Energy transport and heating by torsional Alfvén waves in the partially ionised chromosphere

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Introduction

- Observations show that **Alfvénic** (Alfvén and/or kink) waves are present in all layers of the solar atmosphere:
    - Photosphere: e.g., Jess et al. (2009)
    - Chromosphere: e.g., De Pontieu et al. (2014), Srivastava et al. (2017)
    - TR and Corona: e.g., McIntosh et al. (2011), Morton et al. (2015)

- The driver is probably located at the photosphere
    - Horizontal flows: e.g., Spruit (1981), Choudhuri et al. (1993), Huang et al. (1995), Stangalini et al. (2014)
    - Vortex motions: e.g., Shelyag et al. (2011, 2012), Wedemeyer-Böhm et al. (2012), Morton et al. (2013)
    - **Estimated driven energy flux (averaged):** $\sim 10^7$ **erg cm^{-2} s^{-1}**

- Waves may carry sufficient energy to heat the plasma
- Quiet-Sun energy requirements (Withbroe & Noyes 1977):
    - Lower chromosphere radiative losses: 10^{-1} erg cm^{-3} s^{-1}
    - Middle and upper chromosphere radiative losses: 10^{-3}–10^{-2} erg cm^{-3} s^{-1}
    - Corona total energy loss: $\sim 3 \times 10^5$ erg cm^{-2} s^{-1}

Introduction

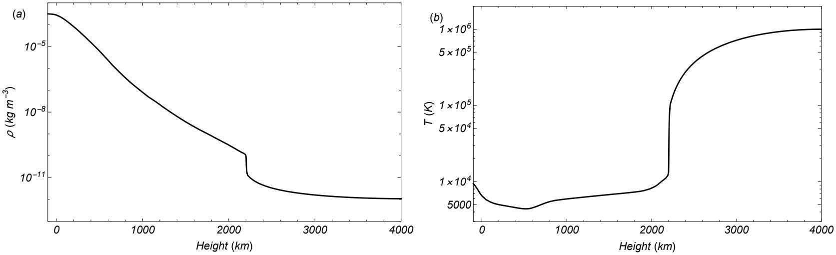
- Despite the observational evidence, many open questions are still under debate:
  1. How are Alfvén waves driven in the weakly ionized and probably unmagnetized photosphere?
  2. Can the waves transport sufficient energy to the outer atmosphere and solar wind?
  3. What are the physical mechanisms that can dissipate the wave energy?
  4. Is the plasma heating/particle acceleration efficient enough?

Before considering complicated scenarios, we aim to understand propagation and deposition of energy by Alfvén waves in a simple model of the lower solar atmosphere

- Previous works in this line: e.g., Goodman (2011), Tu & Song (2013), Arber et al. (2016), Shelyag et al. (2016), Soler et al. (2017),. . .

A Simple Model for the Lower Solar Atmosphere

- Background atmosphere based on FAL93-C chromospheric model (Fontenla et al. 1993) extended up to 4,000 km
- Quiet Sun: Photosphere + Chromosphere + TR + Low Corona
- Partially ionized plasma
- Species: e, p, H, He I, He II, and He III



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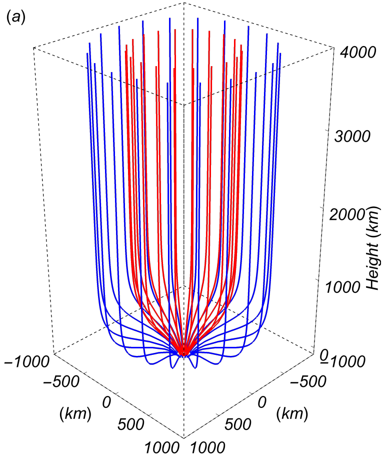


- Potential magnetic flux tube
- Vertical and untwisted
- Photospheric field strength ∼ 1 kG
- Coronal field strength ∼ 10 G
- Expansion with height $R_{\rm corona}/R_{\rm photosphere} \sim 10$

