Propagation of Torsional Alfvén Waves from the Photosphere to the Corona

Reflection, Transmission, and Heating in Expanding Flux Tubes

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Our mysterious Sun
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Introduction

- Alfvén waves are observed in all layers of the solar atmosphere
- Alfvén waves are believed to be driven at the photosphere
- Energy estimations suggest that Alfvén waves can carry sufficient energy to heat the solar atmosphere

- Many open questions still under debate:
  - What are the reflection and transmission properties of the waves as they propagate through the various atmospheric layers?
  - What are the physical mechanisms that may lead to the efficient dissipation of wave energy and efficient plasma heating?

- **Magnetic field expansion may play an important role**

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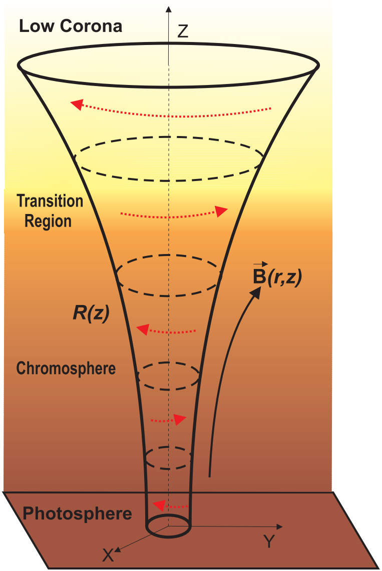
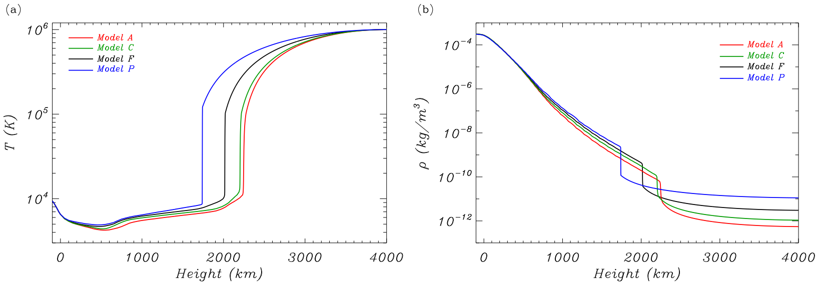
A Simple Model



A Simple Model

- Background chromosphere based on FAL93 models (Fontenla et al. 1993) extended up to the low corona
- Species: e, p, H, He I, He II, and He III
- Strong thermal coupling



A Simple Model

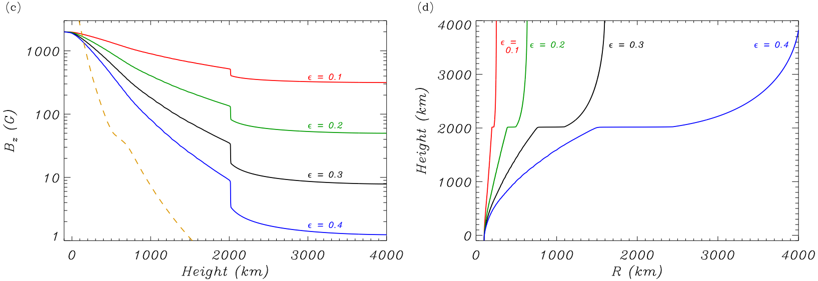
- Thin tube approximation: conservation of the magnetic flux

$$R^2(z)B_z(z) \approx \text{constant}$$

- Prescription of the vertical component of magnetic field (Leake et al. 2005)

$$B_z(z) = B_{\rm ph}\left(\frac{\rho(z)}{\rho_{\rm ph}}\right)^{\epsilon}$$

- Photospheric field strength: $B_{\rm ph} \approx$ 1–2 kG
- Expansion exponent: $\epsilon \lesssim 0.4$



Multi-Fluid Equations

- All ions (p, He II, He III) treated as a single ionic fluid
- Inertia of electrons is neglected
- Friction between ions and neutrals
- Multi-fluid equations for the discussion of linear Alfvén waves

