Propagation of Torsional Alfvén Waves from the Photosphere to the Corona

Reflection, Transmission, and Heating in Expanding Flux Tubes

Roberto Soler, J. Terradas, R. Oliver, J. L. Ballester

Solar Physics Group
Universitat de les Illes Balears (Spain)

Our mysterious Sun
Tbilisi, 25–29 September 2017

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**

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**

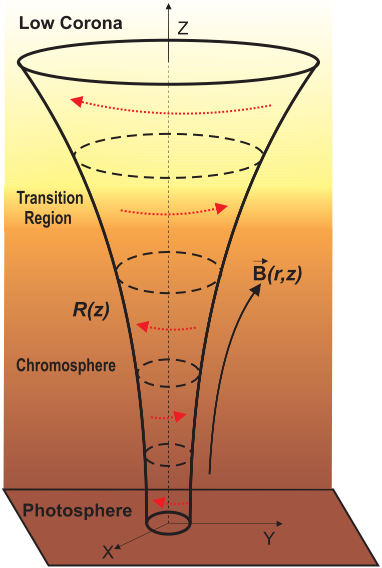
Introduction

- 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?

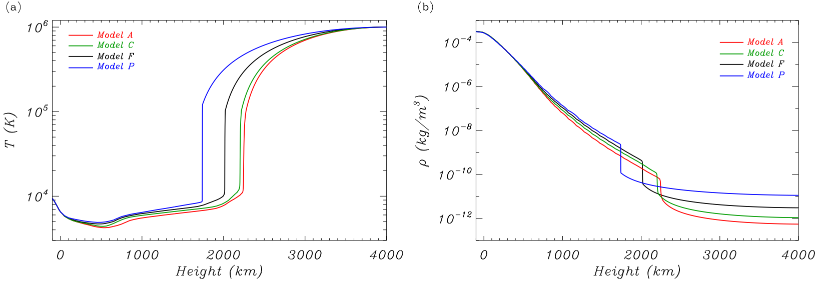
- **Magnetic field expansion may play an important role**

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

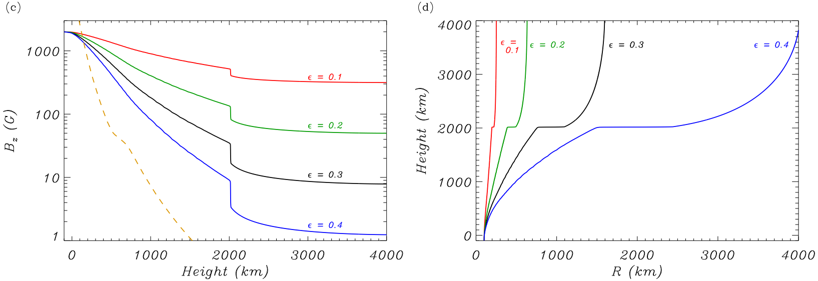
- Thin tube approximation: conservation of the magnetic flux

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

- 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

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

- 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

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

$$U = \frac{1}{2}\rho_{\mathrm{i}}\left|\mathbf{v}_{\mathrm{i}}\right|^2 + \frac{1}{2}\rho_{\mathrm{H}}\left|\mathbf{v}_{\mathrm{H}}\right|^2 + \frac{1}{2}\rho_{\mathrm{HeI}}\left|\mathbf{v}_{\mathrm{HeI}}\right|^2 + \frac{1}{2\mu}\left|\mathbf{b}\right|^2$$

$$\Pi = \frac{1}{\mu}\left[\left(\mathbf{B}\cdot\mathbf{b}\right)\mathbf{v}_{\mathrm{i}} - \left(\mathbf{v}_{\mathrm{i}}\cdot\mathbf{b}\right)\mathbf{B}\right]$$

$$H = \alpha_{\mathrm{iH}}\left|\mathbf{v}_{\mathrm{i}} - \mathbf{v}_{\mathrm{H}}\right|^2 + \alpha_{\mathrm{iHeI}}\left|\mathbf{v}_{\mathrm{i}} - \mathbf{v}_{\mathrm{HeI}}\right|^2 + \alpha_{\mathrm{HHeI}}\left|\mathbf{v}_{\mathrm{H}} - \mathbf{v}_{\mathrm{HeI}}\right|^2$$

