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# Time Dependent 2.5D Model of the Chromosphere

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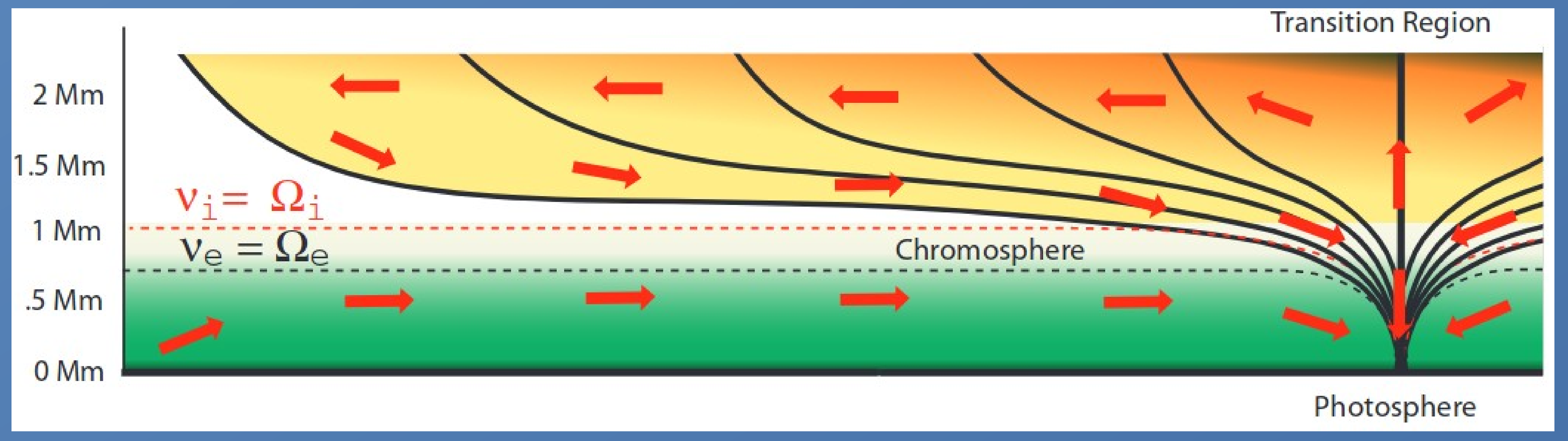
## 1. The Chromosphere

The sun's atmosphere is called the chromosphere. Compared to the sun's corona we don't have many observations of the chromosphere. We do know that, strangely, the chromosphere is much colder than the corona. The plasma in the chromosphere is therefore partially ionized—it has about a thousand times more neutral atoms than ions or electrons

## 2. The Problem

The chromosphere is a difficult region to simulate. The plasma behaves very differently depending on the height of interest. The plasma beta changes several orders of magnitude and the plasma changes from being dominated by magnetic forces near the top and dominated by thermal forces near the bottom.




Analytical solution of the steady-state chromosphere. (Song et al 2014)

## 3. The Simulation

The code is written from scratch and uses a semi-implicit TVD-MUSCL scheme. It is also GPU-accelerated taking advantage of new technologies on the frontier of scientific computing. The model is a two-fluid (plasma, neutrals) collisional MHD model. The governing equations are as follows:

$$\frac{\partial n_{i,n}}{\partial t} + \nabla \cdot n_{i,n} \boldsymbol{V} = S - L$$