$$\begin{aligned}
\rho_{\mathrm{i}} \frac{\partial \mathbf{v}_{\mathrm{i}}}{\partial t} &= \frac{1}{\mu} \left(\nabla \times \mathbf{b} \right) \times \mathbf{B} - \alpha_{\mathrm{iH}} \left(\mathbf{v}_{\mathrm{i}} - \mathbf{v}_{\mathrm{H}} \right) - \alpha_{\mathrm{iHeI}} \left(\mathbf{v}_{\mathrm{i}} - \mathbf{v}_{\mathrm{HeI}} \right) \\
\rho_{\mathrm{H}} \frac{\partial \mathbf{v}_{\mathrm{H}}}{\partial t} &= -\alpha_{\mathrm{Hi}} \left(\mathbf{v}_{\mathrm{H}} - \mathbf{v}_{\mathrm{i}} \right) - \alpha_{\mathrm{HHeI}} \left(\mathbf{v}_{\mathrm{H}} - \mathbf{v}_{\mathrm{HeI}} \right) \\
\rho_{\mathrm{HeI}} \frac{\partial \mathbf{v}_{\mathrm{HeI}}}{\partial t} &= -\alpha_{\mathrm{HeIi}} \left(\mathbf{v}_{\mathrm{HeI}} - \mathbf{v}_{\mathrm{i}} \right) - \alpha_{\mathrm{HeIH}} \left(\mathbf{v}_{\mathrm{HeI}} - \mathbf{v}_{\mathrm{H}} \right) \\
\frac{\partial \mathbf{b}}{\partial t} &= \nabla \times \left(\mathbf{v}_{\mathrm{i}} \times \mathbf{B} \right)
\end{aligned}$$

- Torsional Alfvén waves strictly polarized in the azimuthal direction, φ
- Stationary state of wave propagation: temporal dependence as $\exp\left(-i\omega t\right)$

Torsional Alfvén waves

Wave Equation

$$\frac{\partial^2}{\partial z^2}\left(\frac{v_{\mathrm{i},\varphi}}{R}\right)+\frac{\omega\Omega_{\mathrm{col}}}{B_z^2/\mu\rho_{\mathrm{i}}}\frac{v_{\mathrm{i},\varphi}}{R}=0$$

$$\Omega_{\mathrm{col}}\equiv\omega+i\nu_{\mathrm{i}}+\frac{\nu_{\mathrm{iH}}\nu_{\mathrm{Hi}}\left(\omega+i\nu_{\mathrm{HeI}}\right)+i\nu_{\mathrm{iH}}\nu_{\mathrm{HHeI}}\nu_{\mathrm{HeIi}}}{\left(\omega+i\nu_{\mathrm{H}}\right)\left(\omega+i\nu_{\mathrm{HeI}}\right)+\nu_{\mathrm{HHeI}}\nu_{\mathrm{HeIH}}}+\frac{\nu_{\mathrm{iHe}}\nu_{\mathrm{HeIi}}\left(\omega+i\nu_{\mathrm{H}}\right)+i\nu_{\mathrm{iHe}}\nu_{\mathrm{HeIH}}\nu_{\mathrm{Hi}}}{\left(\omega+i\nu_{\mathrm{H}}\right)\left(\omega+i\nu_{\mathrm{HeI}}\right)+\nu_{\mathrm{HHeI}}\nu_{\mathrm{HeIH}}}$$

Energy Equation

$$\frac{\partial U}{\partial t}+\nabla\cdot\Pi=-H$$

$$\begin{aligned}U&=\frac{1}{2}\rho_{\mathrm{i}}\left|\mathbf{v}_{\mathrm{i}}\right|^2+\frac{1}{2}\rho_{\mathrm{H}}\left|\mathbf{v}_{\mathrm{H}}\right|^2+\frac{1}{2}\rho_{\mathrm{HeI}}\left|\mathbf{v}_{\mathrm{HeI}}\right|^2+\frac{1}{2\mu}\left|\mathbf{b}\right|^2\\ \Pi&=\frac{1}{\mu}\left[\left(\mathbf{B}\cdot\mathbf{b}\right)\mathbf{v}_{\mathrm{i}}-\left(\mathbf{v}_{\mathrm{i}}\cdot\mathbf{b}\right)\mathbf{B}\right]\\ H&=\alpha_{\mathrm{iH}}\left|\mathbf{v}_{\mathrm{i}}-\mathbf{v}_{\mathrm{H}}\right|^2+\alpha_{\mathrm{iHeI}}\left|\mathbf{v}_{\mathrm{i}}-\mathbf{v}_{\mathrm{HeI}}\right|^2+\alpha_{\mathrm{HHeI}}\left|\mathbf{v}_{\mathrm{H}}-\mathbf{v}_{\mathrm{HeI}}\right|^2\end{aligned}$$

