ATMOSPHERIC, OCEANIC AND SPACE SCIENCES
UNIVERSITY of MICHIGAN

Global Multi-fluid Solar Corona Model with Alfvén Wave Turbulence

Bart van der Holst

Center for Space Environment Modeling
Space Weather Modeling Framework

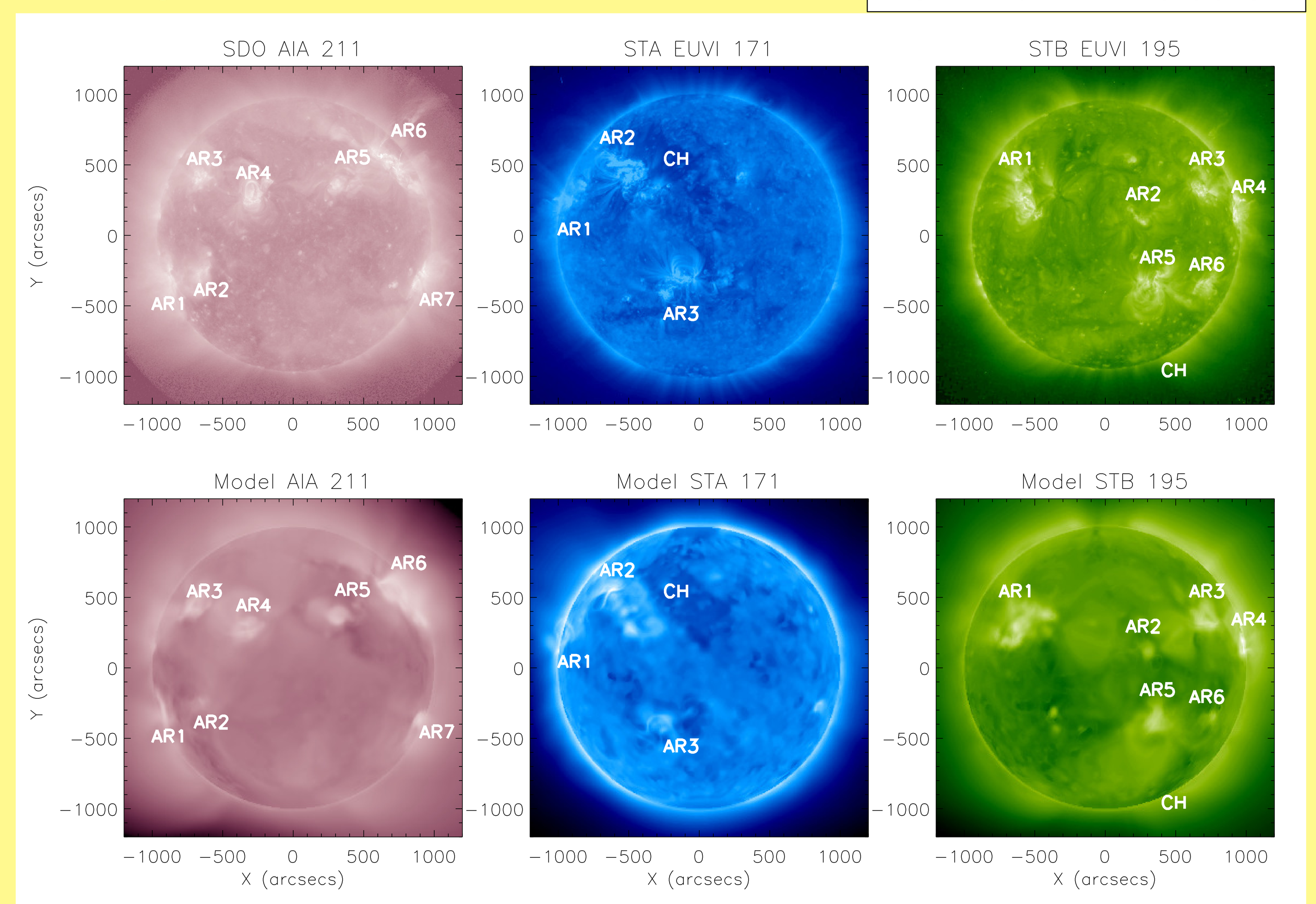
Abstract

The mechanisms that heat and accelerate the fast and slow wind have not yet been conclusively identified, and their understanding is one of the major science goals of the Solar Orbiter (SO) and Solar Probe Plus (SPP) missions. Helium abundance and properties in the solar wind are critical tracers for both processes so that understanding them is key towards gaining insight in the solar wind phenomenon, and being able to model it and predict its properties. We present a generalization of the recently developed global solar corona and inner heliosphere model with low-frequency Alfvén wave