Basic Equations

- All ions (p, He II, He III) treated as a single ionic fluid
- Inertia of electrons is neglected → Ohm's Law
- Dissipation: Ohm's diffusion + Ion-neutral friction
- Linearized equations for torsional Alfvén waves strictly polarized in the azimuthal direction, φ

$$\begin{aligned}
\rho_{\mathrm{i}} \frac{\partial v'_{\mathrm{i},\varphi}}{\partial t} &= \frac{1}{\mu r}\mathbf{B}\cdot\nabla\left(rB'_{\varphi}\right) - \alpha_{\mathrm{iH}}\left(v'_{\mathrm{i},\varphi} - v'_{\mathrm{H},\varphi}\right) - \alpha_{\mathrm{iHeI}}\left(v'_{\mathrm{i},\varphi} - v'_{\mathrm{HeI},\varphi}\right) \\
\rho_{\mathrm{H}} \frac{\partial v'_{\mathrm{H},\varphi}}{\partial t} &= -\alpha_{\mathrm{Hi}}\left(v'_{\mathrm{H},\varphi} - v'_{\mathrm{i},\varphi}\right) - \alpha_{\mathrm{HHeI}}\left(v'_{\mathrm{H},\varphi} - v'_{\mathrm{HeI},\varphi}\right) \\
\rho_{\mathrm{HeI}} \frac{\partial v'_{\mathrm{HeI},\varphi}}{\partial t} &= -\alpha_{\mathrm{HeIi}}\left(v'_{\mathrm{HeI},\varphi} - v'_{\mathrm{i},\varphi}\right) - \alpha_{\mathrm{HeIH}}\left(v'_{\mathrm{HeI},\varphi} - v'_{\mathrm{H},\varphi}\right) \\
\frac{\partial B'_{\varphi}}{\partial t} &= r\mathbf{B}\cdot\nabla\left(\frac{v'_{\mathrm{i},\varphi}}{r}\right) + \eta\left(\nabla^2 B'_{\varphi} - \frac{1}{r^2}B'_{\varphi}\right) + \frac{\partial\eta}{\partial z}\frac{\partial B'_{\varphi}}{\partial z}
\end{aligned}$$

Steady-state propagation

- Steady state of wave propagation: temporal dependence as $\exp(-i\omega t)$
- Partial differential equation for the magnetic field perturbation:

$$i\omega B'_\varphi + r\mathbf{B}\cdot\nabla\left[\frac{i}{\omega}\frac{1}{\mu\rho_{\rm eff}}\frac{1}{r^2}\mathbf{B}\cdot\nabla\left(rB'_\varphi\right)\right] + \eta\left(\nabla^2 B'_\varphi - \frac{1}{r^2}B'_\varphi\right) + \frac{\partial\eta}{\partial z}\frac{\partial B'_\varphi}{\partial z} = 0$$

- $\rho_{\rm eff} \equiv$ effective plasma density containing the effect of particle-particle collisions (inertia + damping)
- Governing equation numerically integrated with finite elements in a non-uniform mesh
- Perturbations decomposed into upward (↑) and downward (↓) propagating waves with the help of the Elsässer variables → Separation between upward and downward energy fluxes

Wave Driver

- Broadband wave driver for B'_{φ} at the photosphere
  - Frequency range: 0.1 mHz $\leq f \leq$ 300 mHz
  - Spectral weighting function (Tu & Song 2013; Arber at al. 2016):

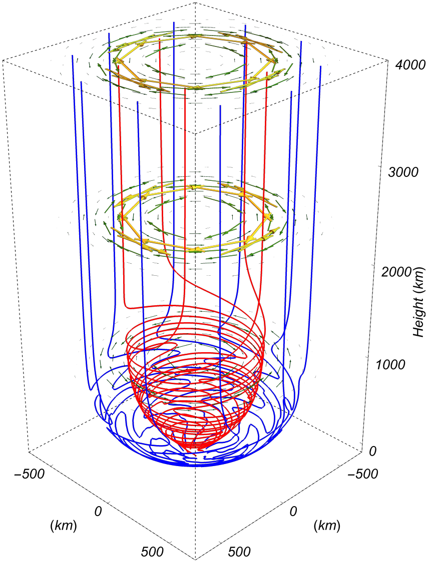
$$A\left(f\right) \sim \begin{cases} \left(\frac{f}{f_p}\right)^{5/6}, & \text{if}, \quad f \leq f_p, \\ \left(\frac{f}{f_p}\right)^{-5/6}, & \text{if}, \quad f > f_p, \end{cases}$$

