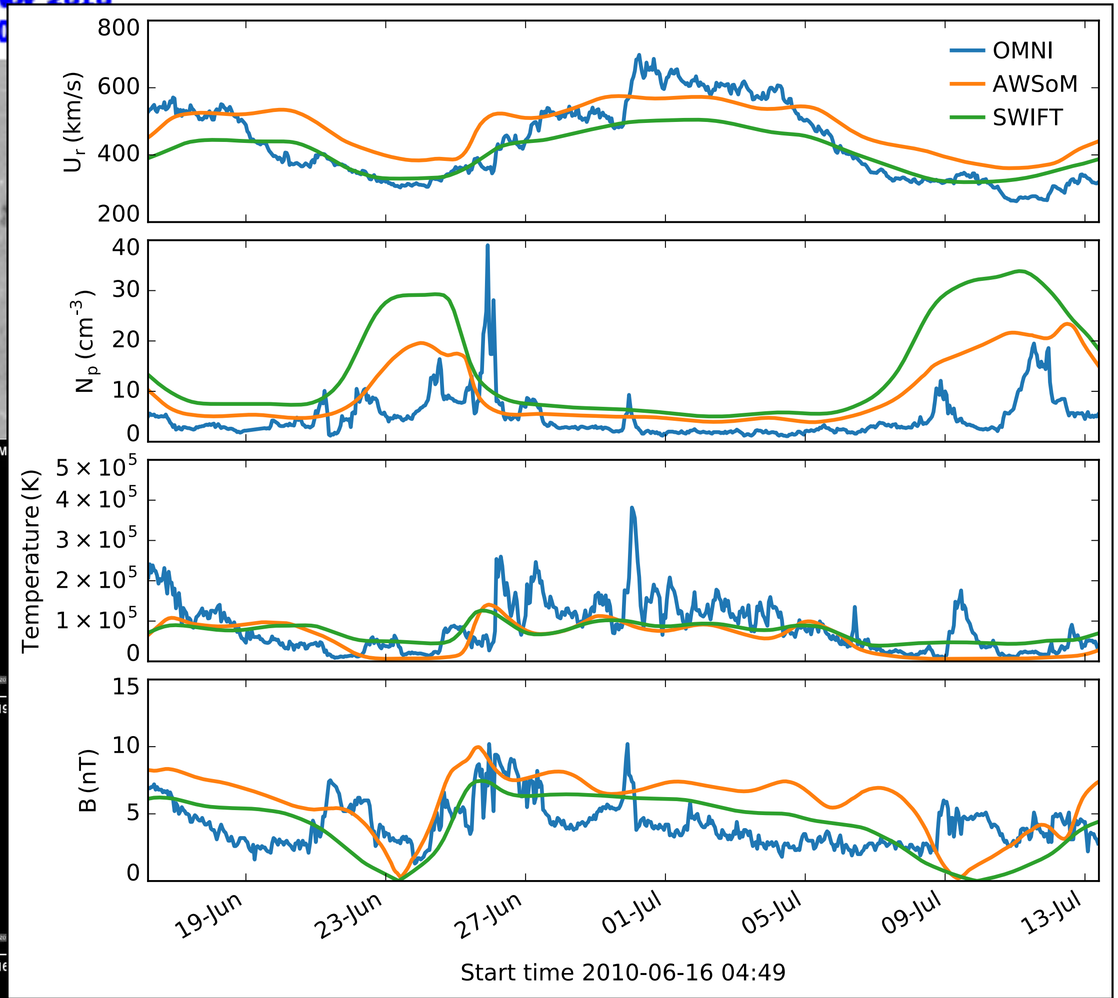
Objectives

From solar surface predict the MHD variables at L1 and 1 A.U.







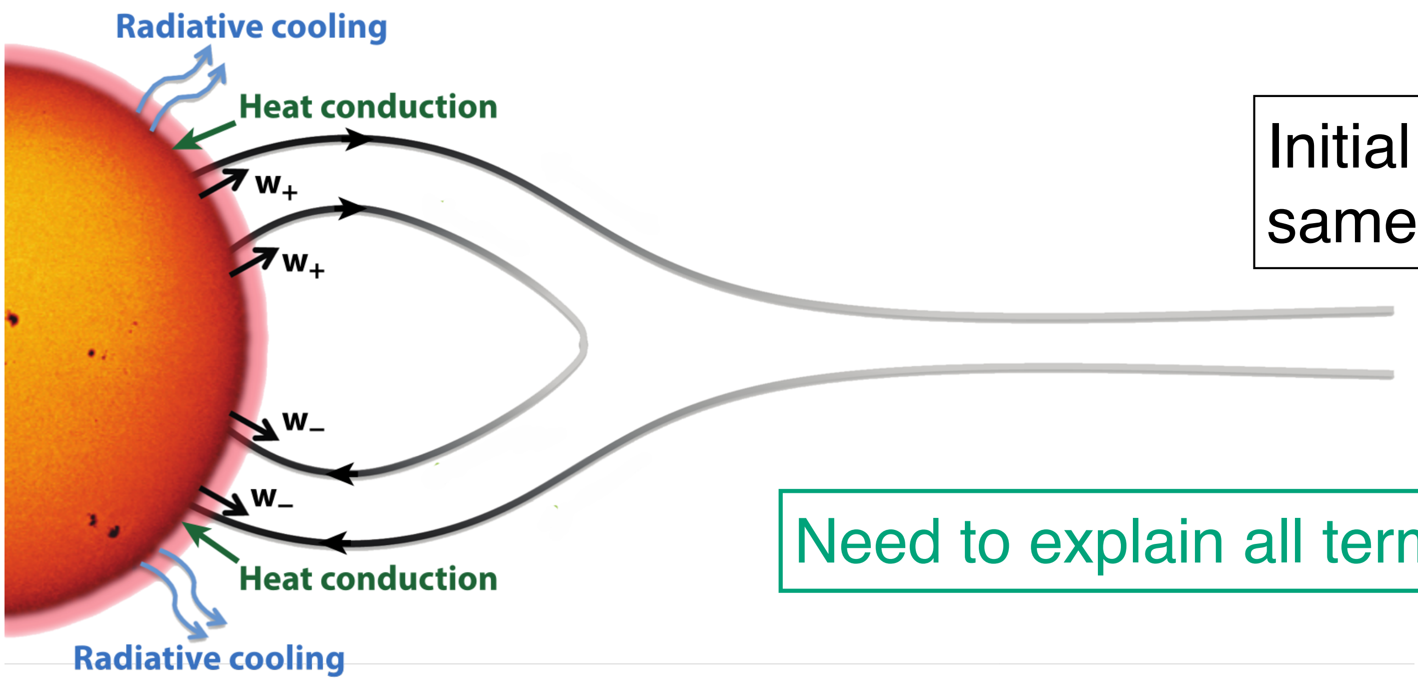
Multi-layered coupled modelling

GONG data used to get potential B-field out to 2.5 R_{sun}

Schatten current-sheet potential field from 2.5 R_{sun} to 21.5 R_{sun}

Use potential field as starting point for AWSoM simulation

At 20 Solar radii data interpolated from AWSoM onto inertial SWIFT grid and solution propagated to 1 AU



Initial potential field model same as in WSA-ENLIL

Need to explain all terms in GREEN

Talk Plan

Break talk into three sections with breaks

Explain WSA-ENLIL-Cone model

Common space weather tool which sets scene for PROGRESS model

Explain turbulent heating model for corona

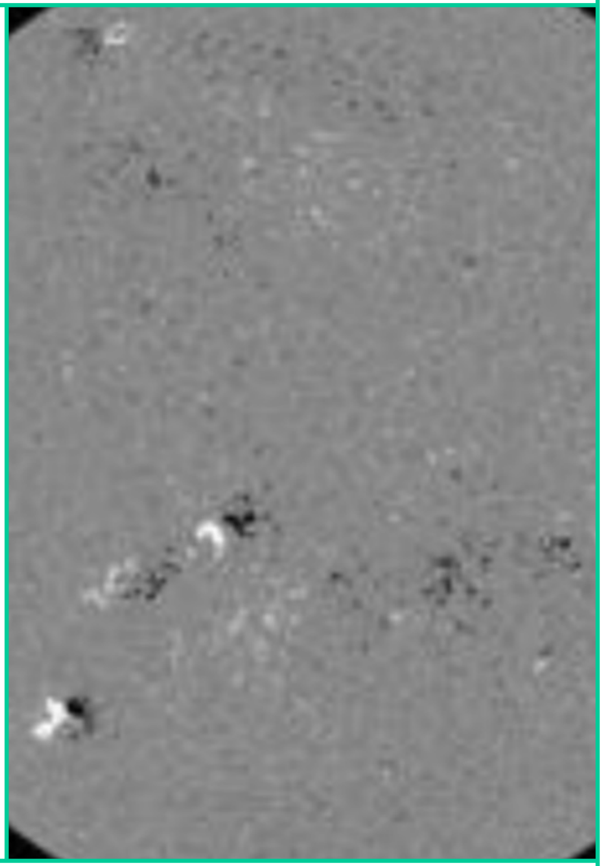
Used in AWSoM code to solve for full MHD structure of corona

