Energy transport and heating by torsional Alfvén waves in the quiet-Sun atmosphere

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Introduction

- Observations show that **Alfvénic waves** (torsional and kink) 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)

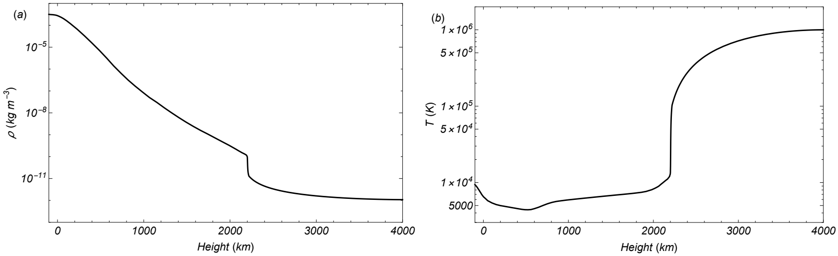
- The driver is probably located at the photosphere
  - Horizontal flows: e.g., Spruit (1981), Choudhuri et al. (1993), Huang et al. (1995), Stangalini et al. (2014)
  - Vortex motions: e.g., Shelyag et al. (2011, 2012), Wedemeyer-Böhm et al. (2012), Morton et al. (2013)
  - **Estimated driven energy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

- Waves may carry **sufficient energy to heat the plasma**:
  - e.g., De Pontieu et al. (2001), Leake at al. (2005), 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

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

- 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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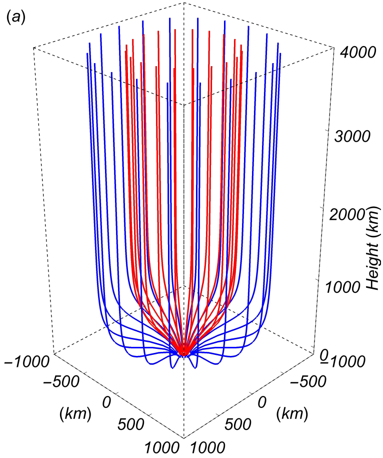

- Potential magnetic flux tube
- Vertical and untwisted
- Photospheric field strength ~ 1 kG
- Coronal field strength ~ 10 G
- Expansion with height $R_{\rm corona}/R_{\rm photosphere} \sim 10$

Some Hints of the Method

- Multi-fluid equations numerically integrated with finite elements in a non-uniform mesh
- Dissipation mechanisms: Ohm's diffusion + Ion-neutral friction
- Steady state of torsional wave propagation (linear regime)

- Broadband wave driver at the photosphere:
  - Torsional motion, frequency range: 0.1 mHz $\leq f \leq$ 300 mHz
  - Spectral weighting function (Tu & Song 2013; Arber at al. 2016):

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

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

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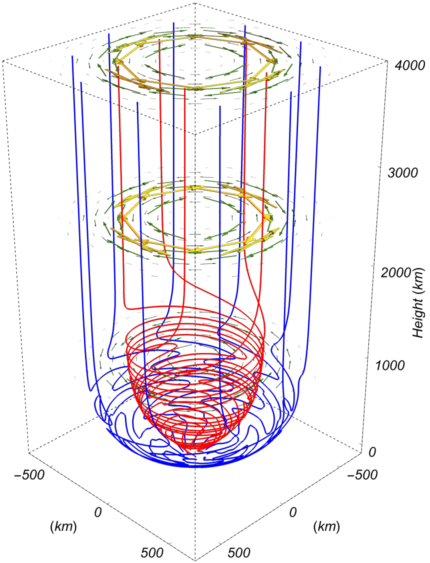
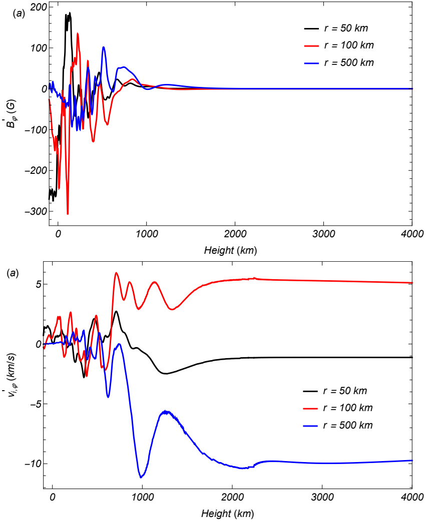
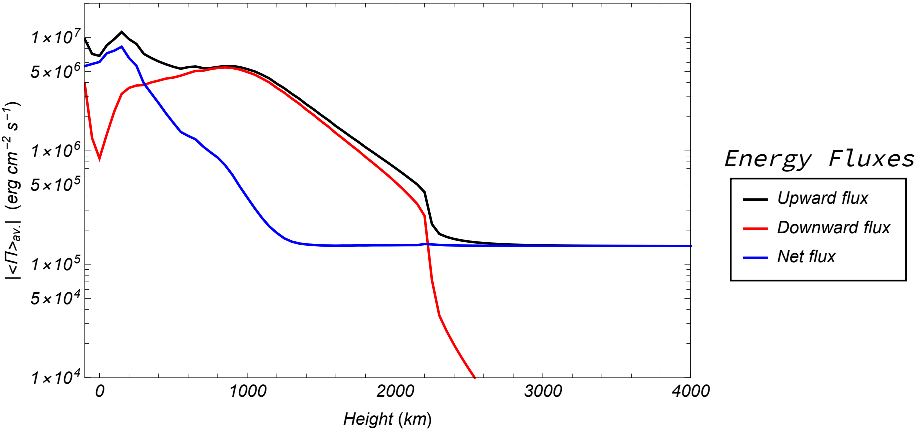
Perturbations



