Global Multi-Fluid Solar Corona Model with Temperature Anisotropy

COLLEGE OF ENGINEERING CLIMATE & SPACE UNIVERSITY OF MICHIGAN

Bart van der Holst[1], B. Chandran[2], J. Kasper[1], J. Szente[1], I.V. Sokolov[1], G. Tóth[1], T.I. Gombosi[1]

[1]University of Michigan, [2]University of New Hampshire

SH13C-2448

Abstract

The mechanisms that heat and accelerate the fast and slow wind have not yet been conclusively identified. Plasma properties of Helium 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 AWSoM model, a global solar corona model with low-frequency Alfven wave turbulence (van der Holst et al., 2014) to include alpha-particle dynamics. To apportion the wave dissipation to the isotropic electron temperature, parallel and perpendicular ion temperatures, we employ the results of the theories of linear wave damping and nonlinear stochastic heating as described by Chandran et al. (2011, 2013). We account for the instabilities due to the developing temperature anisotropies for the protons (Meng et al., 2012) and alpha particles (Verscharen et al., 2013). We investigate the feasibility for Alfvén wave turbulence to simultaneously address the coronal heating and alpha-proton differential streaming.

Heat partitioning

- Dissipation mechanisms considered are stochastic heating, electron and proton Landau and transit-time damping.
- The stochastic heating for ion i (proton or alpha particle) is:

$$Q_{i\perp} = c_1 \rho_i \frac{(\delta u_i)^3}{r_i} \exp\left(-\frac{c_2}{\varepsilon_i}\right)$$

where r_i is the gyro radius of ion i, $\varepsilon_i = \delta u_i / V_{i\perp}$, $V_{i\perp}$ is the perpendicular ion thermal speed, c_1, c_2 are constants. δu_i is the rms amplitude of the **E**x**B** velocity fluctuation at the ion gyro radius scale r_i:

For protons: $$\rho_p \delta u_p^2 = (w_+ + w_-)\sqrt{\frac{r_p}{L_\perp}}$$

For alpha particles: $$\rho_p \delta u_\alpha^2 = \left\{\left[1 + \frac{1}{r_{A\alpha}}\left(\frac{\Delta u_{\alpha p}}{V_{Ap}}\right)^2\right](w_+ + w_-) - \frac{2}{\sqrt{r_{A\alpha}}}\frac{\Delta u_{\alpha p}}{V_{Ap}}(w_+ - w_-)\right\}\sqrt{\frac{r_\alpha}{L_\perp}}$$

where $L_\perp$ is the perpendicular correlation length, w_+ and w_- are the energy densities of the forward and backward propagating Alfvén waves, r_{Ai} is the ion gyro-scale Alfvén ratio, and $\Delta u_{\alpha p}$ is the field-aligned velocity difference between alphas and protons.