Describe coupled ASWoM-SWIFT model used in PROGRESS

Explain coupling, thermal conduction and show initial results

Conclude with prospects for improving models

GONG data disk image



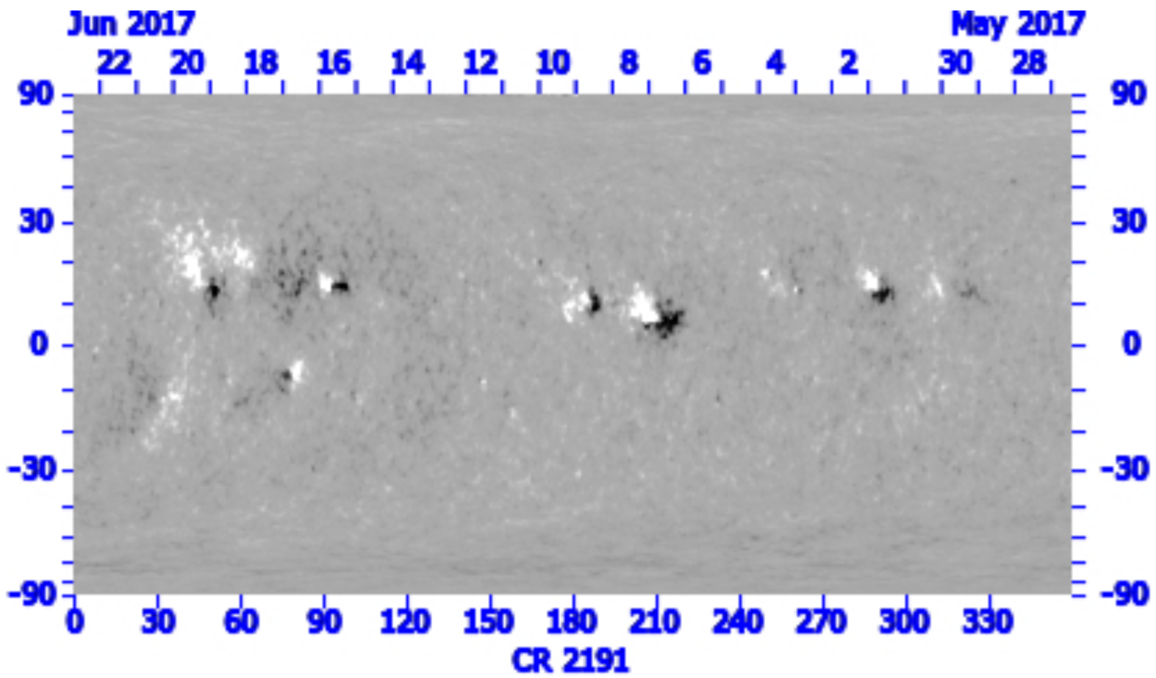
Line-of-sight so only 120 degrees used

Poor resolution at poles so fitting schemes needed

Project onto longitude-latitude

GONG Data

6 GONG sites take full-disk images every ~minute



These are averaged into 10 minute images

Image covers 120 degrees

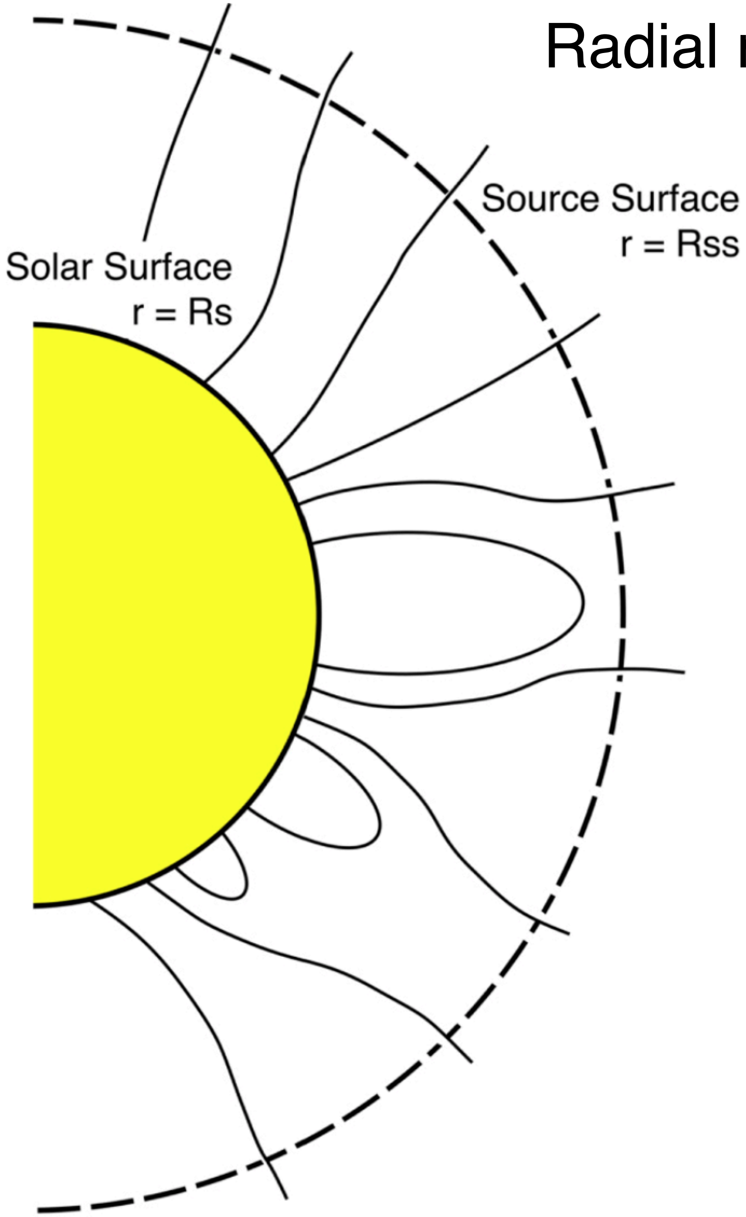
Overlapping images averaged with a weight based on $cos^4(\phi)$

A full rotation image can be updated every ~8hrs

Hourly updates need special treatment of western edge weighting

Poles are poorly resolved and need extrapolation…

Potential Field Source Surface (PFSS)



Radial magnetic field at the solar surface from GONG

Chose a surface R_{ss}, usually at 2.5 R_{sun}

On R_{ss} fix the field to be radial to match field structure expected due to solar wind

Potential field between R_{sun} and R_{ss}

$$\mathbf{B} = -\nabla\Phi \qquad \mathbf{j} = \nabla \times \mathbf{B} = 0$$

$$\nabla^2\Phi = 0$$

Schatten Current Sheet (SCS)

At R_{ss} replace B_r with $abs(B_r)$ and repeat PFSS out to 21.5 R_{sun}

Then add sign back on to B-field.

Gives a pseudo-potential field with a current sheet to mimic solar wind effect of large scale field

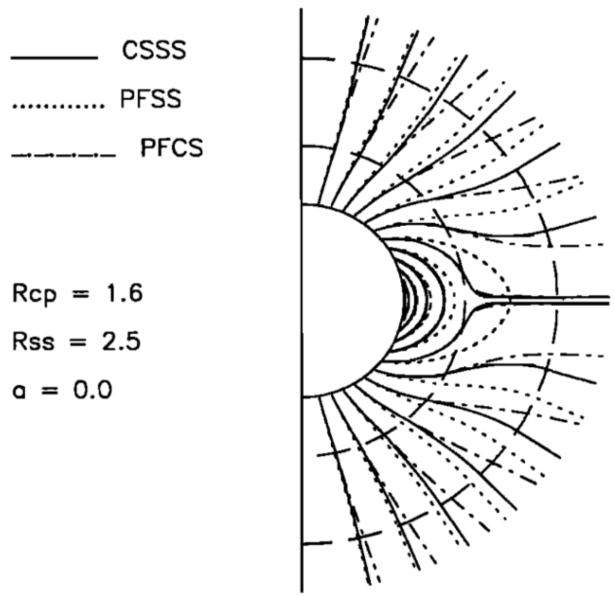
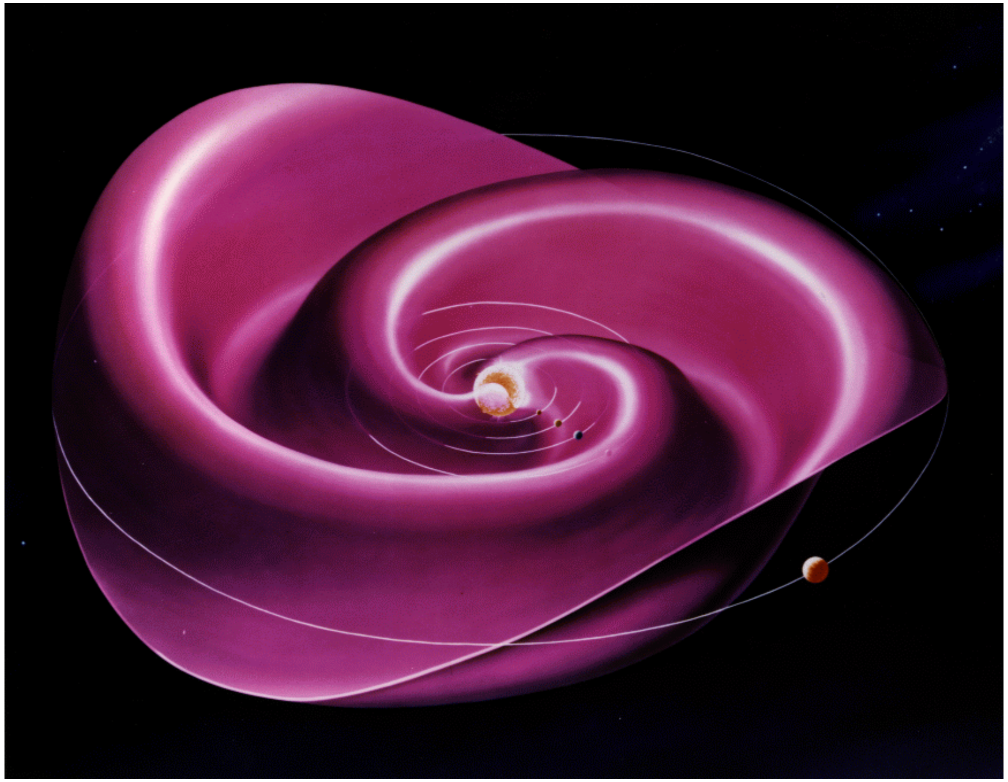


Figure 4. Comparison of the magnetic field configurations calculated using the current sheet–source surface (CSSS) model developed in this paper, the potential field source surface (PFSS) model, and the potential field current sheet (PFCS) model with the same vertical dipole field boundary condition.