Vertical cuts



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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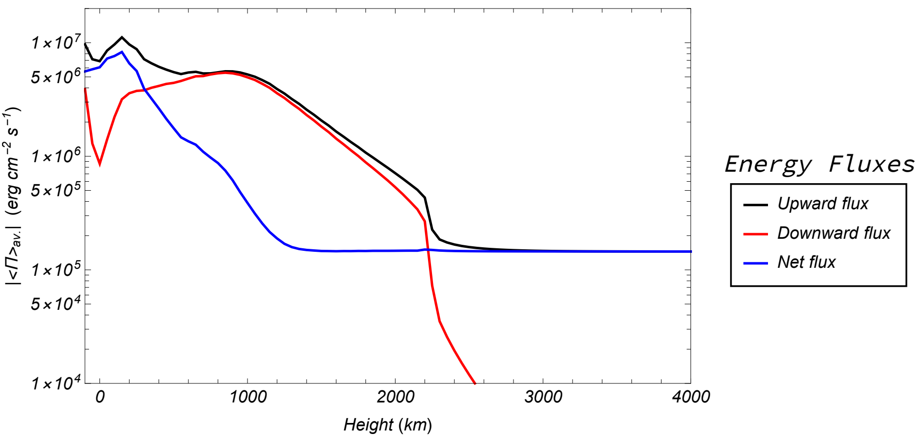

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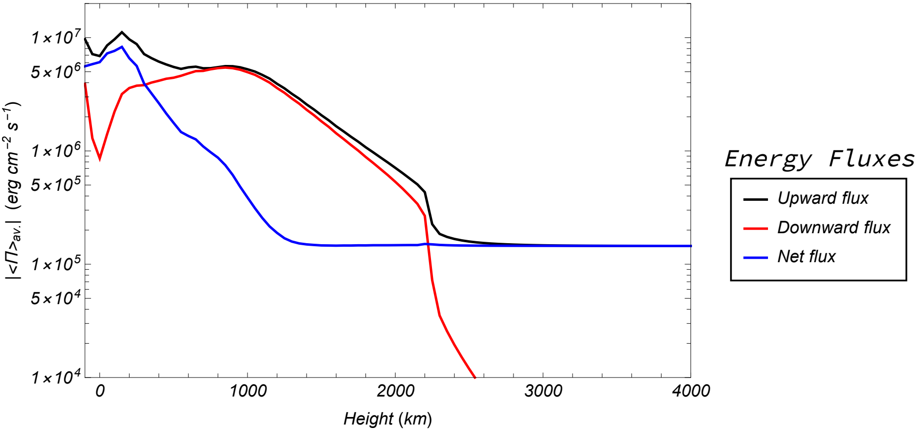

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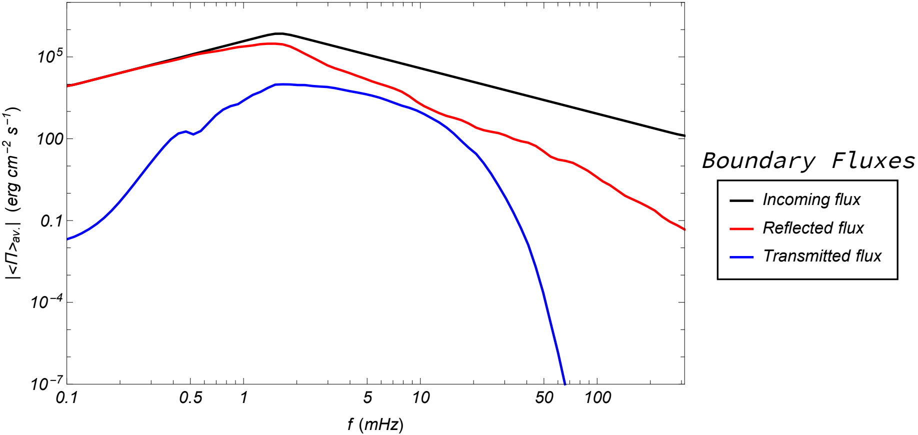
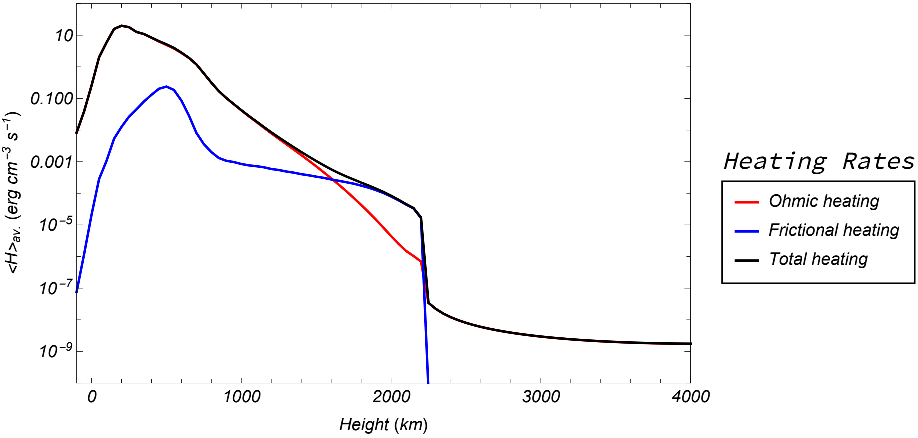
Energy Fluxes at the Boundaries



- Low frequencies are reflected (incoming flux $\approx$ reflected flux)
- High frequencies are dissipated $\rightarrow$ 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 heats the lower and middle chromosphere
- Ion-neutral friction heats the upper chromosphere
- **Chromospheric heating rates compatible with the required rates**

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

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