Coronal heating by MHD waves

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Topics review paper

- Introduction
  - Brief historical overview
  - Observational motivation
- Observations
  - Impulsively excited standing waves (brief, discount → Terradas & Arregui 2017)
  - Decayless waves
  - Energy estimates
- Models
  - (RMHD) Alfvén wave heating models
  - (KHI/Uni) turbulence models
  - Phase mixing models
- Conclusions & Critical assessment

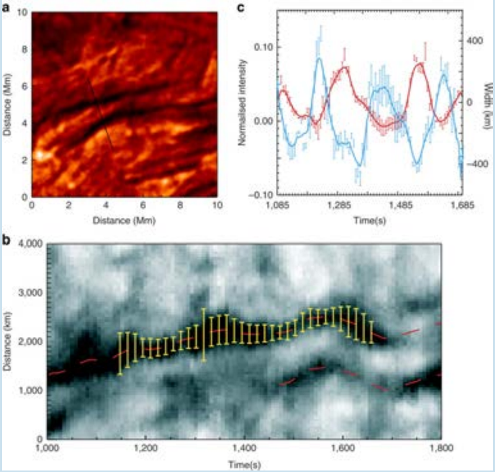
Introduction of review

Elected not to include explicitly in this talk

- Brief historical overview
  - Heating with Alfvén waves (Hollweg, ...)
  - Heating with resonant absorption (Poedts, Goossens, De Groof)
  - Chromospheric heating with slow shocks (Carlsson, ...)
- Observational motivation (1999, 2007)
  - Standing kink waves (Aschwanden, Nakariakov)
  - Lower atmospheric wave motion? (Kukhianidze, De Pontieu)
  - CoMP waves (Tomczyk)
  - Decayless waves (Wang, Anfinogentov, Nistico)

Energy flux in lower atmosphere

Morton et al. (2012): energy flux in sausage modes in mottles



Energy flux of $11.7 \pm 3.8 kW/m^2$

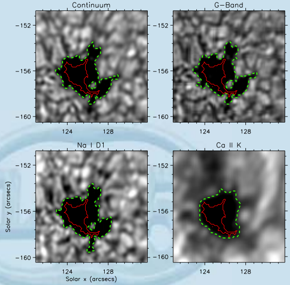
Energy flux in lower atmosphere

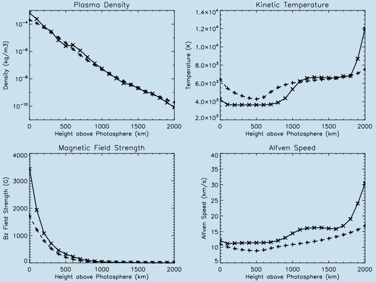
Moreels et al. (2015b), Grant et al. (2015)

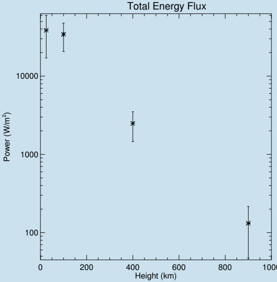
Energy in slow waves:

$$F_{\mathrm{Slow}} = \frac{1}{2} f \rho_{0,\mathrm{i}} \omega_{\mathrm{T,i}}^2 \Xi_z^2 v_{\mathrm{T,i}}$$

$v_{\mathrm{T,i}}$ is internal tube speed, Ξ_z is longitudinal displacement amplitude

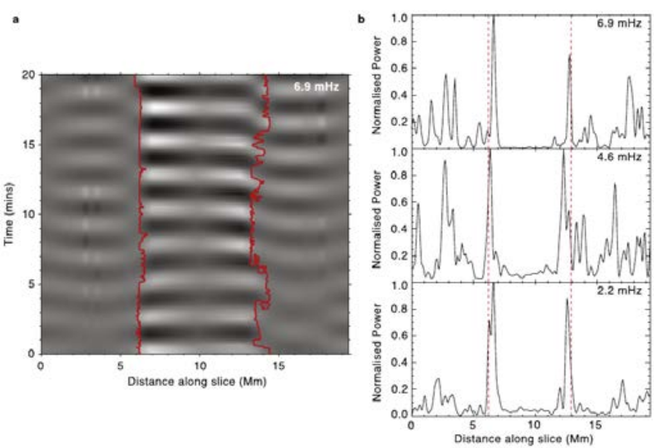






Energy flux in lower atmosphere

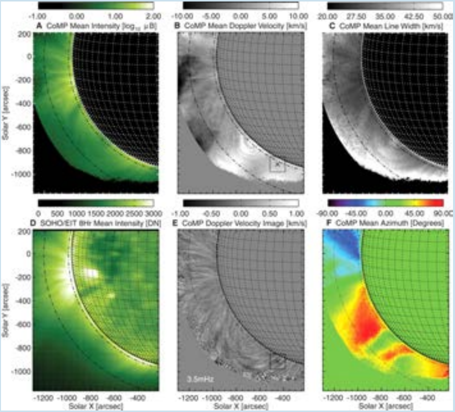
Keys et al. (2018): body and surface slow modes in pores.