Zhao & Hoeksema, JGR 1995

Wang-Sheeley-Arge (WSA)

PFSS + SCS give B_r at 21.5 R_{sun} from GONG data

What about all other MHD variables?

Expansion factor

$$f = \left(\frac{R_\odot}{r}\right)^2 \frac{B(R_\odot)}{B(r)}$$

Radial velocity

$$v(\mathrm{km\ s^{-1}}) = 285 + \frac{650}{f^{5/9}}$$

Density

$$\rho = \rho_{fsw} \left(\frac{v_{fsw}}{v}\right)^2$$

Temperature

$$T = T_{fsw} \left(\frac{\rho_{fsw}}{\rho}\right)$$

Radial velocity based on empirical fit

Latest versions using angular distance from open field regions …

WSA-ENLIL

Use WSA method to provide data to an MHD code at 21.5 R_{sun}
At this radius wind is super-Alfvenic
Ought to solve full temperature MHD equations

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

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{uB} - \mathbf{Bu}) = 0,$$

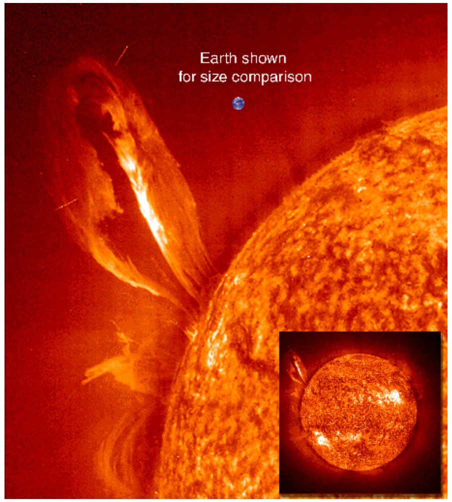
$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left(\rho \mathbf{uu} - \frac{\mathbf{BB}}{\mu_0} \right) + \nabla \left(P_i + P_e + \frac{B^2}{2\mu_0} + P_A \right) = -\frac{GM_\odot \rho \mathbf{R}}{R^3},$$

ENLIL often uses same *abs(B)* as SCS to avoid heliospheric current sheet reconnection. Then needs a separate equation for polarity *s*

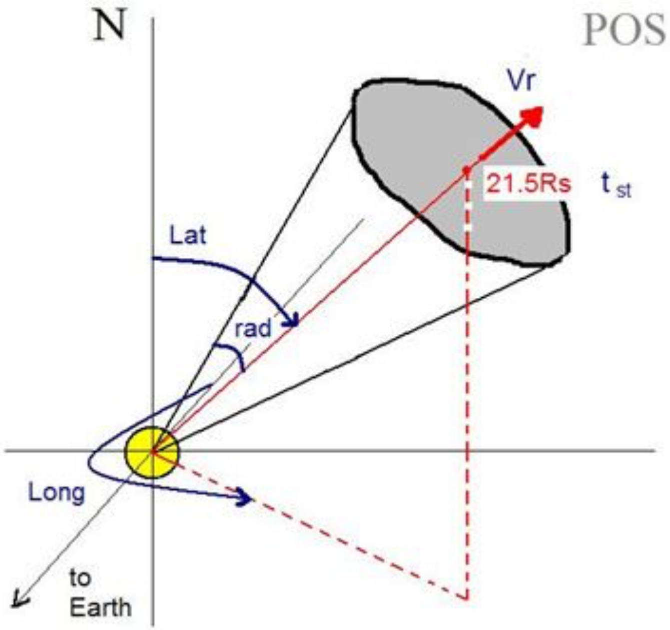
$$\frac{\partial s}{\partial t} + \nabla . (s\mathbf{v}) = 0$$

Energy equation is adiabatic with a modified ratio of specific heats

WSA-ENLIL-CONE



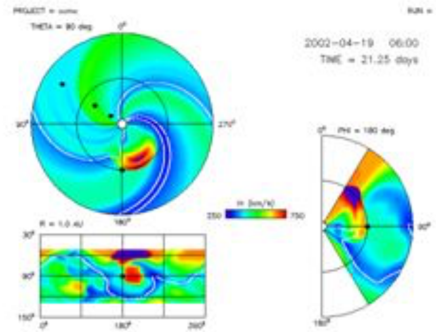
Cone Model Parameters – Input to the ENLIL Cone Model



Date=2002-04-17
Tstart=11:20 (UT)
Lat=77 deg
Long=202 deg
Rad=49 deg
Vr=1134 km/s