Torsional Alfvén waves

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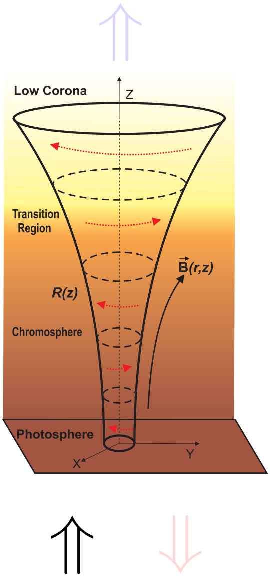
Method



- Reflectivity: fraction of incident energy that is reflected back to the photosphere

$$\mathcal{R} = \frac{|\langle \Pi \rangle|_{\text{Reflected}}}{|\langle \Pi \rangle|_{\text{Incident}}}$$

- Transmissivity: fraction of incident energy that is transmitted to the corona

$$\mathcal{T} = \frac{|\langle \Pi \rangle|_{\text{Transmitted}}}{|\langle \Pi \rangle|_{\text{Incident}}}$$

- Absorption: fraction of incident energy that is deposited in the chromosphere

$$\mathcal{A} = 1 - \mathcal{R} - \mathcal{T}$$

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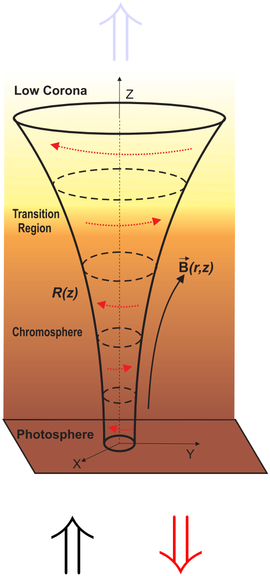

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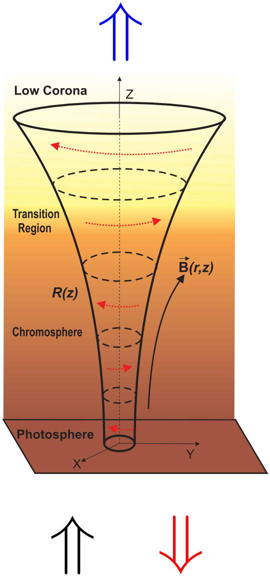

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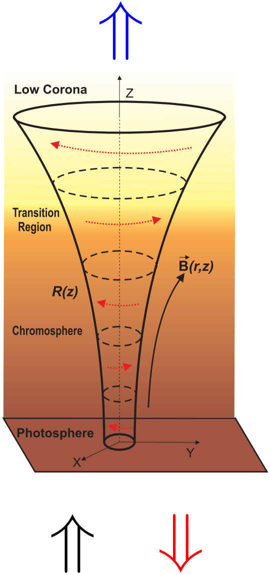

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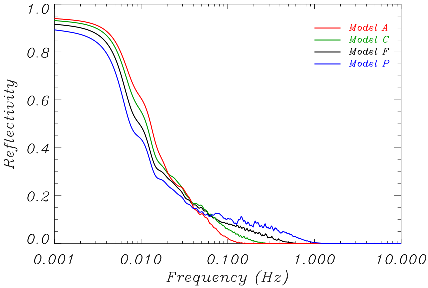
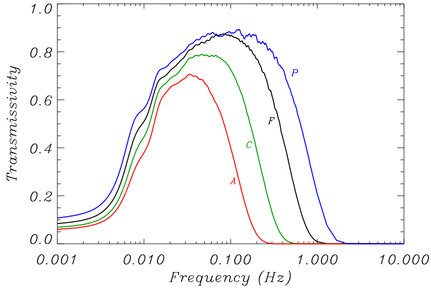
Dependence on Frequency

$B_{\rm ph} = 2$ kG, $\epsilon = 0.3$

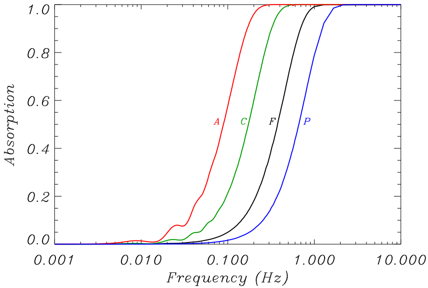
(a)



(b)



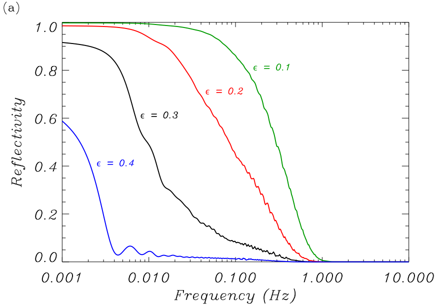
(c)