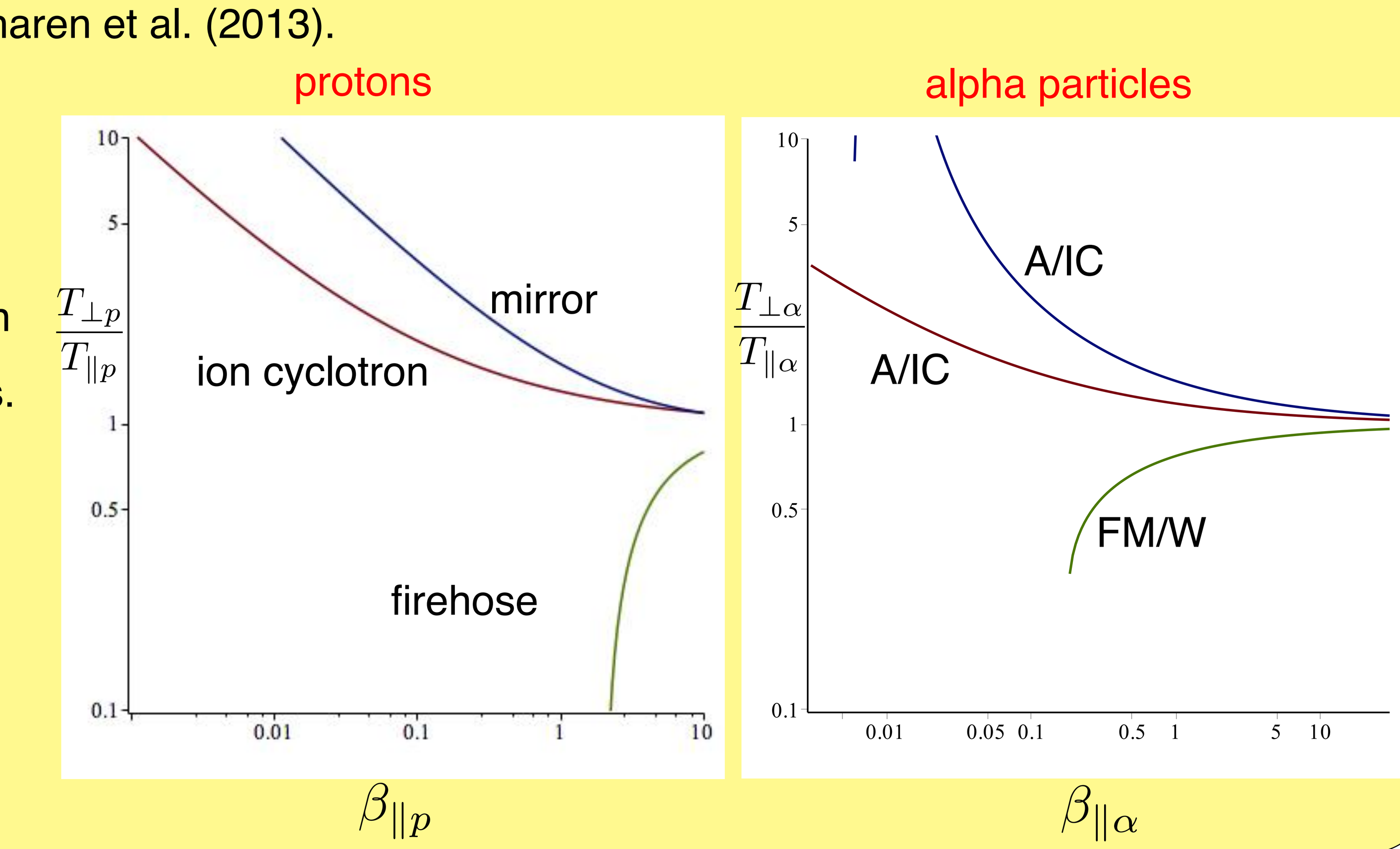
Limiting anisotropic ion pressure

Protons: The instability-based anisotropic pressure is relaxed towards the marginal stable pressure $\overline{p_\parallel}$ while keeping averaged pressure p unmodified: $\frac{\delta p_\parallel}{\delta t} = \frac{\overline{p_\parallel} - p_\parallel}{\tau}$ applied in firehose, mirror and proton cyclotron unstable regions. τ is taken to be growth rates of these instabilities (Hall 1979, 1980, 1981, Southwood & Kivelson 1993).

Alpha particles: Parallel-propagating Alfvén/ion-cyclotron (A/IC) waves (left-circularly polarized components of electric field) and fast-magnetosonic/whistler (FM/W) waves (right-circularly polarized components of electric field) are driven unstable for significant α-particle temperature anisotropy and beam speed (Gary et al. 2000, 2003). Necessary and sufficient conditions are derived in Verscharen et al. (2013).

Left panel: Marginal stability curves for protons. Pressure anisotropies in the observations can be more significant than marginal curves due to finite growth rates.

Right panel: Marginal stability curves are for zero alpha-proton drift speed. With nonzero drift speed more restrictive curves are obtained.



Multi-fluid Global Solar Corona Model

- Continuity equation for the ion mass density ρ_i where the index i indicates protons or alpha particles $$\frac{\partial \rho_i}{\partial t} + \nabla\cdot(\rho_i \mathbf{u}_i) = 0$$
- Equation for the momentum $\rho_i\mathbf{u}_i$ includes the wave pressure (p_A) gradient force

$$\frac{\partial \rho_i \mathbf{u}_i}{\partial t} + \nabla\cdot(\rho_i\mathbf{u}_i\mathbf{u}_i) + \nabla\cdot\mathbf{P}_i - \mathbf{F}_{wi} + \frac{q_i n_i}{e n_e}[\nabla p_e - \mathbf{J}\times\mathbf{B}] = q_i n_i(\mathbf{u}_i - \mathbf{u}_+)\times\mathbf{B} - \rho_i\frac{GM_\odot}{r^3}\mathbf{r} + \frac{\delta \mathbf{M}_i}{\delta t} + \frac{q_i n_i}{e n_e}\frac{\delta \mathbf{M}_e}{\delta t}$$

in which $n_e = 1/e\sum_i q_i n_i$ is the electron number density and $\mathbf{u}_+ = \frac{1}{e n_e}\sum_i q_i n_i \mathbf{u}_i$ is the charge-averaged ion-velocity and $\frac{\delta\mathbf{M}_e}{\delta t}$ and $\frac{\delta\mathbf{M}_i}{\delta t}$ are the Coulomb collisional momentum exchanges and $\mathbf{F}_{wi}$ is the force due to Alfvén waves [Isenberg et al. (1982)]