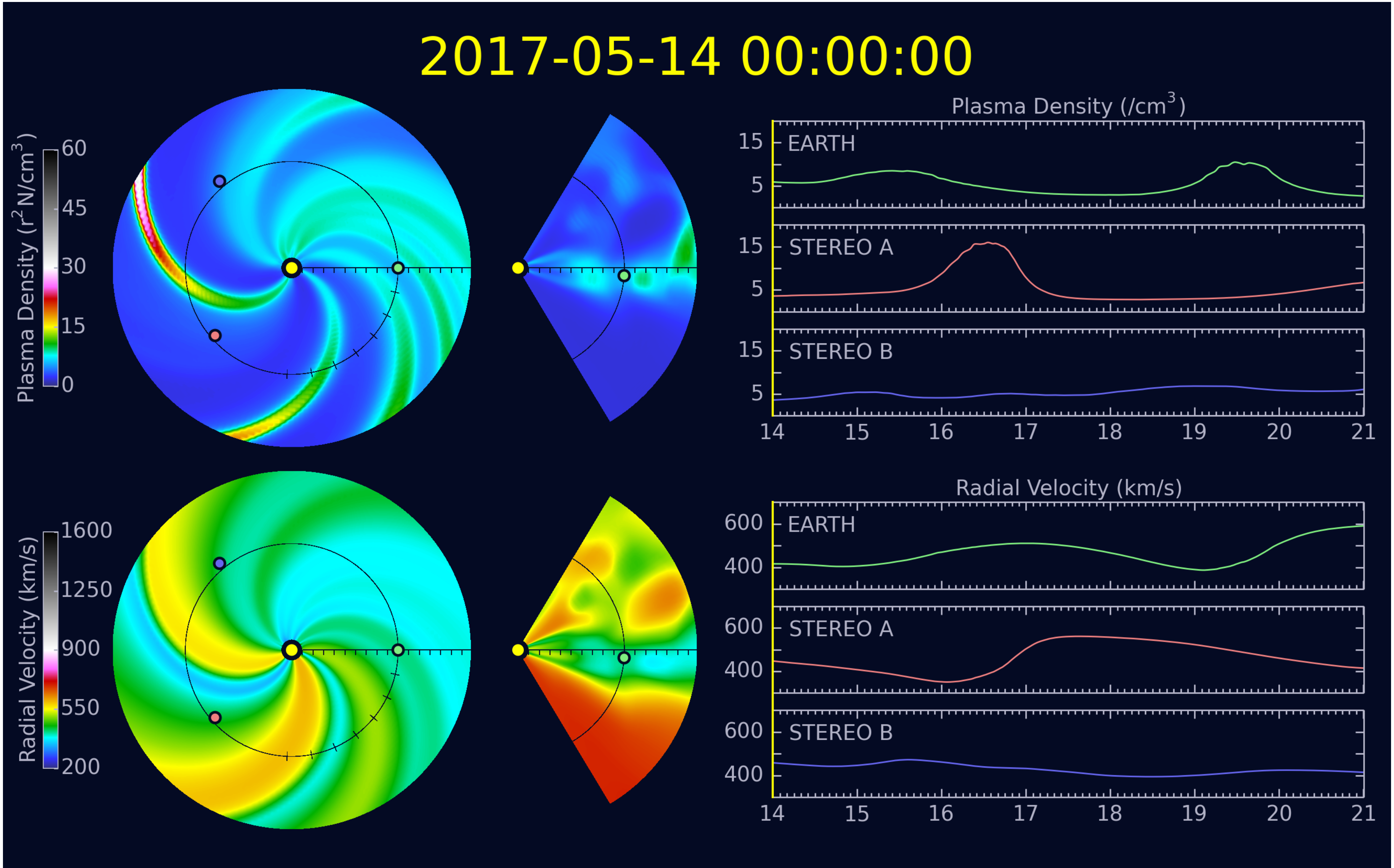
Input to ENLIL cone model run

ENLIL cone model

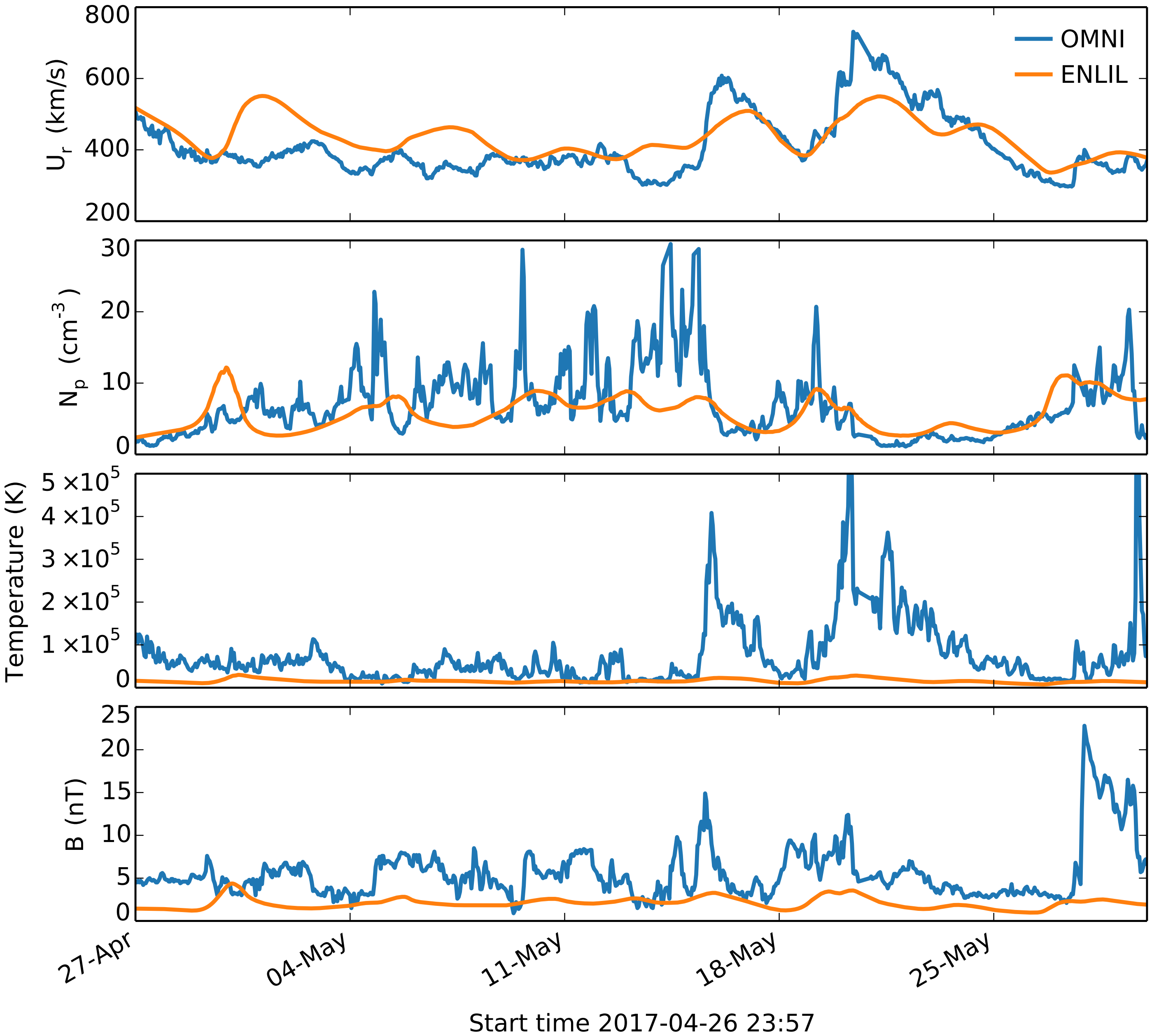


- tstart - when cloud at 21.5Rs
- Latitude
- Longitude
- Radius (angular width)
- Vr - radial velocity

WSA-ENLIL typical results



WSA-ENLIL compared to OMNI



Summary so far

GONG data used to get potential B-field out to 2.5 R_{sun}

Schatten current-sheet potential field from 2.5 R_{sun} to 21.5 R_{sun}

WSA model adds velocity, temperature and density

ENLIL solves single temperature MHD out to 1 A.U.

WSA-ENLIL-Cone handles CME's

WSA-ENLIL-Cone can predict quite SW ~4 days in advance

WSA-ENLIL-Cone can predict CME's 1-2 days in advance

PROGRESS Project

Aim to predict MHD variables at 1 A.U. from GONG data

Replace empirical models of WSA with first principles model

Allow full vector B-field and flux rope CMEs

Use 2 temperature MHD

Shock heating of ions, thermal conduction in electrons

Two coupled codes AWSoM and SWIFT

AWSoM assumes coronal heating and solar wind drive due to MHD turbulence

MHD in conservative form

$$\frac{\partial \rho}{\partial t} = -\nabla.(\rho \mathbf{v})$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} = -\nabla.\left(\rho \mathbf{v}\mathbf{v} + \mathbf{I}(P + \frac{B^2}{2}) - \mathbf{B}\mathbf{B}\right)$$

$$\frac{\partial E}{\partial t} = -\nabla.\left(\left(E + P + \frac{B^2}{2\mu_0}\right)\mathbf{v} - \mathbf{B}(\mathbf{v}.\mathbf{B})\right)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla(\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v})$$

$$E = \frac{P}{\gamma - 1} + \frac{\rho v^2}{2} + \frac{B^2}{2\mu_0}$$ The total energy density

Scale-free

Replace x=ax, t=bt etc.
and equations unchanged

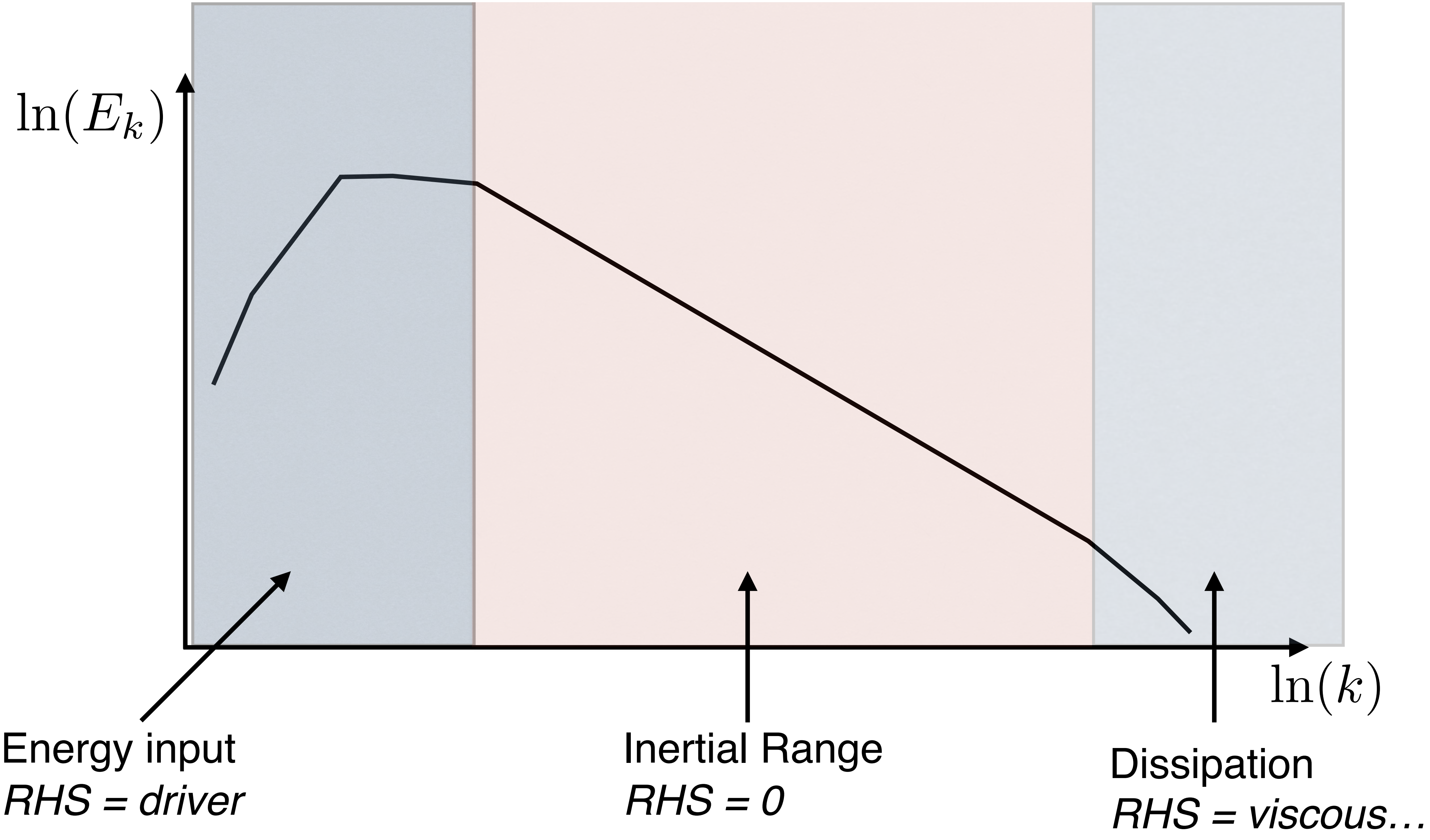
Scale only introduced from *RHS* e.g. resistivity/ viscosity etc.