Torsional Alfvén waves

Wave Equation

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

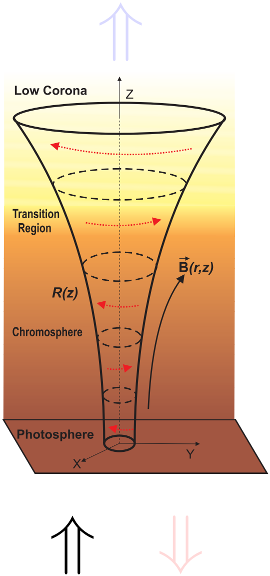
$$\Omega_{\mathrm{col}} \equiv \omega + i\nu_{\mathrm{i}} + \frac{\nu_{\mathrm{iH}}\nu_{\mathrm{Hi}}\left(\omega + i\nu_{\mathrm{HeI}}\right) + i\nu_{\mathrm{iH}}\nu_{\mathrm{HHeI}}\nu_{\mathrm{HeIi}}}{\left(\omega + i\nu_{\mathrm{H}}\right)\left(\omega + i\nu_{\mathrm{HeI}}\right) + \nu_{\mathrm{HHeI}}\nu_{\mathrm{HeIH}}}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

Energy Equation

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

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

Method



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

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

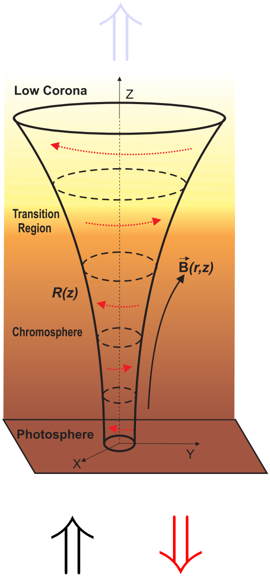
- Transmissivity: fraction of incident energy that is transmitted to the corona

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

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

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

Method



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

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

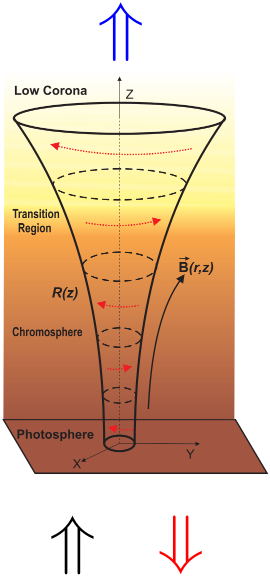
- Transmissivity: fraction of incident energy that is transmitted to the corona

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

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

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

Method



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

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

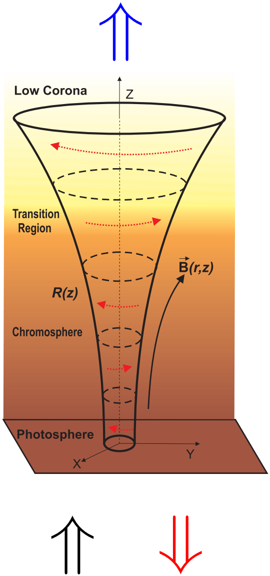
- Transmissivity: fraction of incident energy that is transmitted to the corona

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

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

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

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

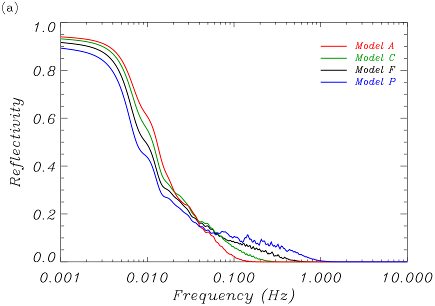
$$\mathcal{T} = \frac{|\langle \Pi \rangle|_{\text{Transmitted}}}{|\langle \Pi \rangle|_{\text{Incident}}}$$