turbulence [van der Holst et al. (2014)] to include alpha-particle dynamics. This new multi-fluid model uses the stochastic heating mechanism to partition the turbulence dissipation into coronal heating of the electrons and ions. The momentum and energy exchange rates due to Coulomb collisions are accounted for. We discuss the feasibility for Alfvén wave turbulence to simultaneously address the coronal heating and proton-alpha particle differential streaming.

Validation: EUV Images for One-fluid Model

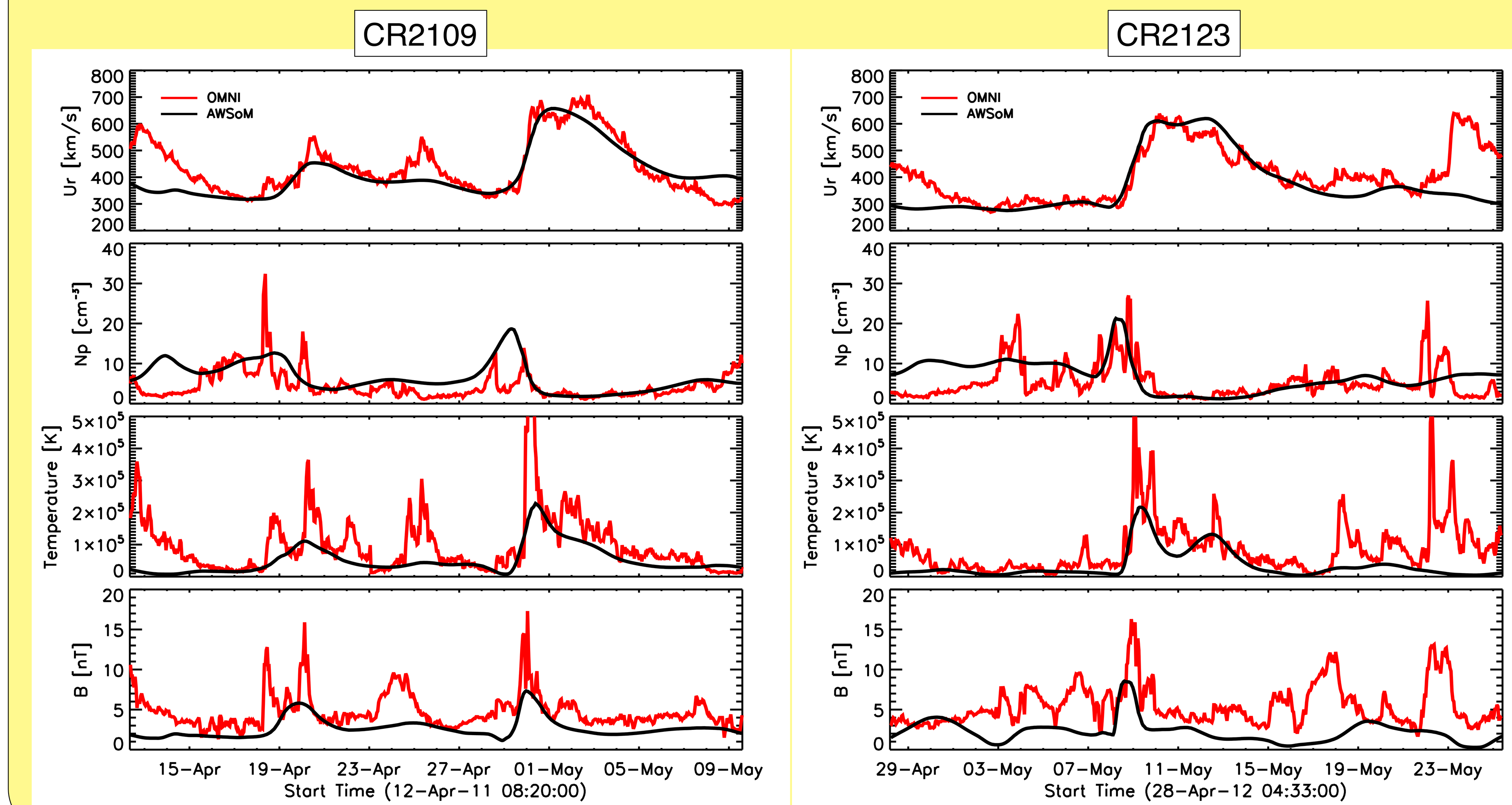
- Synthesized EUV images, obtained from electron temperature and density, used to validate coronal heating by low-frequency Alfvén wave turbulence
- Active regions with concentrated magnetic field ➔ enhanced reflection due to Alfvén speed gradients ➔ enhanced wave dissipation and coronal heating ➔ intensified EUV emission