All of the form

$$\boxed{\frac{\partial U}{\partial t} + \nabla.F(U) = RHS}$$

Turbulence

MHD equations $$\frac{\partial U}{\partial t} + \nabla . F(U) = RHS$$

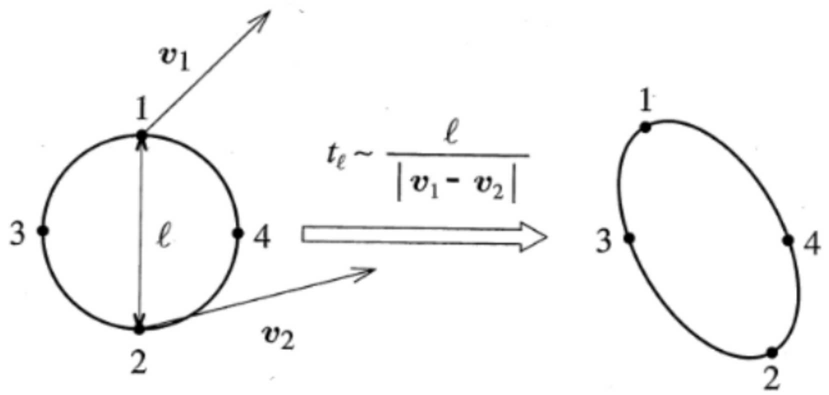


Eddy mixing

Energy transfer rate through inertial range is constant $\mathcal{E}$

$\mathcal{E}$ local dissipation rate

Fluctuations in flow moves energy between scales



Eddie turn over time

$$\tau_l \sim \frac{l}{v_l}$$

Energy transfer from scale *l* to smaller scales

$$\Pi(l) \sim \frac{v_l^2}{\tau_l} = \frac{v_l^3}{l}$$

Kolmogorov - K41

$$\Pi(l) \sim \frac{v_l^2}{\tau_l} = \frac{v_l^3}{l}$$ but $$\Pi(l) = \varepsilon$$

$$v_l \sim l^{1/3}\varepsilon^{1/3}$$

Energy associated with flow at scale *l* = lv_l^2

$$E_l \sim \varepsilon^{2/3} l^{5/3}$$

More commonly $$E_k \sim \varepsilon^{2/3} k^{-5/3}$$

Ignores anisotropy of MHD

$$S_3(l) = < (u(x+l) - u(x))^3 > = -\frac{4}{5}\varepsilon l$$

Iroshnikov-Kriachnan

In MHD Alfven waves interact weakly and pass by in time-scale

$$\frac{l}{v_A}$$

Eddie turn-over time is $\frac{l}{v_l}$

Time-scale for energy transfer is now $\tau_l \sim \frac{l}{v_l}\frac{v_A}{v_l}$

Repeat K41 but now get $E_k \sim (\varepsilon v_A)^{1/2} k^{-3/2}$

Incompressible MHD Turbulence

To get turbulent cascade and heating need non-linear interactions

$$\partial_t \mathbf{v} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\rho_0}\nabla p + \frac{1}{4\pi\rho_0}(\mathbf{B}\cdot\nabla)\mathbf{B} + \nu\nabla^2\mathbf{v}$$
$$\partial_t \mathbf{B} = \nabla\times[\mathbf{v}\times\mathbf{B}] + \eta\nabla^2\mathbf{B}$$

Separate the uniform magnetic field: $\mathbf{B} = \mathbf{B}_0 + \mathbf{b}$

Introduce the Elsasser variables: $\mathbf{z}^{\pm} = \mathbf{v} \pm \frac{1}{\sqrt{4\pi\rho_0}}\mathbf{b}$

Then the equations take a symmetric form:

$$\boxed{\begin{aligned} \partial_t \mathbf{z}^+ - (\mathbf{v}_A\cdot\nabla)\mathbf{z}^+ + (\mathbf{z}^-\cdot\nabla)\mathbf{z}^+ &= -\nabla P \\ \partial_t \mathbf{z}^- + (\mathbf{v}_A\cdot\nabla)\mathbf{z}^- + (\mathbf{z}^+\cdot\nabla)\mathbf{z}^- &= -\nabla P \end{aligned}}$$

With the Alfven velocity $\mathbf{v}_A = \mathbf{B}_0/\sqrt{4\pi\rho_0}$

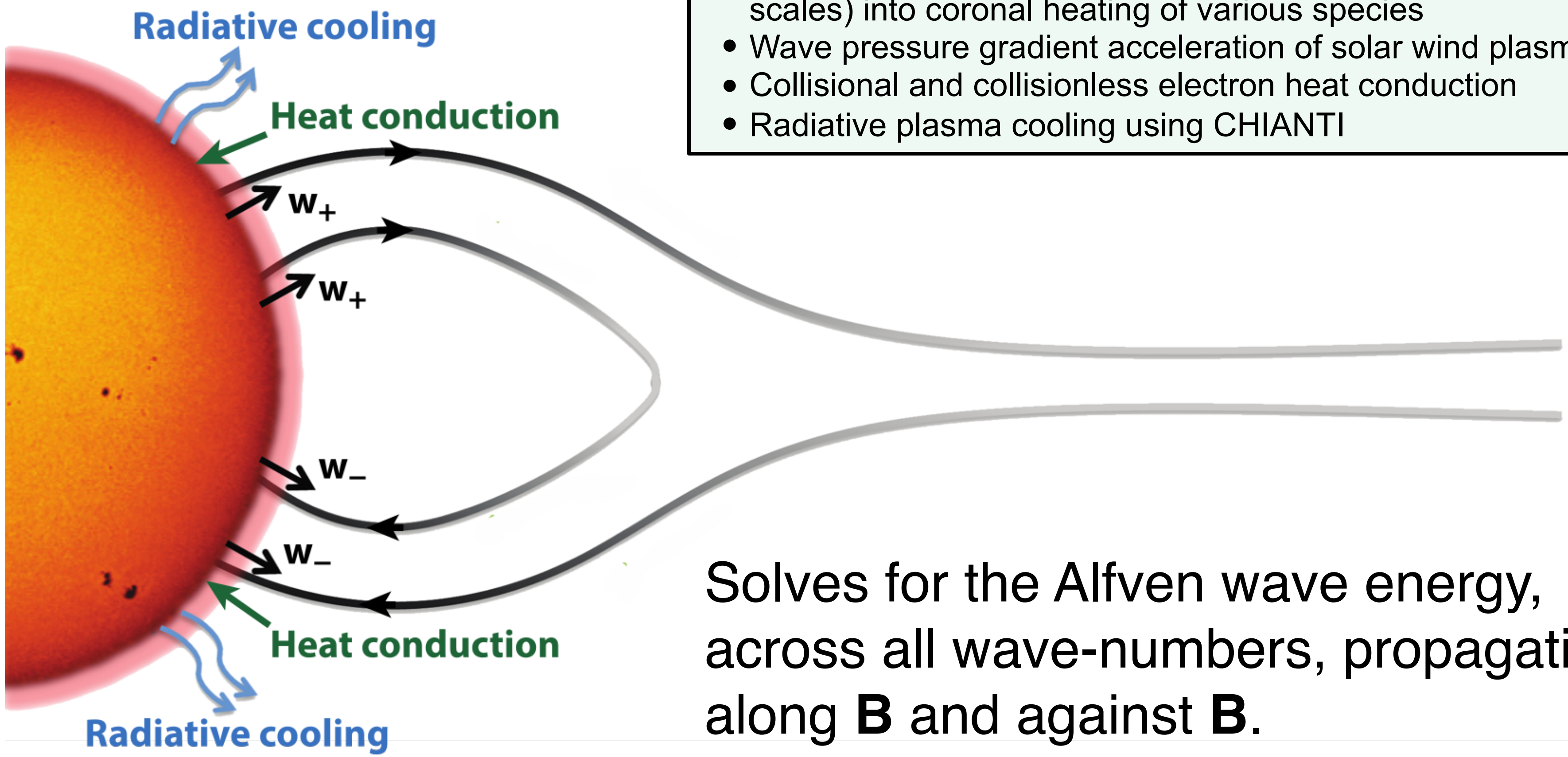
http://www.astro.princeton.edu/~kunz/Boldyrev.pdf

Alfvén Wave Solar Model (AWSoM)

B. van der Holst et al. ApJ **782**, 81 (2014).

Extended MHD physics:

- Two (T_i, T_e) or three ($T_{i||}$, $T_{i\perp}$, T_e) temperatures
- Equations for parallel and antiparallel propagating turbulence ($w_\pm$)
- Physics-based reflection of $w_\pm$ results in turbulent cascade
- Physics-based apportioning of turbulence dissipation (at the gyro-radius scales) into coronal heating of various species
- Wave pressure gradient acceleration of solar wind plasma
- Collisional and collisionless electron heat conduction
- Radiative plasma cooling using CHIANTI



Solves for the Alfven wave energy, across all wave-numbers, propagating along **B** and against **B**.

Mathematical Models

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

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{uB} - \mathbf{Bu}) = 0,$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left(\rho \mathbf{uu} - \frac{\mathbf{BB}}{\mu_0} \right) + \nabla \left(P_i + P_e + \frac{B^2}{2\mu_0} + P_A \right) = -\frac{G M_\odot \rho \mathbf{R}}{R^3},$$

Normal MHD + 2T and Alfven pressure

$$P_A = \frac{1}{2}(w_+ + w_-)$$

Mathematical Models

$$\frac{\partial}{\partial t}\left(\frac{P}{\gamma-1}+\frac{\rho u^2}{2}+\frac{\mathbf{B}^2}{2\mu_0}\right)+\nabla\cdot\left\{\left(\frac{\rho u^2}{2}+\frac{\gamma P}{\gamma-1}+\frac{B^2}{\mu_0}\right)\mathbf{u}-\frac{\mathbf{B}(\mathbf{u}\cdot\mathbf{B})}{\mu_0}\right\}=$$
$$=-(\mathbf{u}\cdot\nabla)P_A+\nabla\cdot(\kappa\cdot\nabla T)-Q_{\mathrm{rad}}+\Gamma_-w_-+\Gamma_+w_+-\frac{GM_\odot\rho\mathbf{r}\cdot\mathbf{u}}{r^3},$$

Heating from Alfven wave turbulence

$$\Gamma_\pm=\frac{2}{L_\perp}\sqrt{\frac{w_\mp}{\rho}}$$

Mathematical Models

$$\frac{\partial w_\pm}{\partial t} + \nabla \cdot [(\mathbf{u} \pm \mathbf{V}_A) w_\pm] + \frac{w_\pm}{2}(\nabla \cdot \mathbf{u}) = \mp \mathcal{R} \sqrt{w_- w_+} - \Gamma_\pm w_\pm$$

Turbulence energy advection and reflection

$$\mathcal{R} = \min\left\{ \sqrt{(\mathbf{b} \cdot [\nabla \times \mathbf{u}])^2 + [(\mathbf{V}_A \cdot \nabla) \log V_A]^2}, \max(\Gamma_\pm) \right\} \times$$
$$\times \left[\max\left(1 - \frac{I_{\max}}{\sqrt{w_+/w_-}}, 0\right) - \max\left(1 - \frac{I_{\max}}{\sqrt{w_-/w_+}}, 0\right) \right],$$