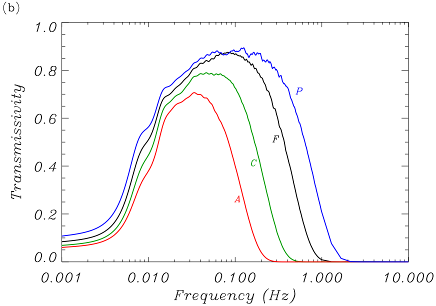
- Absorption: fraction of incident energy that is deposited in the chromosphere

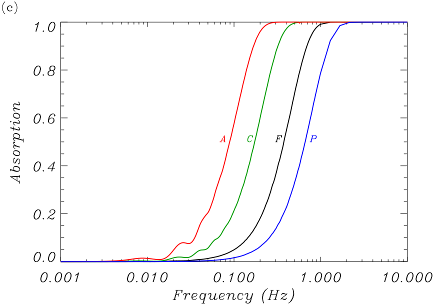
$$\mathcal{A} = 1 - \mathcal{R} - \mathcal{T}$$

Dependence on Frequency

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



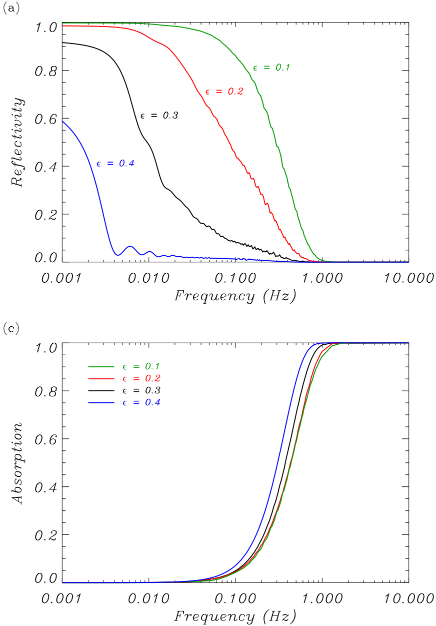




1. Low frequencies reflected back to the photosphere
2. Intermediate frequencies transmitted to the corona
3. High frequencies damped in the chromosphere

Model parameters have a strong impact on absorption

Dependence on Magnetic Field Expansion



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

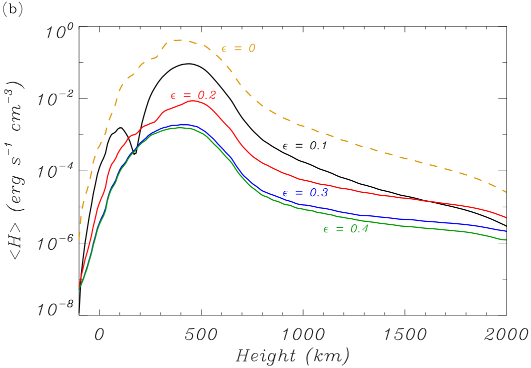
1. Transmissivity is enhanced
2. Maximum transmissivity shifted towards lower frequencies
3. Absorption weakly affected

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}



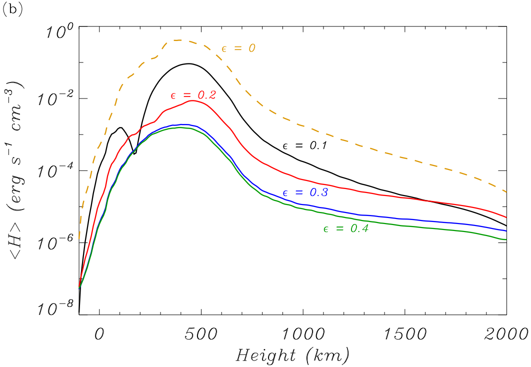
- Required volumetric heating:
  - Low chromosphere: 10^{-1} erg cm^{-3} s^{-1}
  - Middle and high chromosphere: 10^{-3}–10^{-2} erg cm^{-3} s^{-1}

