Heating of the Chromosphere and Temperature Minimum Region by Flare-Generated Alfvénic Waves

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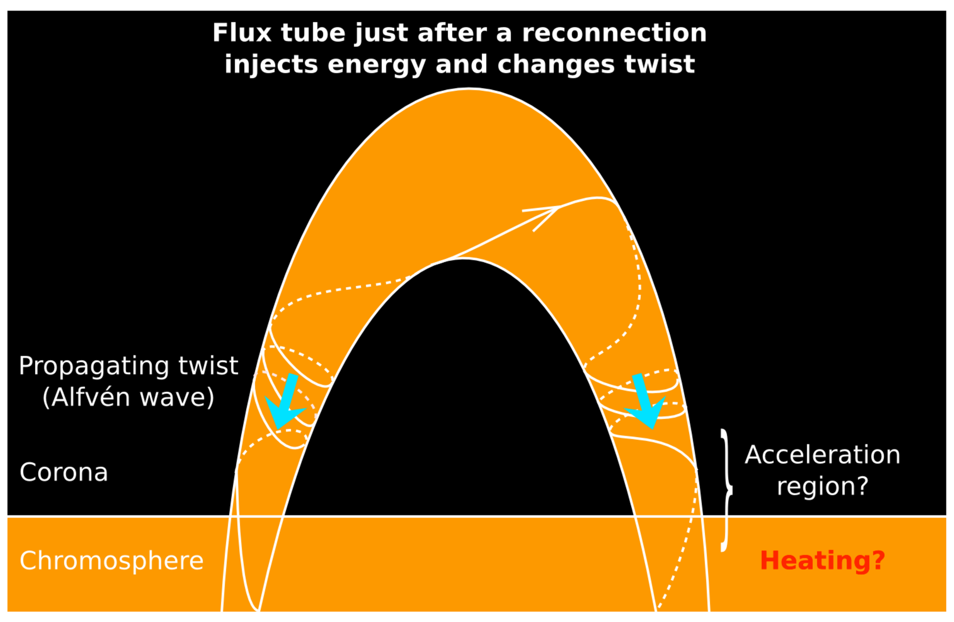
Flare optical emissions typically imply heating at the chromospheric temperature minimum region (TMR) of 100-300 K. This is too deep to be heated directly by electron beams, hence thick-target models often invoke backwarming. There is, however, a less-explored alternative: flare-generated Alfvénic waves damping by ion-neutral friction. This is investigated as part of larger efforts to understand the role of MHD waves and Poynting flux in solar flares.

1. Alfvénic Waves and Solar Flares

Big Picture



- Magnetic reconnections on flare timescales (e.g. elementary flare bursts) launch Alfvénic waves.
- At active-region coronal Alfvén speeds, even small amplitude waves carry significant Poynting flux compared to the power of a flare.
- Various MHD waves are spatially localised so could potentially contribute to ribbon or kernel emission (Russell & Stackhouse 2013, *A&A*, **558**:76).
- Separating energy-release and electron-acceleration regions may substantially ease number and resupply problems and would be more consistent with auroral physics.

TMR Heating Questions

- How much wave energy crosses from the corona to the chromosphere?
- How well does wave damping heat the TMR and rest of chromosphere?