Alfvén Wave Turbulence

- **Wave energy densities of counter-propagating transverse Alfvén waves parallel (+) and anti-parallel (-) to magnetic field:**

energy reduction in expanding flow wave dissipation

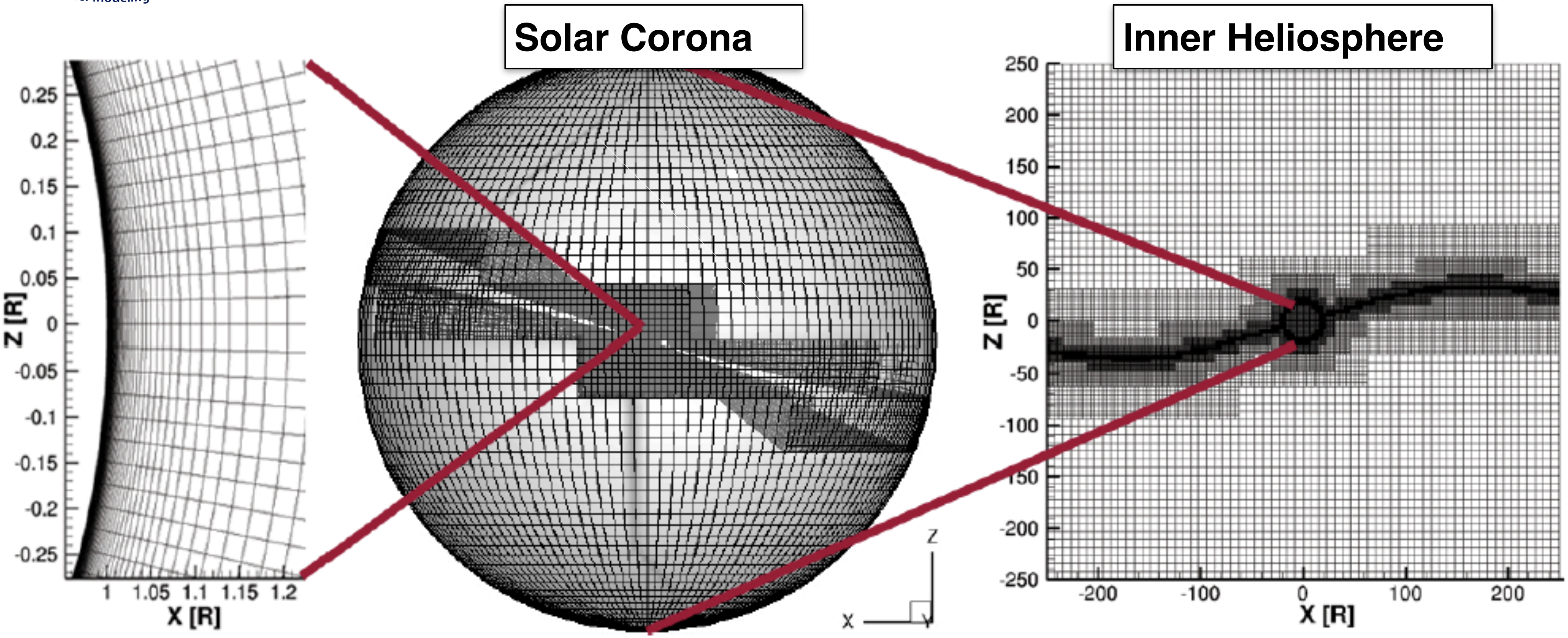
$$\frac{\partial w_\pm}{\partial t} + \nabla \cdot [(\mathbf{u} \pm \mathbf{V}_A) w_\pm] + \frac{w_\pm}{2}(\nabla \cdot \mathbf{u}) = \mp \mathcal{R}\sqrt{w_- w_+} - \Gamma_\pm w_\pm$$

wave reflection

Alfvén wave advection

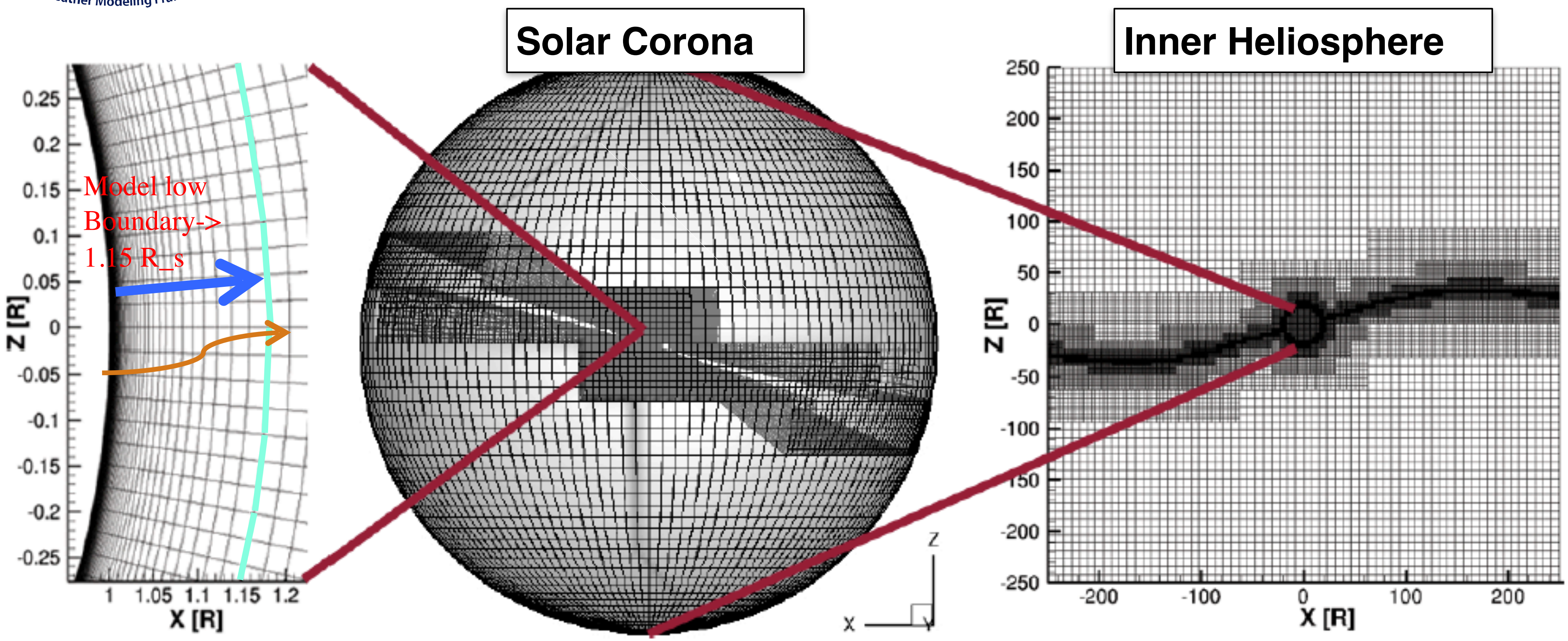
- **The wave reflection is due to field-aligned component of the Alfvén speed gradient and vorticity.**
- **Phenomenological wave dissipation (Dmitruk et al., 2002):** $\Gamma_\pm = \frac{2}{L_\perp}\sqrt{\frac{w_\mp}{\rho}}$
- **Similar to Hollweg (1986), we use a simple scaling law for the transverse correlation length** $L_\perp \sqrt{B} = 150\ \mathrm{km}\ \sqrt{\mathrm{T}}$
- **Poynting flux of outward propagating turbulence:** $(S_A/B)_\odot = 1.1 \times 10^6\ \mathrm{W\,m^{-2}\,T^{-1}}$

Computational Grid: AWSoM



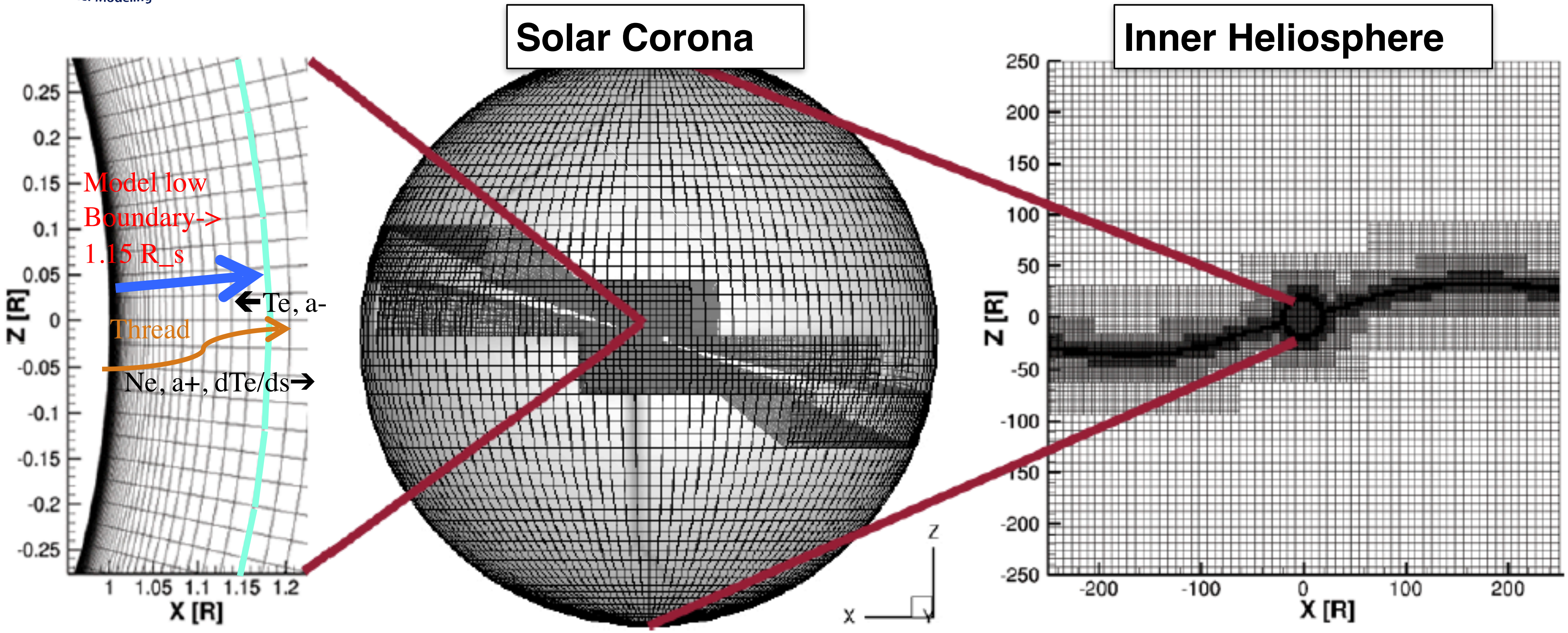
- **AWSoM uses stretched spherical grid for solar corona**
- **Significant grid stretching to grid resolve the upper chromosphere and transition region in addition to artificial transition region broadening**
- **Due to the very high resolution below 1.15R_{sun} AWSoM is too slow to achieve faster than real-time.**

