Alfven Wave Turbulence as a Solar Wind Driver and a Coronal Heater.

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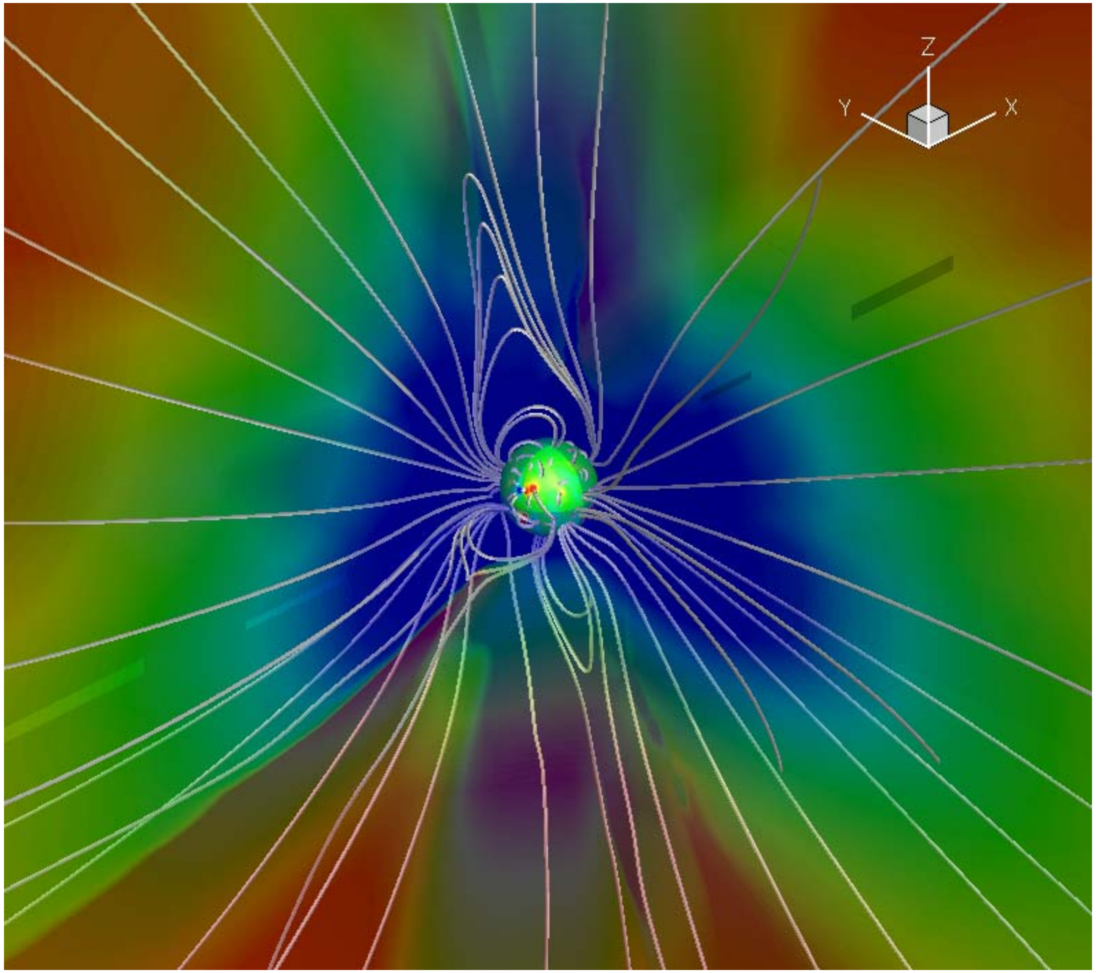
Outline

- Dialogue:
  - Does your wife work?
  - Yes, she is a popular model.
  - Wow!
  - Yes, in advertisements of new medicines and diets her photo is always at the panel “Before treatment”
  - ---
  - Does the varied polytropic index stuff work for solar corona/inner heliosphere in the SWMF?
  - Yes, it is a popular model.
  - I will give some “After treatment” pictures.

The SC/IH model of the SWMF

- Current model (Cohen et. al. 2007) is based on a 3D MHD code (BATSRUS). The model mimics heating by varying the plasma polytropic index, γ.

- Validated with long series of the solar wind data at 1AU and several CMEs with weak shock waves
- Runs on request and real time simulations in CCMC



CR2006 (Courtesy O. Cohen)

Introducing Alfven Waves Turbulence

- Hinode observations suggest energy input is sufficient to drive the solar wind acceleration and heating (de Pontiue et. al. 2007) . Above the chromosphere the wave energy flux density is $(1.2 \div 2.1) \cdot 10^5 erg/(cm^2 s)$
- Turbulent MHD waves have been suggested in the past as a possible mechanism both to heat the corona and to accelerate the solar wind.
- If the hypothesis on the contribution from the Alfven wave turbulence to the solar wind and coronal heating is not accepted, the significant dissipation of the turbulence till 1 AU is unclear.
- From here, the incorporation of the turbulence into the global space weather models is inevitable.