  - Peak frequency: $f_p \approx 1.59$ mHz
  - **Injected energy flux:** 10^7 **erg cm**$^{-2}$ **s**$^{-1}$

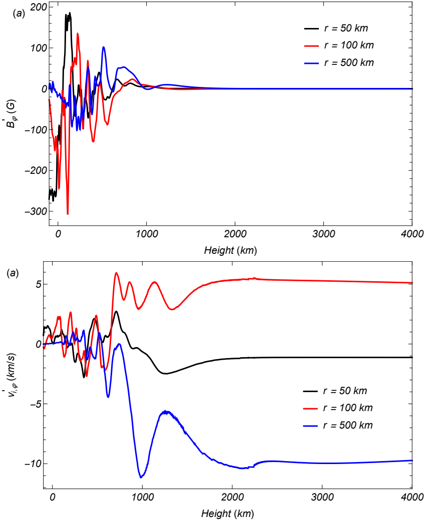
- Appropriate treatment of wave reflection and transmission:
  - Photospheric boundary: driven wave ($\uparrow$) + reflected wave ($\downarrow$)
  - Coronal boundary: transmitted wave ($\uparrow$)

- Only driven wave is imposed
- Reflected and transmitted waves self-consistently computed

Perturbations

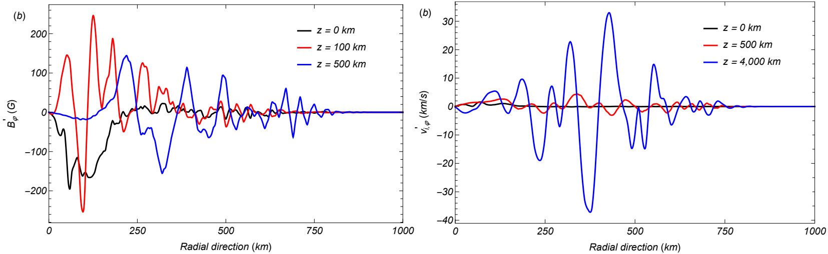


Vertical cuts



Phase mixing

Horizontal cuts



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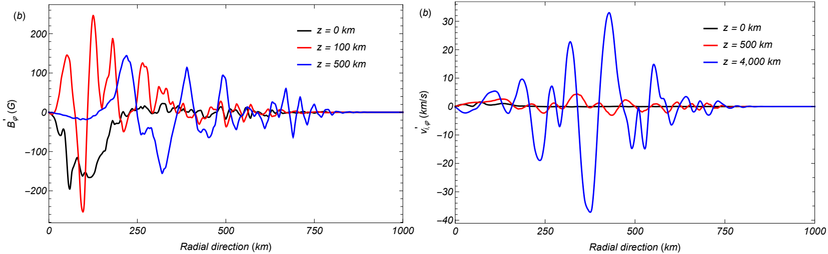
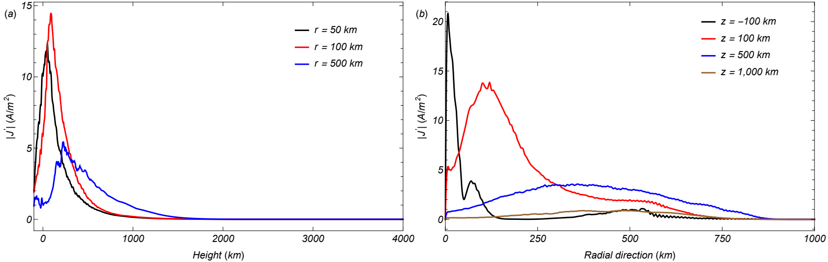
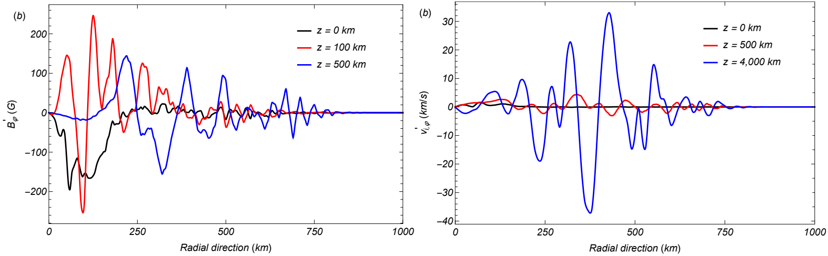