AWSoM-R: Upshift the Inner Boundary



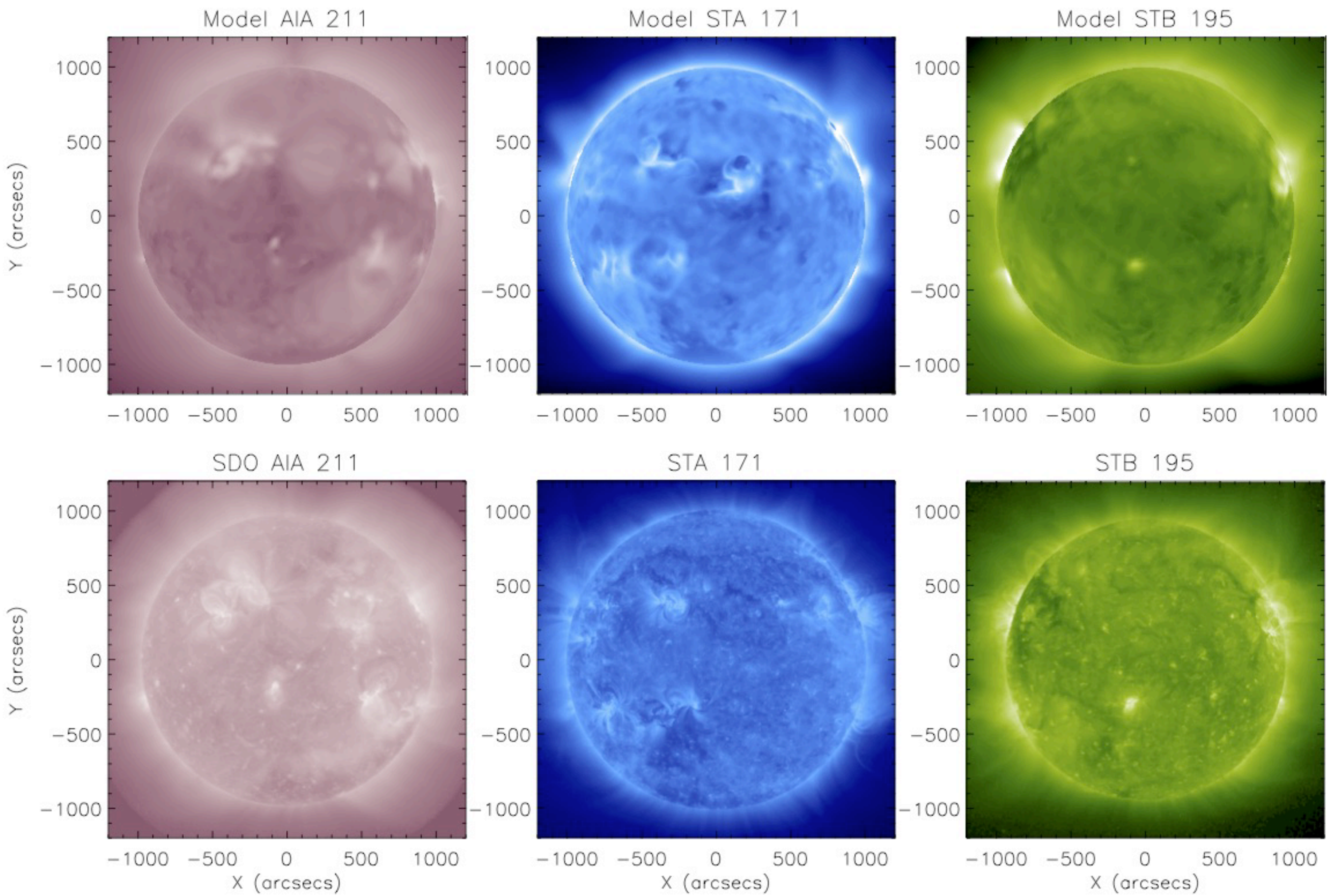
- We use the lower boundary of the AWSoM-R model at R = $1.15R_s$
- We apply 1D thread solutions along PFSS model field lines to bridge the AWSoM-R model to the chromosphere through the transition region.

Apply 1D Thread Solution



- Recognise that between $1R_s$ and $1.15R_s$ **u ll B** and $u \ll V_{slow}, V_A, V_{fast}$
- Quasi-steady-state mass, momentum, energy transport and wave turbulence transport is solved along the connecting field line implicitly (**1D** equations!)
- The speed-up of AWSoM-R is about a factor 200 compared to AWSoM

Validation: EUV Images for CR2107



AWSoM summary

GONG data used to get potential B-field out to 2.5 R_{sun}

Schatten current-sheet potential field from 2.5 R_{sun} to 21.5 R_{sun}

Solve for MHD with radiation, conduction, Alfven wave turbulent heating based on specified Poynting flux and initial field as in WSA-ENLIL. However:

- B-field can change due to plasma
- Gives density and temperature at 21.5 R_{sun} from physics
- Usually run to steady state for each new GONG dataset
- Each run requires ~14hrs on 128 cores of an HPC cluster

AWSoM - SWIFT Coupling

AWSoM provides MHD variable at 21.5 R_{sun}

AWSoM is in co-rotating frame but output to buffer in inertial

SWIFT uses the inertial frame buffer MHD values as driver for 2T MHD solution of

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

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{uB} - \mathbf{Bu}) = 0,$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left(\rho \mathbf{uu} - \frac{\mathbf{BB}}{\mu_0}\right) + \nabla \left(P_i + P_e + \frac{B^2}{2\mu_0} + P_A\right) = -\frac{GM_\odot \rho \mathbf{R}}{R^3},$$

Energy equations for each species

$$\frac{\partial}{\partial t}\left(\frac{P}{\gamma - 1}\right) + \nabla . \left(\frac{P}{\gamma - 1}\mathbf{u}\right) + P\nabla . \mathbf{u} = -\nabla . \mathbf{q_e} + H_{shock}$$

Shock heating of ions, thermal conduction for electrons

SWIFT Thermal Conduction

Electron mean-free-path in SW is roughly 1 A.U.

Classical Spitzer-Harm conduction not valid

Instead adopt approach of Hollweg

Maximum heat carried by electrons $\mathbf{q_e} = \alpha P_e \mathbf{u_e}$

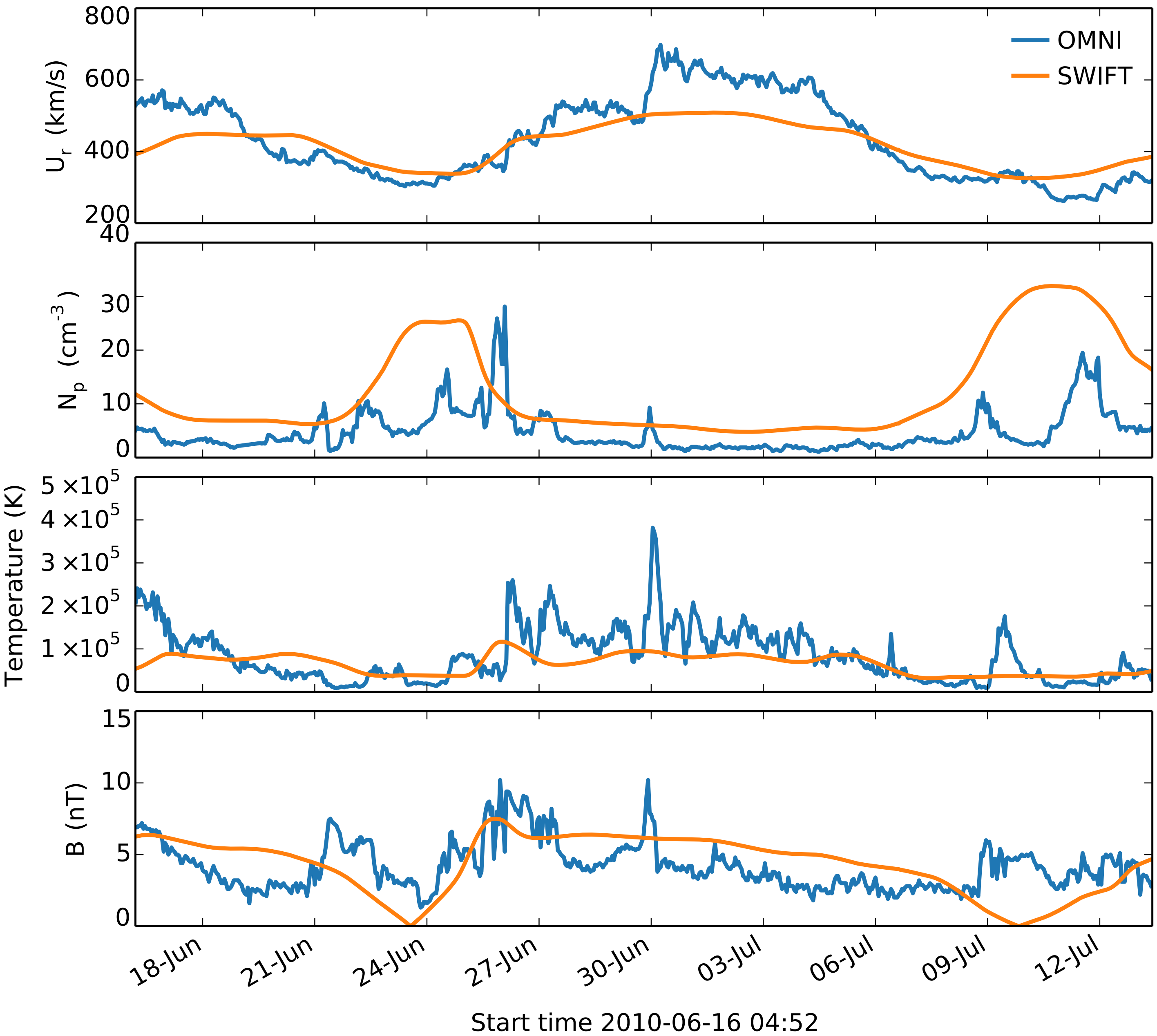
$$\frac{\partial}{\partial t}\left(\frac{P_e}{\gamma - 1}\right) + \nabla . \left(\frac{P_e}{\gamma_c - 1}\mathbf{u}\right) + P_e \nabla . \mathbf{u} = 0$$