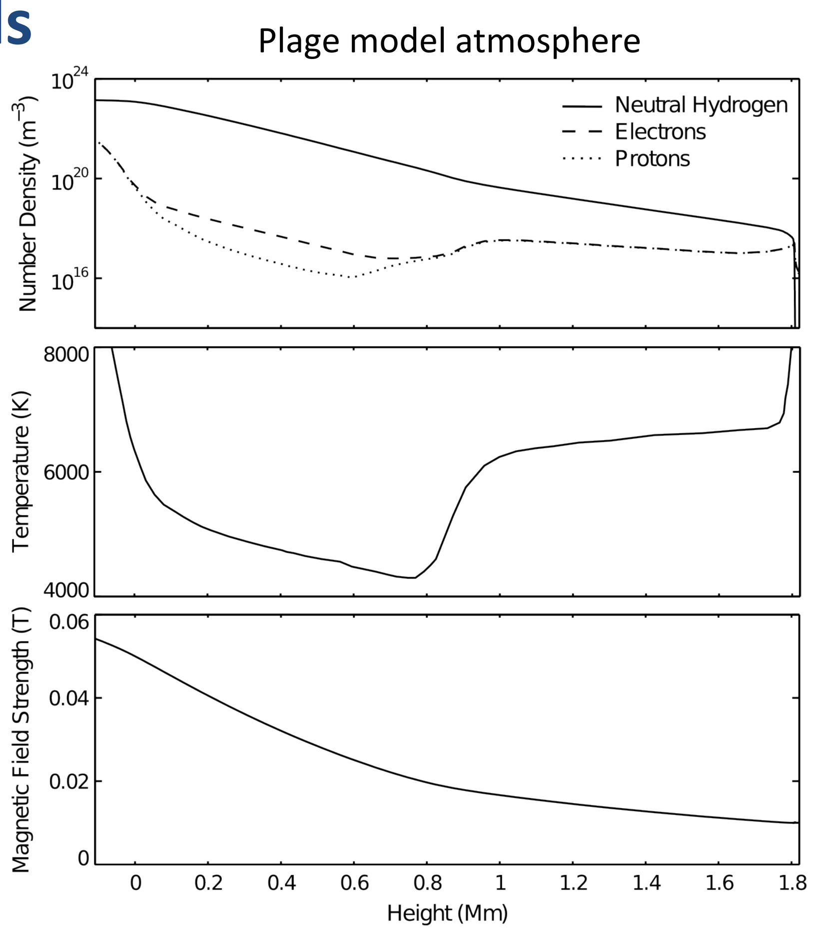
2. Atmospheric and Physical Models

1D models of the chromosphere were built using semiempirical density and temperature profiles from Fontenla et al. (2009) and magnetic field $B(z) \sim P(z)^{\alpha}$ after Zweibel & Haber (1983). One such model is shown on the right (active region plage).

Linear wave propagation and damping were simulated using a two-fluid approach, where the ion-electron part of the plasma (MHD) was coupled to the neutral fluid by ion-neutral collisions. The ion-neutral coupling time is on the order of ms. Electron-neutral collisions enhance resistivity and this also was accounted for.

The chromospheric part of the model was joined to a uniform coronal region, where an incident Alfvén wave pulse was launched downwards at $t = 0$.