2011 March 7 20:00 UT



1AU Validation of One-fluid Model

- Solar wind speed, proton number density, proton average temperature, and magnetic field magnitude along the Earth orbit for the Alfvén wave turbulence model (black) and ACE data (red).
- Simulations were performed with synoptic GONG magnetograms.



Multi-fluid Global Solar Corona Model

The multi-fluid equations can be obtained by taking the velocity moments of the Boltzmann equation. Each equation is coupled to the next higher-order velocity moment. Simplification is achieved by using a closure relation that relates a higher-order velocity moment of the distribution function to lower-order ones. The obtained multi-fluid MHD equations are [Schunk and Nagy (2009)]:

- Continuity equation for the ion mass density ρ_s, where the index s indicates protons or alpha particles

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

- Equation for the momentum $\rho_s\mathbf{u}_s$ includes the wave pressure (p_A) gradient force

$$\frac{\partial \rho_s \mathbf{u}_s}{\partial t} + \nabla\cdot(\rho_s\mathbf{u}_s\mathbf{u}_s) + \nabla p_s + \frac{q_s n_s}{e n_e}\left[\nabla(p_e+p_A) - \frac{1}{\mu_0}(\nabla\times\mathbf{B})\times\mathbf{B}\right] = q_s n_s(\mathbf{u}_s-\mathbf{u}_+)\times\mathbf{B} - \rho_s\frac{GM_\odot}{r^3}\mathbf{r} + \frac{\delta\mathbf{M}}{\delta t}$$

in which the electron number density is $n_e = \frac{1}{e}\sum_s q_s n_s$ and ion charge density weighted velocity $\mathbf{u}_+ = \frac{1}{e n_e}\sum_s q_s n_s \mathbf{u}_s$

and ion-ion momentum exchange $\frac{\delta \mathbf{M}_s}{\delta t} = \sum_t \rho_s \nu_{st}(\mathbf{u}_t - \mathbf{u}_s)\Phi_{st}$, t indexes ions and electrons, and ν is the collision frequency.

- The time evolution of the ion pressure p_s is: $\frac{\partial}{\partial t}\left(\frac{p_s}{\gamma-1}\right) + \nabla\cdot\left(\frac{p_s}{\gamma-1}\mathbf{u}_s\right) + p_s(\nabla\cdot\mathbf{u}_s) = \frac{\delta E_s}{\delta t} + Q_s,$

with ion-electron and ion-ion energy exchange $\frac{\delta E_s}{\delta t} = \sum_t n_s \mu_{st}\nu_{st}\left[\frac{3k_B(T_t-T_s)}{m_t}\Psi_{st} + (\mathbf{u}_t-\mathbf{u}_s)^2\Phi_{st}\right]$

- The electron pressure p_e includes electron-ion energy exchange, heat conduction, optically thin radiative cooling, and coronal heating

$$\frac{\partial}{\partial t}\left(\frac{p_e}{\gamma_e-1}\right) + \nabla\cdot\left(\frac{p_e}{\gamma_e-1}\mathbf{u}_+\right) + p_e\nabla\cdot\mathbf{u}_+ = \frac{\delta E_e}{\delta t} - \nabla\cdot\mathbf{q}_e - Q_{\rm rad} + Q_e \qquad \frac{\delta E_e}{\delta t} = \sum_s n_s \nu_{se} 3k_B(T_s - T_e)$$