- The time evolution of the ion pressure $\mathbf{P}_i = p_{i\perp} I + (p_{i\parallel} - p_{i\perp})\mathbf{bb}$, $p_i = (2p_{i\perp} + p_{i\parallel})/3$

$$\frac{\partial p_i}{\partial t} + \nabla\cdot(p_i\mathbf{u}_i) + (\gamma-1)p_{i\perp}(\nabla\cdot\mathbf{u}_i) + (p_{i\parallel} - p_i)\mathbf{b}\cdot(\nabla\mathbf{u}_i)\cdot\mathbf{b} = \frac{\delta p_i}{\delta t} + (\gamma-1)Q_i$$

$$\frac{\partial p_{i\parallel}}{\partial t} + \nabla\cdot(p_{i\parallel}\mathbf{u}_i) + 2p_{i\parallel}\mathbf{b}\cdot(\nabla\mathbf{u}_i)\cdot\mathbf{b} = \frac{\delta p_{i\parallel}}{\delta t} + 2Q_{i\parallel}$$

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

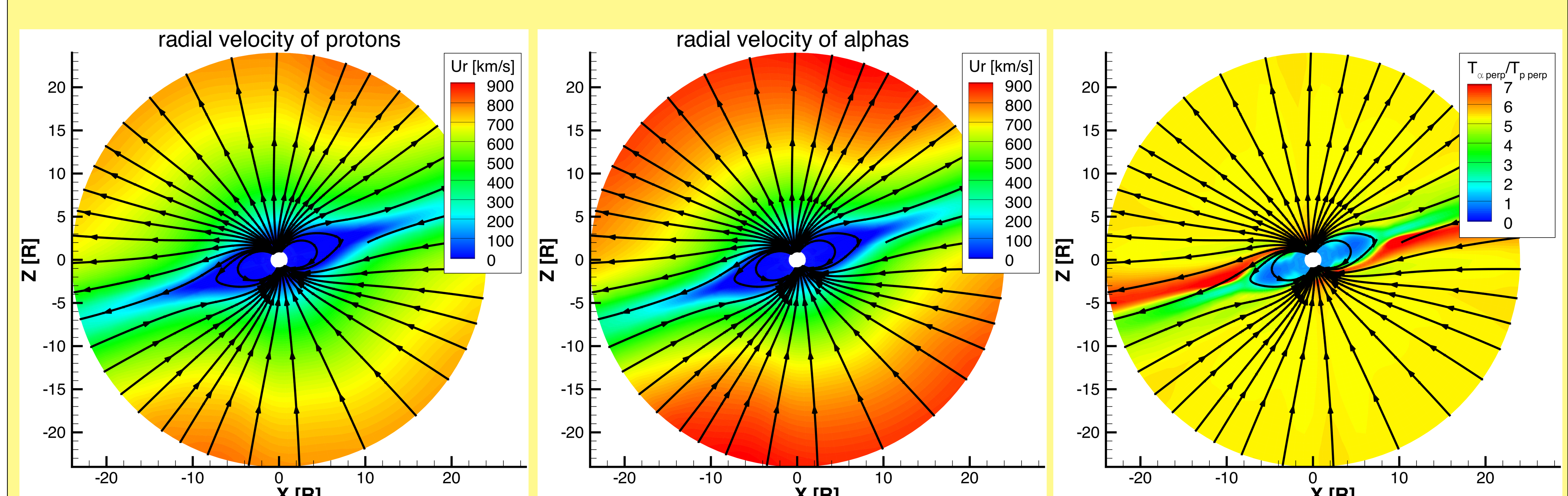
$$\frac{\partial p_e}{\partial t} + \nabla\cdot(p_e\mathbf{u}_e) + (\gamma-1)p_e\nabla\cdot\mathbf{u}_e = \frac{\delta p_e}{\delta t} + (\gamma-1)(Q_e - Q_{\rm rad} - \nabla\cdot\mathbf{q}_e)$$

- The ion coronal heating (Q_i), parallel ion coronal heating ($Q_{i\parallel}$) and electron coronal heating (Q_e) is in this model due to turbulence dissipation of low-frequency Alfvén waves. The wave energy density $w_\pm$ (+ parallel to **B**, - antiparallel) is assumed to be carried by the protons only. The wave reflection is due to Alfvén speed gradients along the field lines [van der Holst et al. (2014)].
- The induction equation $$\frac{\partial\mathbf{B}}{\partial t} - \nabla\times(\mathbf{u}_+\times\mathbf{B}) = 0$$

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.

3D Tilted Dipole Result

A 3D 2.8 Gauss dipole test with 15° tilt. The He^{++} concentration in the upper chromosphere is set uniform and is 7% of the proton concentration.



- The alpha/proton perpendicular temperature ratio is about 6.
- The alpha particle speed is in the fast wind about 110 km/s faster than the proton speed.

Future Work

- Account for the two-stream instability in the heliosphere, see Verscharen et al. (2013) and references therein.
- Connect the multi-fluid solar corona model to the threaded field-line model for computational speed.
- Validate this multi-fluid model with data from Helios, Ulysses, WIND, ACE, and MESSENGER.

References

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