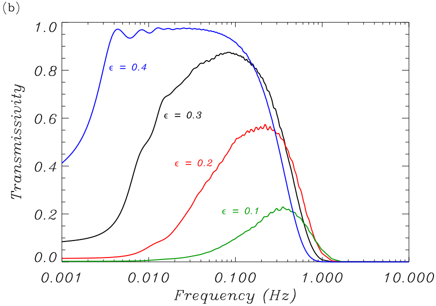


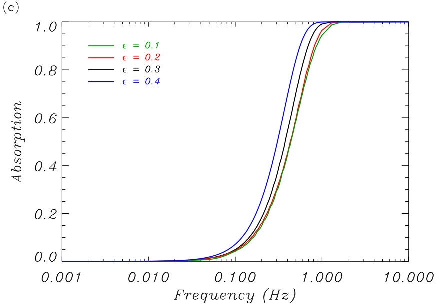
1. Low frequencies reflected back to the photosphere
2. Intermediate frequencies transmitted to the corona
3. High frequencies damped in the chromosphere

Model parameters have a strong impact on absorption

Dependence on Magnetic Field Expansion







$B_{\rm ph} = 2$ kG
Atmospheric model F

1. Transmissivity is enhanced
2. Maximum transmissivity shifted towards lower frequencies
3. Absorption weakly affected

Heating profiles: Broadband Driver

- Broadband driver at the photosphere, model F, $B_{\rm ph} = 2$ kG

$$A_f = \begin{cases} \sim f^{5/6}, & \text{if} \quad f \leq 1.6 \times 10^{-2}\ \text{Hz}, \\ \sim f^{-5/6}, & \text{if} \quad f \geq 1.6 \times 10^{-2}\ \text{Hz} \end{cases}$$

- Incident Poynting flux: 2×10^{7} erg cm^{-2} s^{-1}

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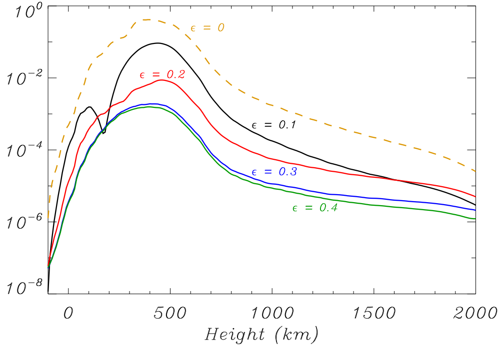

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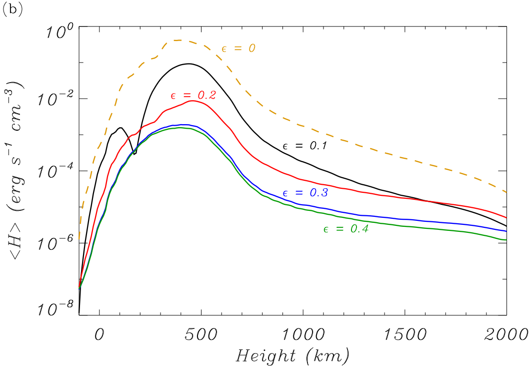

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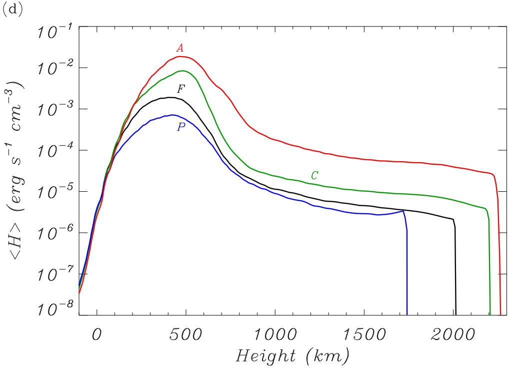

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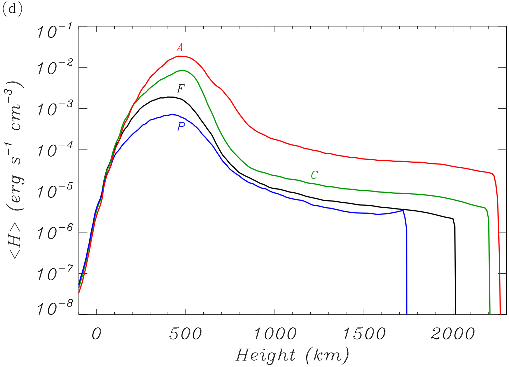

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- Computed heating rates lower than the required rates. . . but strong dependence on the atmospheric model!

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