Current density perturbation

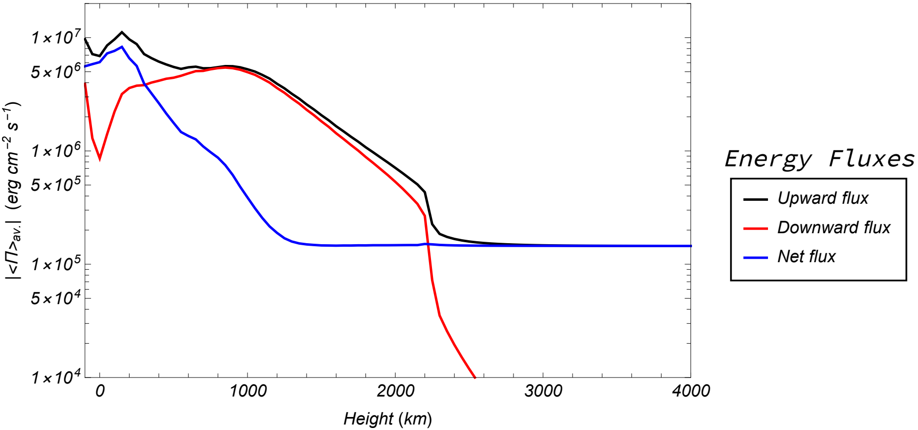


Phase mixing


Horizontal cuts

- **Phase mixing enhances Ohmic diffusion in strongly divergent flux tubes embedded in a stratified plasma**: e.g., Ruderman et al. (1998), De Moortel et al. (2000), Smith et al. (2007), Ruderman & Petrukhin (2017), Petrukhin et al. (2018).

Energy Flux



Only $\sim 1\%$ of the injected flux reaches the corona...but

- Transmitted energy flux: $\sim 1.5 \times 10^5$ erg cm^{-2} s^{-1}
- Quiet-Sun corona total energy loss: $\sim 3 \times 10^5$ erg cm^{-2} s^{-1} (Withbroe & Noyes 1977)

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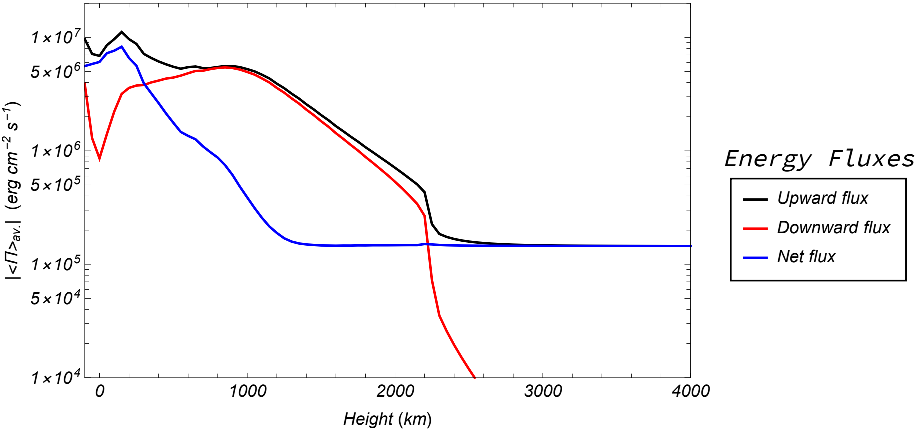

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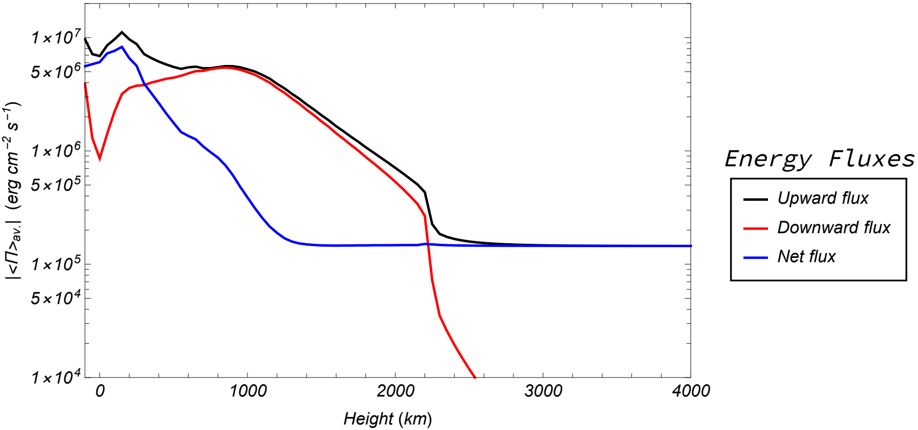