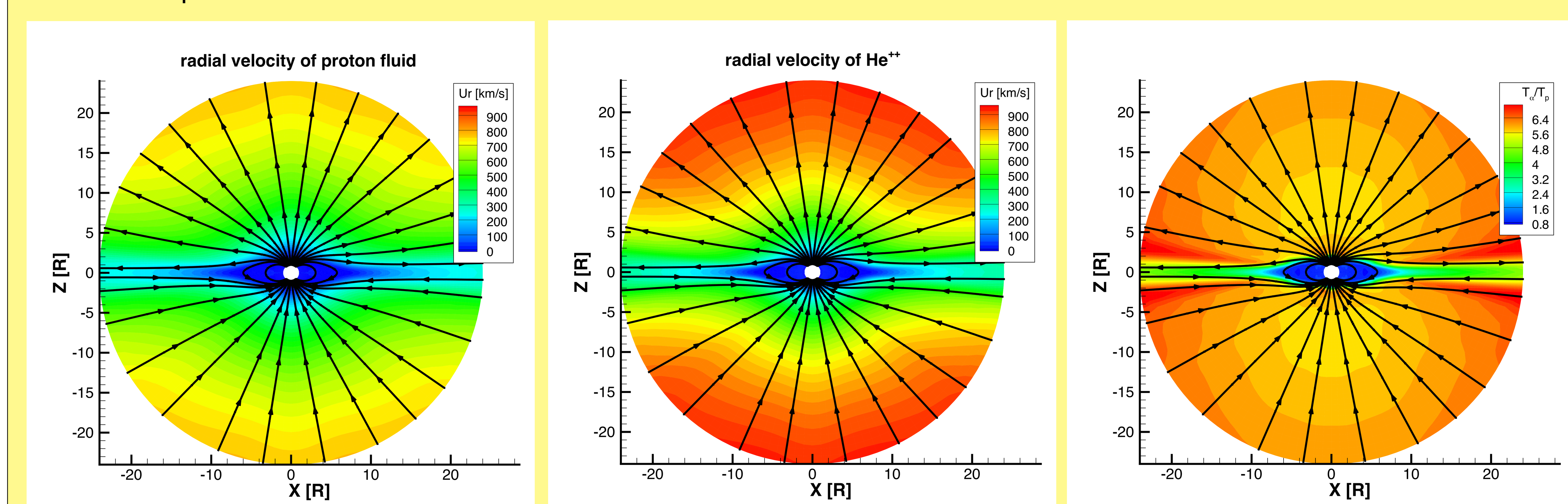
- The coronal heating of the ions (Q_s) and the electrons (Q_e) is in this model due to turbulence dissipation of Alfvén waves. The wave energy density $w_\pm$ (+ parallel to **B**, - antiparallel) is assumed to be carried by the protons only:

$$\frac{\partial w_\pm}{\partial t} + \nabla\cdot[(\mathbf{u}_p \pm \mathbf{V}_{Ap})w_\pm] + \frac{w_\pm}{2}(\nabla\cdot\mathbf{u}_+) = \mp\mathcal{R}\sqrt{w_- w_+} - \Gamma_\pm w_\pm \qquad \text{[van der Holst et al. (2014)]}$$

in which the wave reflection R is due to Alfvén speed gradients and vorticity along the field lines, and $\Gamma_\pm$ is the dissipation rate.

Preliminary Multi-fluid Results

A dipole test with 5.6 Gauss field strength at the pole. The He^{++} concentration in the upper chromosphere is set uniform and is 7% of the proton concentration.



- The alpha/proton temperature ratio is higher than the expected ratio of about 4.
- The alpha particle speed is in the fast wind 150 km/s faster than the proton speed, as in E. Marsch (1982).

Future Work

- Account for the two-stream instability in the heliosphere, see Verscharen et al. (2013) and references therein.
- Validate this multi-fluid model with data from Helios, Ulysses, WIND, ACE, and MESSENGER.

References

1. B. van der Holst et al., `Alfvén Wave Solar Model (AWSoM): Coronal Heating', ApJ **782**, 81 (2014).
2. B.D.G. Chandran et al., ApJ **776**, 45 (2013).
3. D. Verscharen et al., ApJ **773**, 8 (2013).

This work was supported by the NSF grant AGS 1322543. The research leading to these results was partly funded by the European Union's Horizon 2020 research and innovation program under grant agreement No 637302 PROGRESS.

PROGRESS
HORIZON 2020