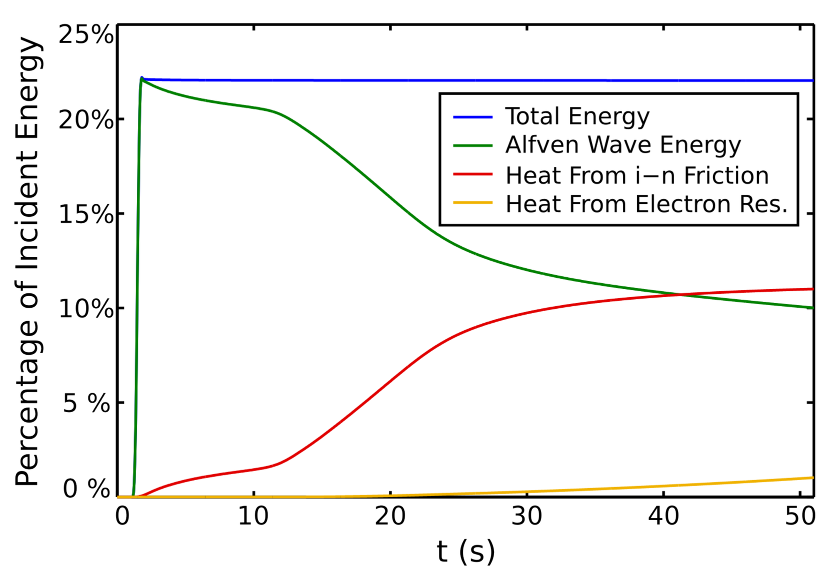
Plage model atmosphere



3. Typical Evolution

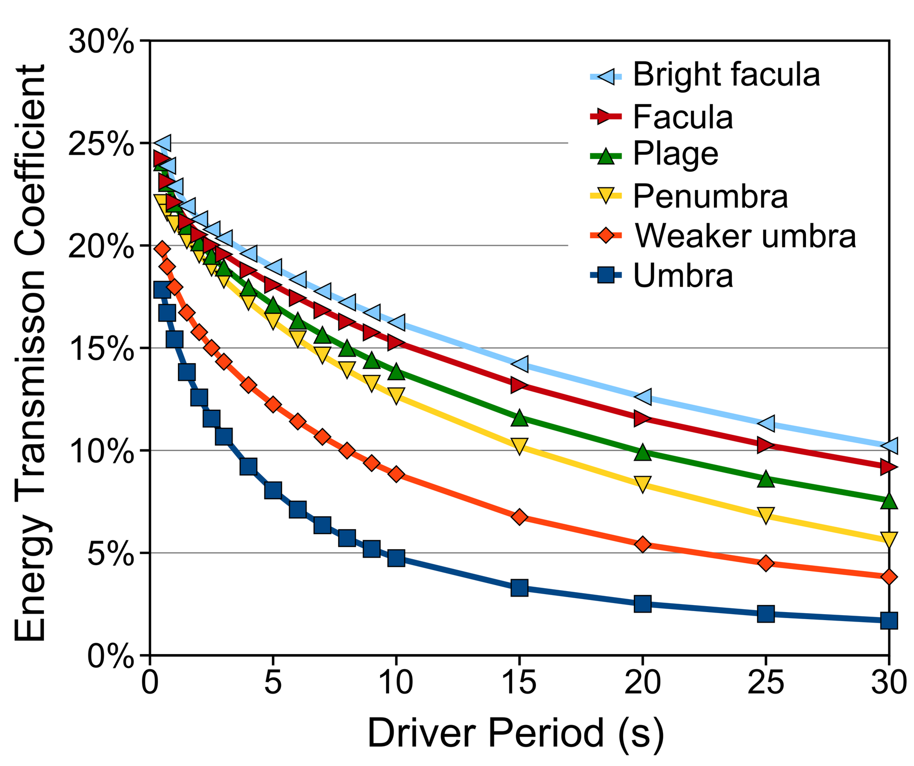
When the incident coronal wave reaches the transition region (TR), it is partially reflected there with some energy transmitted to the chromosphere. If the transmitted pulse has a width less the length scale of wave speed gradients, it propagates on downwards with little subsequent reflection. Wave pulses in the chromosphere are subject to damping via both ion-neutral friction and enhanced electron resistivity, which convert the wave energy to heat. These features can all be seen in the adjacent plot of energies in the chromosphere for a particular run: a plage atmosphere driven by a 1 s wave pulse.

Energy in chromosphere: plage model, 1 s pulse



4. Energy Transmission to the Chromosphere

The previous figure shows 22% of incident wave energy transmitted to the chromosphere for a particular case. The plot below gives a fuller picture. Shorter period waves transmit significantly more energy than longer period waves. Transmission also varies for different solar features.



The shortest period waves reflect only at the TR, whereas longer period waves also reflect from gradients in the chromosphere, hence the sensitivity to period.