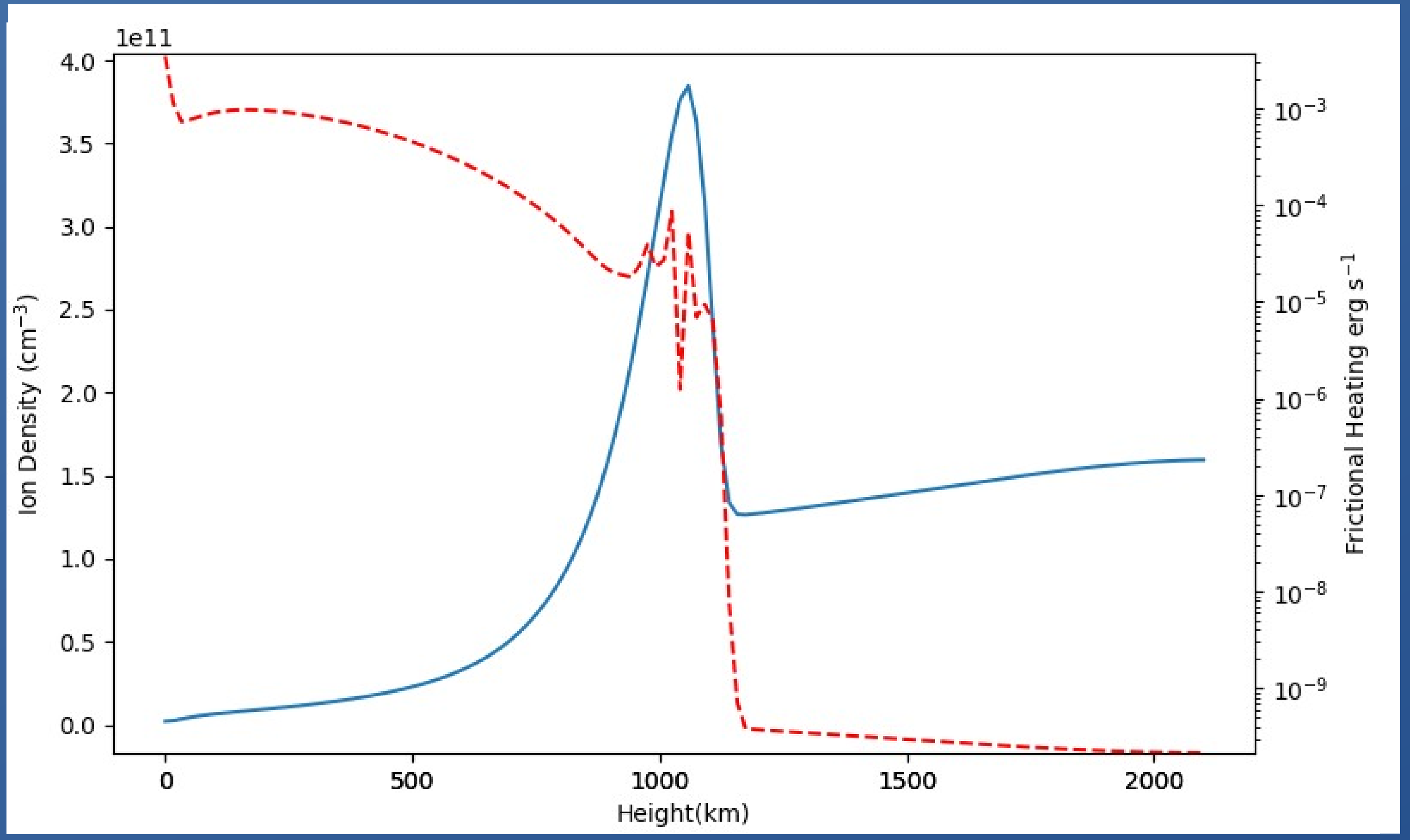
$$\frac{\partial \rho_i \boldsymbol{V}}{\partial t} + \nu_{in}\rho_i(\boldsymbol{V}-\boldsymbol{U}) = -\nabla \cdot \left(\rho_i \boldsymbol{V}\boldsymbol{V} + n_i k T_i + \frac{B^2}{2\mu_0} - \frac{\boldsymbol{B}\boldsymbol{B}}{\mu_0}\right) - \rho_i g$$

$$\frac{\partial \rho_n \boldsymbol{U}}{\partial t} - \nu_{in}\rho_i(\boldsymbol{V}-\boldsymbol{U}) = -\nabla \cdot (\rho_n \boldsymbol{U}\boldsymbol{U} + n_n k T_n) - \rho_n g$$

$$\frac{\partial k T_i}{\partial t} - \frac{2}{3}\frac{m_i}{m_i+m_n}\nu_{\text{in}}[m_n|\boldsymbol{V}-\boldsymbol{U}|^2 + 3(T_n - T_i)] = -\nabla \cdot (k T_i \boldsymbol{V}) + \frac{1}{3} k T_i \nabla \cdot \boldsymbol{V} - \frac{2}{3 n_i}\nabla \cdot (\boldsymbol{q_i} + \boldsymbol{B} \times \eta \boldsymbol{J})$$

$$\frac{\partial k T_n}{\partial t} - \frac{2}{3}\frac{m_n}{m_i+m_n}\nu_{\text{in}}[m_i|\boldsymbol{V}-\boldsymbol{U}|^2 + 3(T_i - T_n)] = -\nabla \cdot (k T_n \boldsymbol{U}) + \frac{1}{3} k T_n \nabla \cdot \boldsymbol{U} - \frac{2}{3 n_n}\nabla \cdot (\boldsymbol{q_n}) - R$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \cdot (\boldsymbol{V}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{V}) - \nabla \times \left(\eta \boldsymbol{J} + \frac{1}{n_e e}\boldsymbol{J} \times \boldsymbol{B}\right)$$




Top: Vertical slice of shock front of jet. You can see that the frictional heating (red dashed line) is enhanced behind the shockfront.
Left: Time series mosaic of jet shooting from the near the photosphere. The left mosaic is of ion density and the mosaic on the right is that of frictional heating.

## 4. Results

Preliminary results show a jet forming in the lower chromosphere between the network and internetwork regions of the sun. This is caused by frictional heating, the heating due to collisions between ions and neutrals. The strong magnetic gradient between the network and inter-network regions causes a speed difference between the two fluids and consequently causing friction. This then causes a shock to form and the shock steepens making large thermal pressure within the jet driving the jet upward and then out of the chromosphere. It was thought that chromospheric jets were only caused by reconnection events and in this cause it's a thermal effect due to collisions.