Heating function and momentum source

Plasma motion is governed by the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (1)$$

momentum equation:

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left[\rho \mathbf{u} \otimes \mathbf{u} - \frac{\mathbf{B} \otimes \mathbf{B}}{4\pi} + \left(P + \frac{B^2}{8\pi}\right) \mathbf{I}\right] = \rho \mathbf{g} + \mathbf{J}_{\mathrm{nonMHD}}, \quad (2)$$

as well as the energy equation:

$$\frac{\partial \left(\frac{\rho u^2}{2} + \frac{B^2}{8\pi} + \frac{P}{\gamma - 1}\right)}{\partial t} + \nabla \cdot \left[\mathbf{u}\left(\frac{\rho u^2}{2} + \frac{B^2}{4\pi} + \frac{\gamma P}{\gamma - 1}\right) - \frac{\mathbf{B}(\mathbf{u} \cdot \mathbf{B})}{4\pi}\right] = \rho(\mathbf{g} \cdot \mathbf{u}) + Q_{\mathrm{nonMHD}}. \quad (3)$$

Wave pressure and turbulent heating

Background momentum equation: solar wind acceleration

$$\frac{\partial n\vec{p}}{\partial t} + \nabla \cdot \vec{F}_p + \nabla \cdot (\sum_\sigma \int \vec{P}_{\omega\sigma} d\omega') = 0$$

wave stress
gradient force

Background energy equation: coronal heating

$$\frac{\partial E_b}{\partial t} + \nabla \cdot \vec{F}_E + \vec{u} \cdot [\nabla \cdot (\sum_\sigma \int \vec{P}_{\omega'\sigma} d\omega')] = -\sum_\sigma \int \gamma_\sigma(\omega') I_\sigma d\omega'$$

Work done by
wave stress

wave energy
dissipation

Alfven wave dissipation at cyclotron frequency (likely intensified by the energy cascade process).

WT Equation - Low Frequency Alfven Waves

• The WT equation for low frequency Alfven wave takes the form (Sokolov et al, 2009):

$$\frac{\partial I_\sigma}{\partial t} + \boxed{\nabla \cdot [(\vec{u} \pm \vec{b} V_A) I_\sigma]} - \boxed{\frac{1}{2}(\nabla \cdot \vec{u}) \frac{\partial I_\sigma}{\partial log\omega'}} = \boxed{\gamma_\sigma(\omega') I_\sigma}$$

Advection in space — Advection in frequency — Dissipation

• For over-simplified description the WT equation may be averaged over wave polarizations and integrated over wave frequency:

$$\frac{\partial E_{\sigma w}}{\partial t} + \nabla \cdot [(\mathbf{u} \pm \mathbf{b} V_A) E_{\sigma w}] + \frac{1}{2} (\nabla \cdot \mathbf{u}) E_{\sigma w} = - \int \gamma_\sigma(\omega) I_{\sigma w} d\omega.$$

Parameterized turbulent heating

- Take some known model of the coronal heating:
  - Unsigned flux model (Abbett, 2007)
  - Cranmer latest model (Cranmer, 2010)
- Solve
  - Boundary condition for the turbulence level,
  - Distribution of the wave absorption coefficient,

  such that the solution of the WT equation and the calculated turbulent heating would provide the same heating function as in the considered model.
  - Surprisingly, both these models as well as the Sudzuki,2006 model for the solar wind give the same boundary condition for the turbulent Poynting vector at the solar surface (above the chromosphere!):

$$S = V_A \sum E_w = B[G](0.7 \div 1.1) \cdot 10^5 erg/(cm^2 sG)$$

Why this boundary condition?

$$S = V_A \sum E_w = B[G](0.7 \div 1.1) \cdot 10^5 erg/(cm^2 sG)$$

•Why the Poynting flux at the boundary scales proportional to B?

- Because this assumption explains the bi-modal structure of the solar wind and an ‘absurd’ (but observationally confirmed) dependence of the fast solar wind speed of the expansion factor (Suzuki,2006);
- Because this assumption results in an ‘absurd’ (but observationally confirmed) ‘adiabatic law’, $P_w \propto \sqrt{\rho} \quad (\gamma = \frac{1}{2}!)$
- Cranmer, 2010 explains this using the wave action conservation as the wave propagates ***along*** the flux tube and citing numerous works, which support this ‘absurd’ consideration.
- In Abbett’s model the total heating (=a surface integral of the Poynting flux) is proportional to the total unsigned magnetic flux. Unless the integrands are proportional, how this could happen?