The energy transmission coefficient for short periods can be estimated assuming a single step in wave speed. A convenient form is:

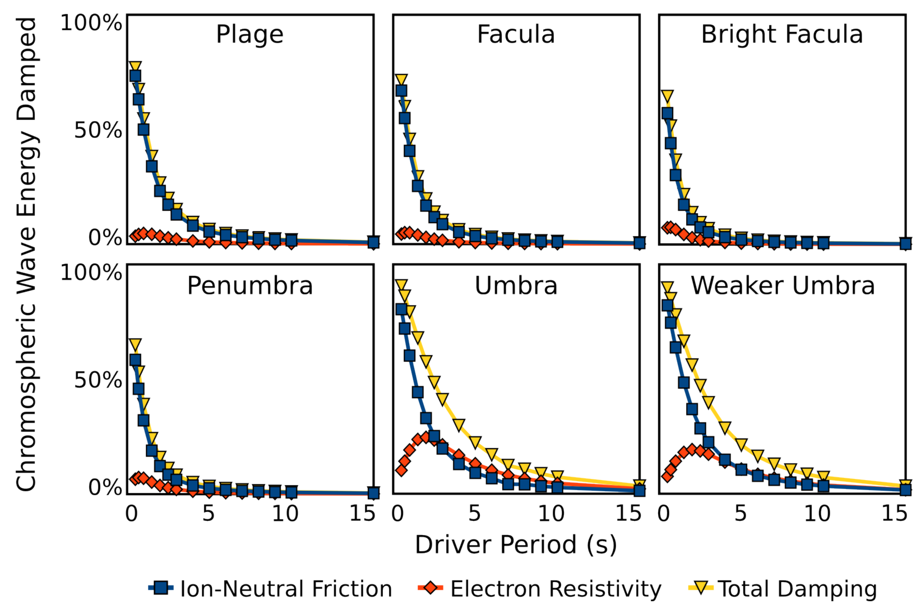
$$2\sqrt{2}\sqrt{\frac{T_{chr}}{T_{cor}}} < \mathcal{T} < 4\sqrt{\frac{T_{chr}}{T_{cor}}}$$

Limit approached for neutral dominated upper chromosphere. Limit approached for fully ionised upper chromosphere.