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}



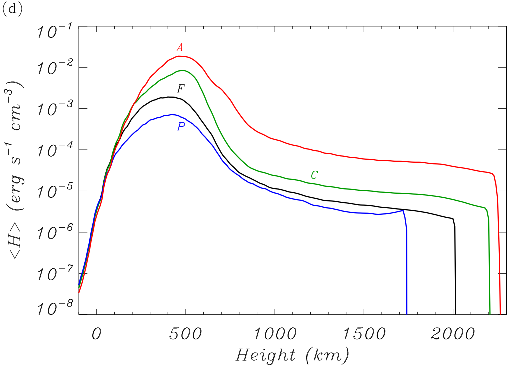
- Required volumetric heating:
  - Low chromosphere: 10^{-1} erg cm^{-3} s^{-1}
  - Middle and high chromosphere: 10^{-3}–10^{-2} erg cm^{-3} s^{-1}

Heating profiles: Comparison between models

- Broadband driver at the photosphere, $B_{\rm ph} = 2$ kG and $\epsilon = 0.3$

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

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



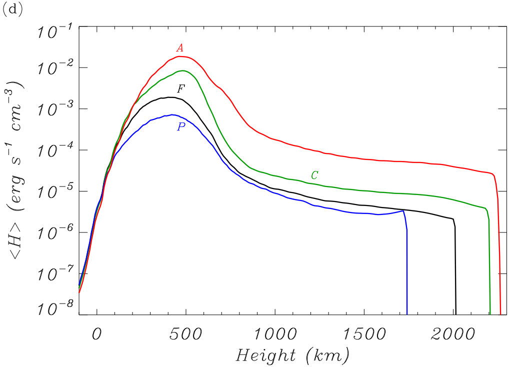
- Required volumetric heating:
  - Low chromosphere: 10^{-1} erg cm^{-3} s^{-1}
  - Middle and high chromosphere: 10^{-3}–10^{-2} erg cm^{-3} s^{-1}

Heating profiles: Comparison between models

- Broadband driver at the photosphere, $B_{\rm ph} = 2$ kG and $\epsilon = 0.3$

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

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



- Required volumetric heating:
  - Low chromosphere: 10^{-1} erg cm^{-3} s^{-1}
  - Middle and high chromosphere: 10^{-3}–10^{-2} erg cm^{-3} s^{-1}

Conclusions

- Low frequencies reflected back to the photosphere
- Intermediate frequencies transmitted to the corona
- High frequencies damped in the chromosphere

- Transmissivity is enhanced by magnetic field expansion
- Maximum transmissivity shifted towards lower frequencies

- Magnetic field expansion systematically decreases the heating rates
- Computed heating rates lower than the required rates. . . but strong dependence on the atmospheric model!

Reference:
Soler, Terradas, Oliver, & Ballester 2017, ApJ 840, 20

Conclusions

- Low frequencies reflected back to the photosphere
- Intermediate frequencies transmitted to the corona
- High frequencies damped in the chromosphere

- Transmissivity is enhanced by magnetic field expansion
- Maximum transmissivity shifted towards lower frequencies

- Magnetic field expansion systematically decreases the heating rates
- Computed heating rates lower than the required rates. . . but strong dependence on the atmospheric model!

Reference:
Soler, Terradas, Oliver, & Ballester 2017, ApJ 840, 20

Conclusions

- Low frequencies reflected back to the photosphere
- Intermediate frequencies transmitted to the corona
- High frequencies damped in the chromosphere

- Transmissivity is enhanced by magnetic field expansion
- Maximum transmissivity shifted towards lower frequencies

- Magnetic field expansion systematically decreases the heating rates
- Computed heating rates lower than the required rates. . . but strong dependence on the atmospheric model!

Reference:
Soler, Terradas, Oliver, & Ballester 2017, ApJ 840, 20

Conclusions

- Low frequencies reflected back to the photosphere
- Intermediate frequencies transmitted to the corona
- High frequencies damped in the chromosphere

- Transmissivity is enhanced by magnetic field expansion
- Maximum transmissivity shifted towards lower frequencies

- Magnetic field expansion systematically decreases the heating rates
- Computed heating rates lower than the required rates... but strong dependence on the atmospheric model!

Reference:
Soler, Terradas, Oliver, & Ballester 2017, ApJ 840, 20