How to parameterize the absorption?

•While parameterized the Abbett's model:

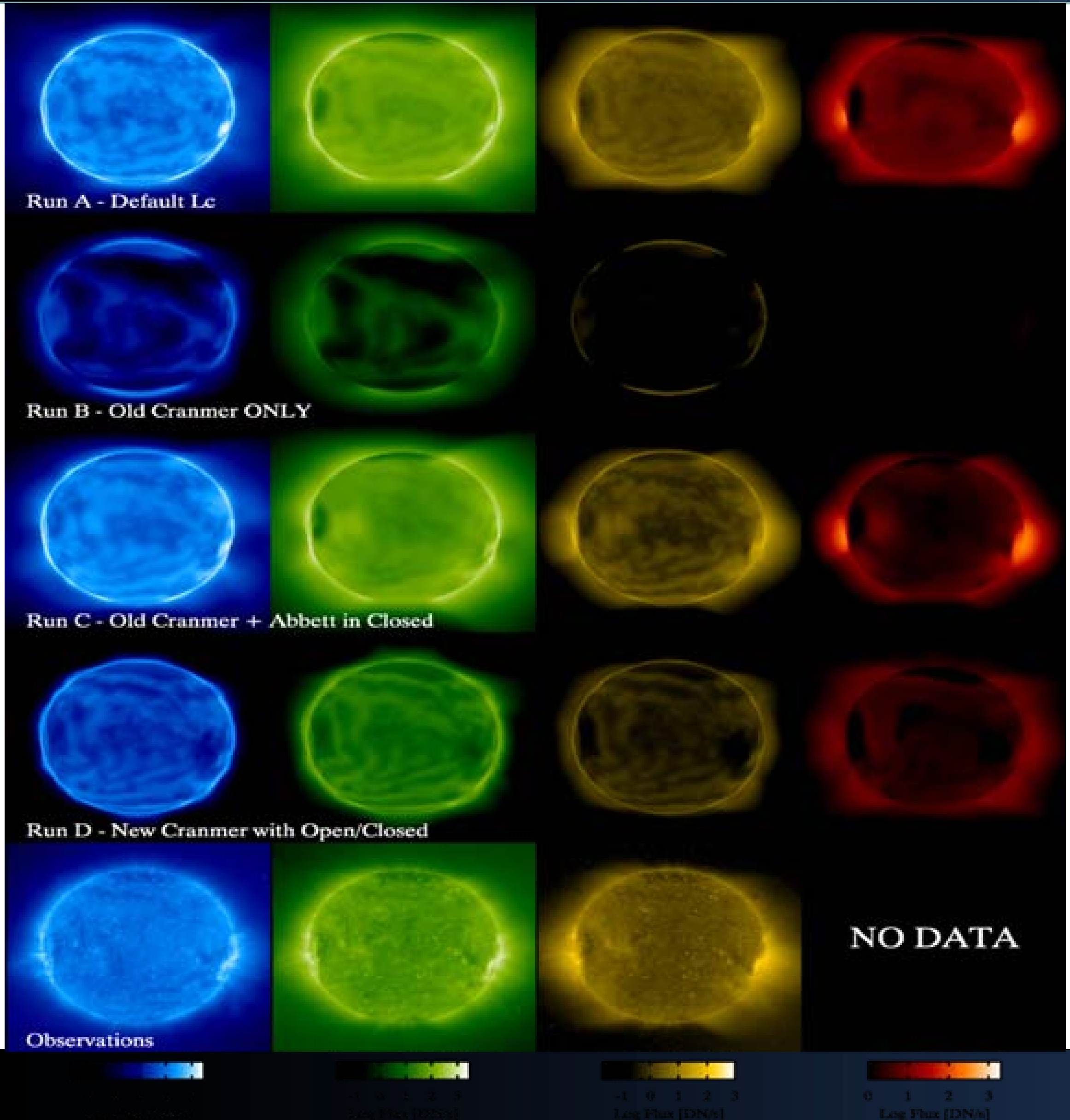
$$\gamma = \frac{V_A}{L}$$

where L is constant along the magnetic field line and changes from 40 Mm at closed magnetic field lines to 500 Mm for the open magnetic field line: L=L(Uwsa)

•This point is more clear within the Cranmer,2010 model, in which the physics of the turbulent cascade is approximately accounted for: the the absorption (=cascade rate) of the outward going waves is proportional to the amplitude of the inward going waves: $\gamma_{\pm} \propto \sqrt{I_{\mathrm{m}}}$

- •In the closed field region the waves are generated from the both footprints of the magnetic field line, absorption is high;
- •In the open field line the much lower absorption is due to non-WKB reflection
- •Electron heat conduction flux to the chromosphere controls the density distribution at the corona base (Lionello et al ,2001, 2009).