e.g. $T_{cor} = 1\ \text{MK},\ T_{chr} = 7000\ \text{K}$

$$\Rightarrow 0.24 < \mathcal{T} < 0.33.$$

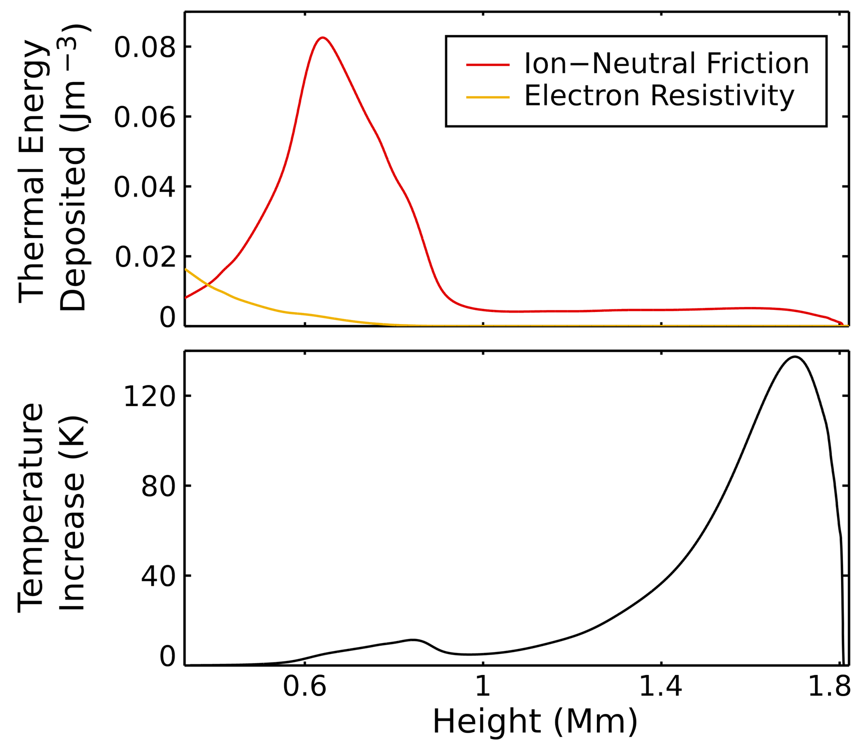
5. Heating



Wave damping and heating are sensitive to period and vary for different solar features (left). For wave pulses of 1 s or less, 37%–100% of wave energy entering the chromosphere is converted to heat, predominantly by ion-neutral friction. Waves with periods 10 s or longer experience relatively little damping. The increased damping for shorter wave periods is attributed to greater slippage between ions and neutrals, with wave energy damping as:

$$\tau_{damping} \sim \upsilon_{ni} \tau_{wave}^2.$$

Energy deposition is concentrated at particular heights where wave damping is strong. The figure on the right shows thermal energy deposited by a 1 s wave pulse of coronal amplitude $\delta B/B_0 = 0.05$ in the plage model. The bulk of the energy is deposited around TMR.



The thermal energy deposited per particle gives an estimate of the temperature increase, not accounting for losses, conduction, expansion etc. The greatest increase is in the upper chromosphere (where densities are low) with a secondary peak at the TMR. For the case described, the TMR temperature increase from a single pulse is 11.4 K. Values scale with $(\delta B/B_0)^2$.

6. Discussion

Our results suggest the observed TMR temperature increase of 100-300 K could be produced by a train of about ten or twenty moderate wave pulses (e.g. each 1 s duration with coronal δB of 5 G on B_0 of 100 G). Significantly fewer pulses suffice if larger amplitudes are considered or if background coronal field strength is increased. Thermal losses have not been accounted for, but the available margin for additional energy deposition is substantial.

Typical flare time scales range from subpulses in X-ray, radio and visible light observations (order of 100 ms), through elementary flare bursts (tens of seconds), to the duration of the rise phase (several minutes). There is, we conclude, reasonable overlap between observed flare timescales and the wave periods that have potential to heat the chromosphere.

Magnetic waves that vary perpendicular to the background magnetic field carry field-aligned electric fields due to inertial, kinetic or resistive effects. In the chromosphere, such waves might contribute to X-ray footpoints by accelerating sufficiently collisionless electrons: e.g. ones that have precipitated from the corona but remain energetic, or that belong to the tail of a thermal distribution. At the same time, wave energy absorbed by slower electrons would be converted to heat by collisions, giving an additional wave damping/heating mechanism not in this study.

In future, we would like to advance the model by including chromospheric feedbacks such as expansion of heated layers, thermal effects like radiation and conduction, and changing ionisation. This will allow treatment of the longer term evolution of the system. Modelling nonlinear waves and more realistic geometries will also be targeted.

7. Conclusions

i. Wave energy transmission to the chromosphere is greatest for short period waves and can exceed 20% of incident energy for wave periods of 1 s or less. Cumulative transmission will be higher if coronal waves are trapped in closed coronal structures e.g., closed magnetic field.

ii. Ion-neutral friction in the chromosphere effectively damps waves with second or subsecond periods, whereas waves with periods longer than 10 s pass through with little damping.

iii. Chromospheric damping of downgoing waves delivers the most energy to the TMR, heating it directly. Energy is also deposited throughout the upper chromosphere, where temperature increases are expected to be larger than at the TMR because of lower number densities.

We conclude that Alfvénic waves with periods of a few seconds or less are capable of heating the temperature minimum region and upper chromosphere during solar flares and should be considered as a complement to backwarming.

Get the paper:
A. J. B. Russell and L. Fletcher (2013), *ApJ*, **765**:81,
"Propagation of Alfvénic waves from corona to chromosphere and consequences for solar flares", doi:10.1088/0004-637X/765/2/81.

You may also like:
A. J. B. Russell and D. J. Stackhouse (2013), *A&A*, **558**:76,
"Solar flares and focused energy transport by MHD waves", doi:0.1051/0004-6361/201321916.

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