Numerical model of a partially-ionized solar atmosphere

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Outline

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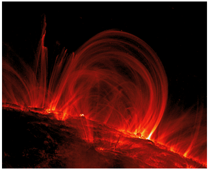
Our goals



Our goals:

- Contribute to solving some problems for weakly ionized plasma (lower solar atmospheric layers, ionospheres/thermospheres of planets)
- Develop our own 2-fluid code

Euler equations:

$$\frac{\partial \rho_n}{\partial t} + \nabla \cdot (\rho_n \mathbf{V_n}) = -S_1, \tag{1}$$

$$\frac{\partial (\rho_n \mathbf{V_n})}{\partial t} + \nabla \cdot (\rho_n \mathbf{V_n} \mathbf{V_n}) + \nabla p_n - \rho_n \mathbf{g} = -S_2, \tag{2}$$

$$\frac{\partial E_n}{\partial t} + \nabla \cdot ((E_n + p_n)\mathbf{V_n}) - \rho_n \mathbf{g} \cdot \mathbf{V_n} - q_n = -S_3. \tag{3}$$

Two-fluid equations

Equations for ions

MHD equations:

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{V_i}) = S_1, \tag{4}$$

$$\frac{\partial (\rho_i \mathbf{V_i})}{\partial t} + \nabla \cdot (\rho_i \mathbf{V_i} \mathbf{V_i}) + \nabla p_i - \rho_i \mathbf{g} - \frac{1}{\mu}(\nabla \times \mathbf{B}) \times \mathbf{B} = S_2, \tag{5}$$

$$\frac{\partial E_i}{\partial t} + \nabla \cdot ((E_i + p_i)\mathbf{V_i}) - \rho_i \mathbf{g} \cdot \mathbf{V_i} - q_i = S_3, \tag{6}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V_i} \times \mathbf{B}) + \mathbf{S}_{\rm e}\,, \quad \nabla \cdot \mathbf{B} = 0. \tag{7}$$

Two-fluid equations

Source terms

$$
\begin{aligned}
S_1 &= -\rho_i(\alpha_r \rho_i - a_i \rho_n)\,, & (8)\\
S_2 &= a_c \rho_i \rho_n (\mathbf{V_n} - \mathbf{V_i}) - \rho_i(\alpha_r \rho_i \mathbf{V_i} - a_i \rho_n \mathbf{V_n})\,, & (9)\\
S_3 &= a_c \rho_i \rho_n (\mathbf{V_n} - \mathbf{V_i}) \cdot \mathbf{V_i}\,. & (10)
\end{aligned}
$$

S_1 - ionization/recombination,
S_2 - ion-neutral collisions,
S_3 - energy source term
(Smith & Sakai 2008, Zaqarashvili et al. 2011, 2012, Meier & Shumlak 2012).

Two-fluid waves

- **HD waves**: 1 acoustic and 1 entropy mode (Goedbloed & Poedts 2004, Murawski et al. 2011)
- **MHD waves**: 1 Alfvén, 2 (slow and fast) magnetoacoustic, and 1 entropy mode
- **Two-fluid waves**:

  MHD waves + extra entropy waves (Zaqarashvili et al. 2011, Soler et al. 2016)

  - dispersive, damped, for real **k** cut-off for slow neutral wave
  - Effective damping of Alfvén and kink waves → plasma heating

Few remarks on waves

- Ion-neutral collisions introduce characteristic scales - waves become dispersive in a homogeneous medium
- Gravity introduces dispersion and cut-off (Lamb/Klein-Gordon equation)
- Shock - abrupt changes in all fluid quantities
- Pseudo-shock/entropy mode - sudden change in mass density alone, while other fluid quantities are smooth across this wave
- Rarefaction wave (nonlinear)

JOANNA code

- Developed by Darek Wójcik
- Targets: HD, MHD, **2-fluid**, any-system of hyperbolic/parabolic eqs
- Multi-physics: non-adiabatic, non-ideal terms
- Shock-capturing algorithms: HLLC, HLLD, MUSTA
- $\nabla \cdot \mathbf{B}$ cleaning by GLM (Dedner et al. 2002)
- Reconstruction: flat, linear, PPM, WENO3
- More on http://kft.umcs.lublin.pl/dwojcik/.

The hydrostatic solar atmosphere

Static equilibrium ($\mathbf{V}_{\mathrm{i,n}} = 0$) with force-free (current-free) $\mathbf{B}$,

$$-\nabla p_{\mathrm{i,n}} + \frac{1}{\mu}(\nabla \times \mathbf{B}) \times \mathbf{B} + \varrho_{\mathrm{i,n}}\mathbf{g} = 0\,. \tag{11}$$

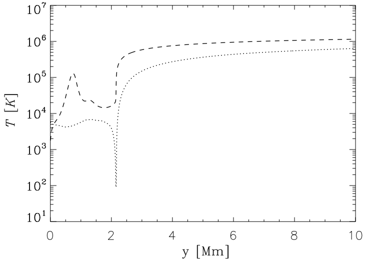


Figure: Solar temperature for ions (dashed line) and neutrals (dotted line) (Avrett & Loeser 2008, Wójcik 2017).

Case study - solar granulation

Show the movie (courtesy of Darek Wójcik 2017).

Conclusions

- Well tested JOANNA code - passed many (HD and MHD) tests (http://kft.umcs.lublin.pl/dwojcik/)
- Robust code - simulation of 2-fluid convection
- Versatile code - can be adopted to any hyperbolic/parabolic set of equations