Turbulent heating agrees with EIT observations (Curtsey of C. Downs)



Adjusted Low Corona model (no turbulence, Downs et al, 2009)

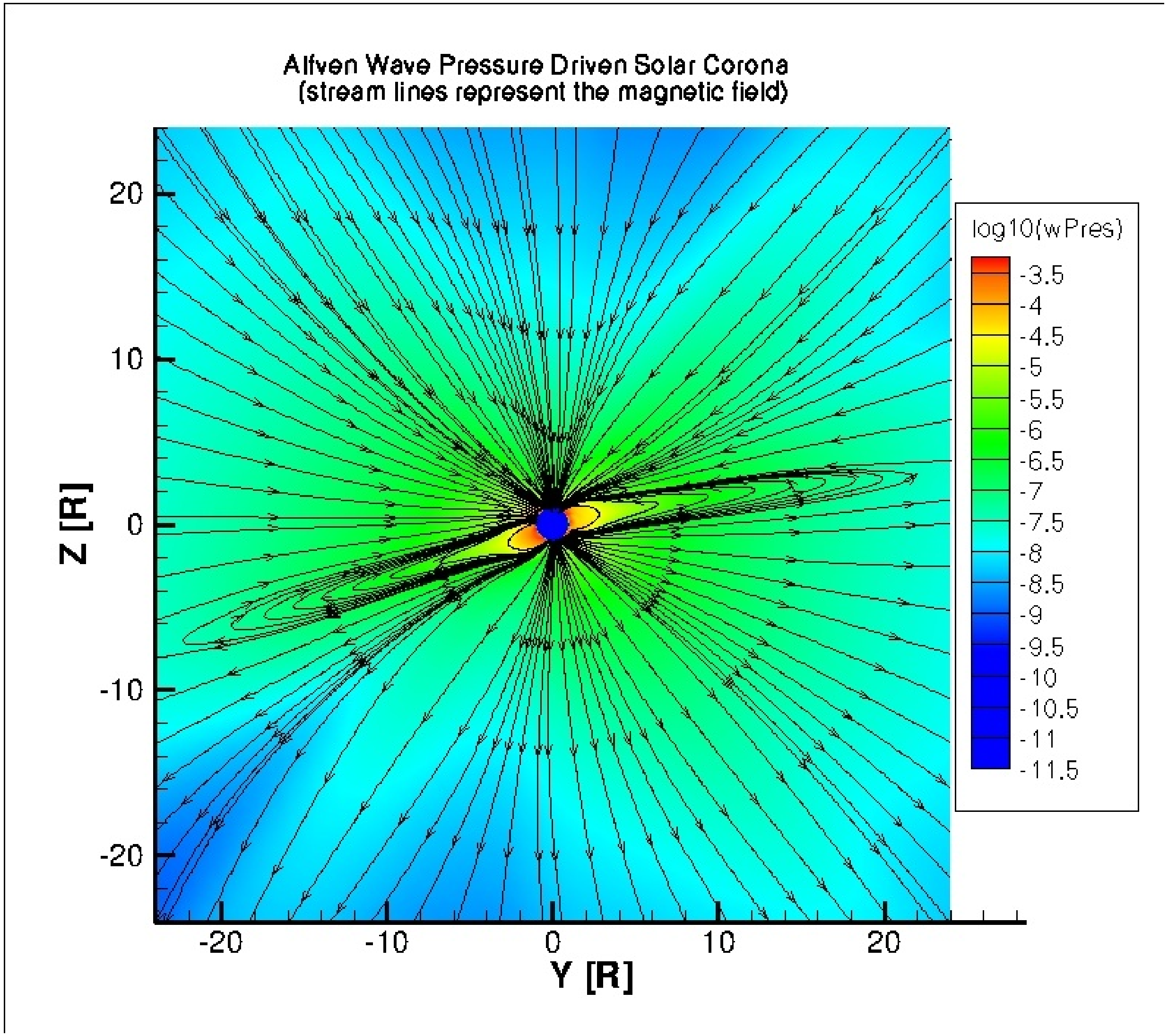
Original Cranmer's model, over-simplified turbulence

Parameterized turbulent heating (Abbett model)

Parameterized turbulent heating (Cranmer model)

Observation for CR2047

Results - CR2029 (Curtsey R.Oran)



Conclusion

- First calculations in the SWMF for SC/IH which is entirely driven by Alfven wave pressure and the turbulent heating.
- The absorption coefficient for waves should be varied from the closed field region to corona holes by a factor of 10-12, to agree with the bi-modal solar wind structure.
- The following tools are ready to delivery and may be of interest:
  - EIT synthetic images
  - Parameterized models of turbulent heating which reproduce or improve some known heating functions (Abbet, Cranmer etc)