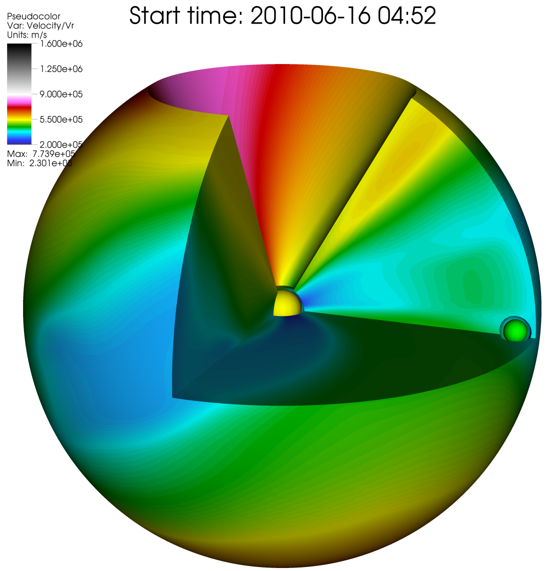
With $$\gamma_c = \frac{\gamma + (\gamma - 1)\alpha}{1 + (\gamma - 1)\alpha}$$

$$\boxed{\begin{gathered}\gamma_c = 1.3 \\ \gamma_i = \frac{5}{3}\end{gathered}}$$

AWSoM - SWIFT Results

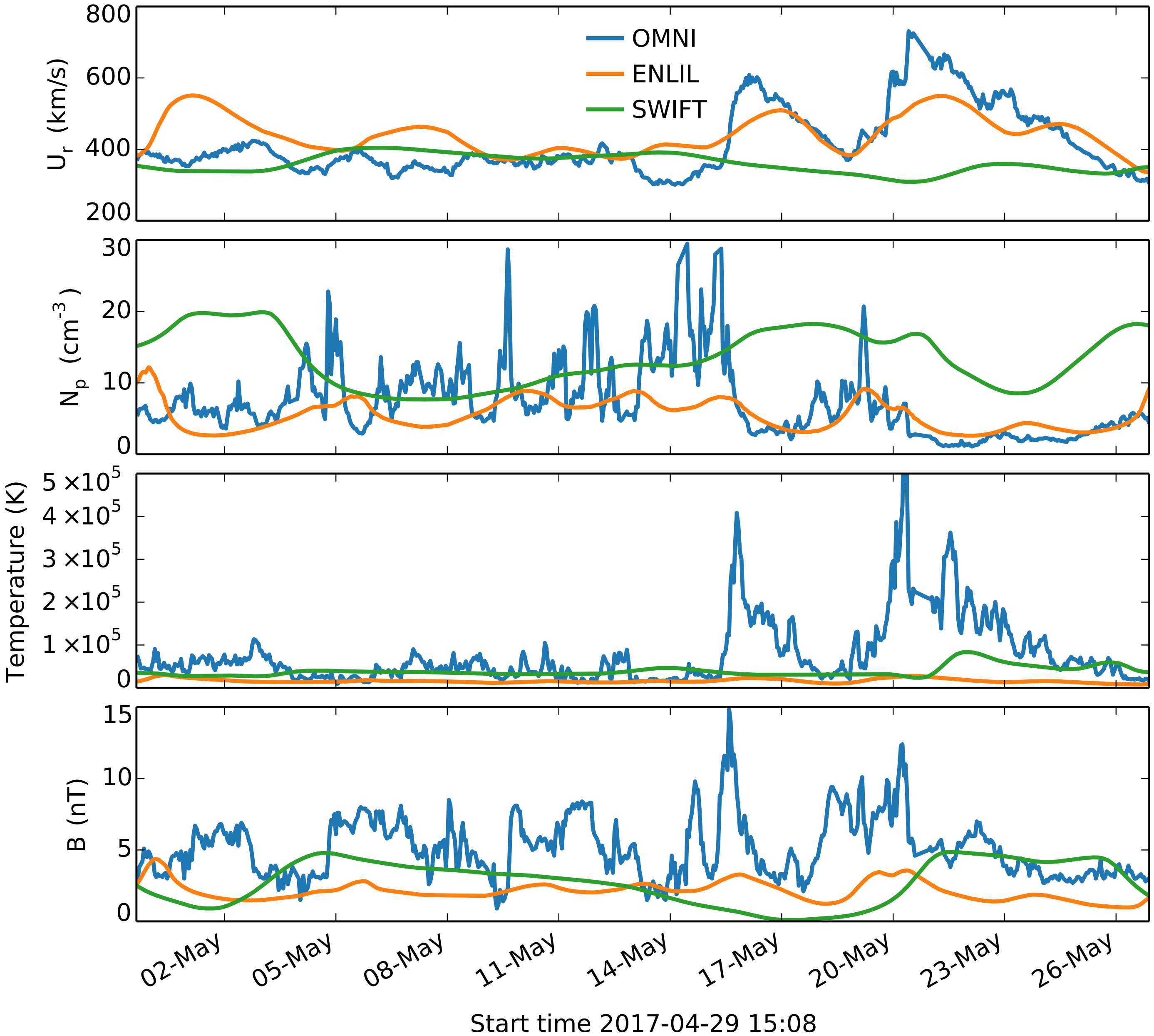
Steady state solution for full Carrington rotation





SWIFT cf. ENLIL Results

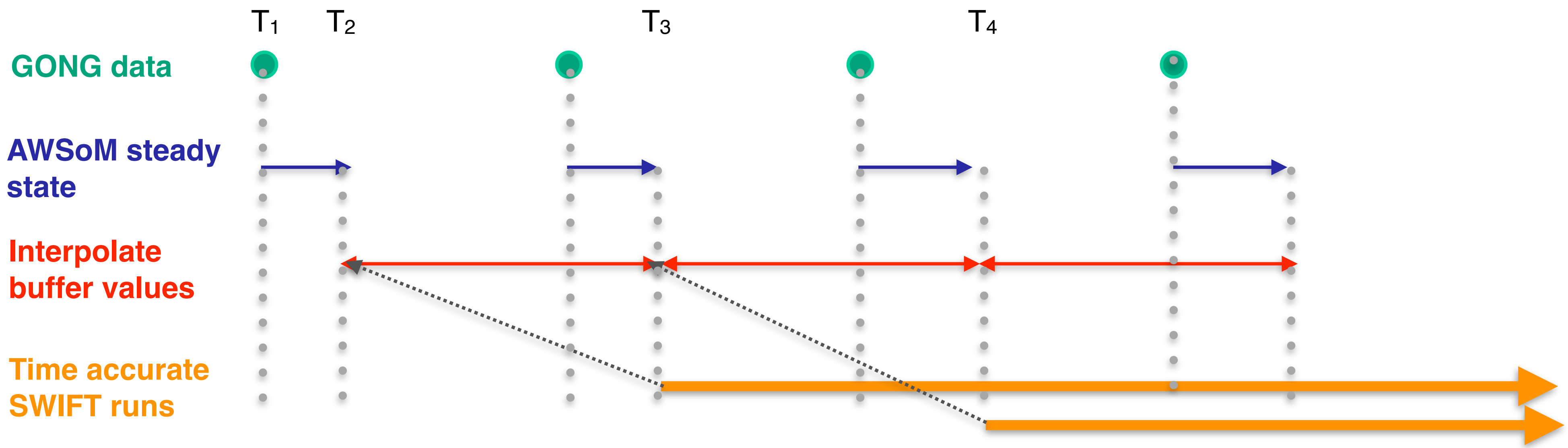
Steady state SWIFT solution for full Carrington rotation
Time dependent WSA-ENLIL for the same rotation



AWSoM-SWIFT Improvements

Auto-tune choice of Poynting flux per unit B and other parameters of AWSoM

Time accurate for comparison with OMNI and WSA-ENLIL



Only at real T_3 can SWIFT time accurate simulations start
These give time accurate answers from simulation time T_2
SWIFT simulations fast and continued after T_3 with buffer fixed
Start a new SWIFT run at T_4 etc.

Thanks for listened.
Questions?