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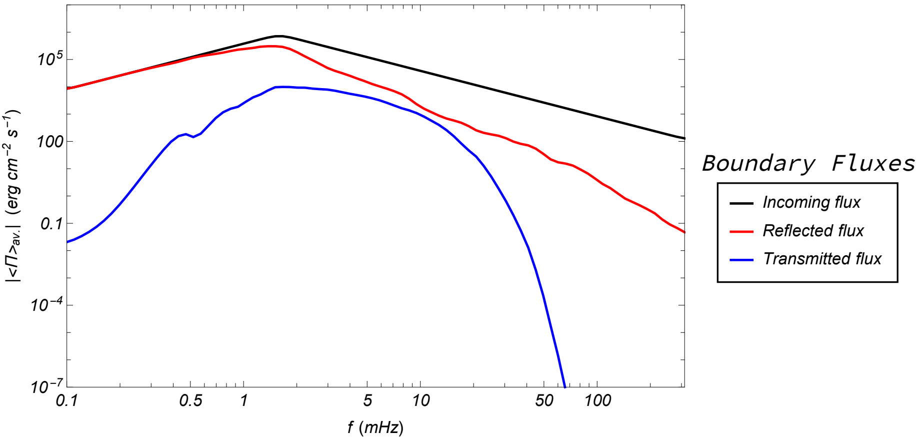
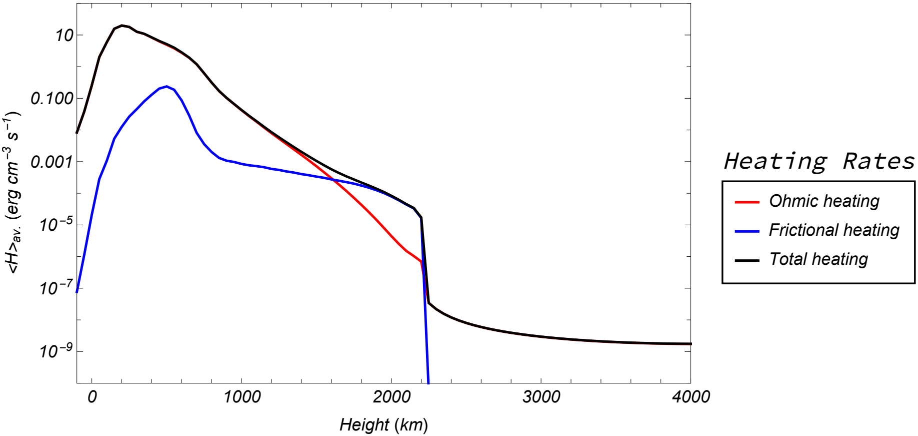
Energy Fluxes at the Boundaries



- Low frequencies are reflected (incoming flux $\approx$ reflected flux)
- High frequencies are dissipated $\longrightarrow$ Heating
  (incoming flux $\gg$ reflected flux + transmitted flux)
- Very small transmissivity (peak $\sim 2 - 5$ mHz)

Heating Rates



- Required volumetric heating (Ulmschneider 1974; Withbroe & Noyes 1977):
  - Lower chromosphere: 10^{-1} erg cm^{-3} s^{-1}
  - Middle and upper chromosphere: 10^{-3}–10^{-2} erg cm^{-3} s^{-1}

Conclusions

Energy fluxes

- Low frequencies reflected back to the photosphere
- High frequencies damped in the chromosphere
- Only $\sim 1\%$ of injected flux is transmitted to the corona, but **it is almost enough to compensate the total coronal energy loss**

Chromospheric Heating

- Ohmic diffusion (enhanced by phase-mixing) heats the lower and middle chromosphere
- Ion-neutral friction heats the upper chromosphere
- **Chromospheric heating rates compatible with (or even larger than) the required rates**

Alfvén waves may play an <u>essential role</u> in the energy transport and dissipation in the solar atmosphere!

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