Energy flux of $22 \pm 10kW/m^2$ for surface, $11 \pm 5kW/m^2$ for body.

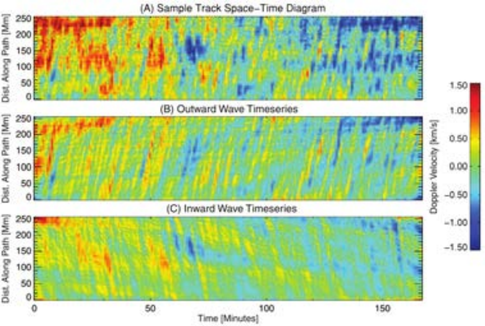
Decayless transverse waves

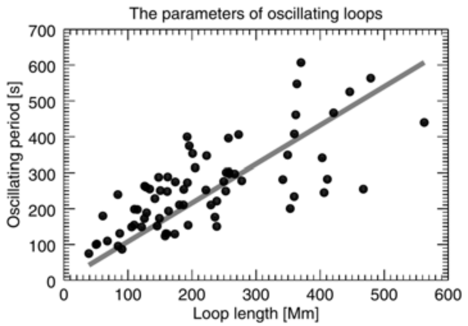
Plenty of decayless transverse waves in the solar corona (Tomczyk et al. (2007), Tomczyk & McIntosh (2009), Wang et al. (2012), Nisticò et al. (2013), Anfinogentov et al. (2013), Anfinogentov et al. (2015))



Decayless transverse waves

Decayless waves appear as propagating in CoMP (Tomczyk & McIntosh 2009), but standing in AIA (Anfinogentov et al. 2015).

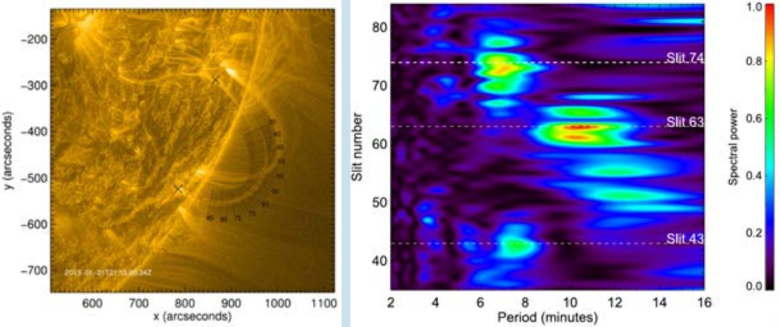




Discuss this point in review? Is it just length scale of loop?

Decayless transverse waves

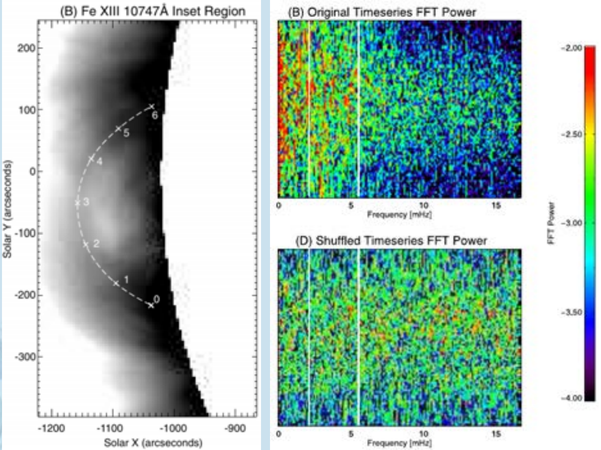
Duckenfield et al. (2018): Detection of overtone in decayless waves.



Suggests/confirms that decayless waves are standing.

Decayless transverse waves

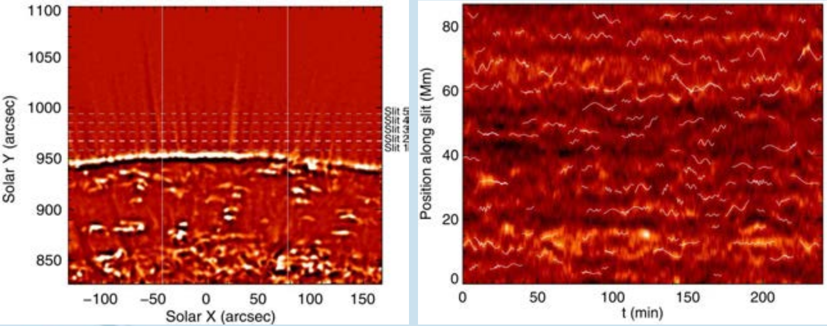
De Moortel et al. (2014), Liu et al. (2014): Decayless waves lead to generation of loop top turbulence



Observational evidence for locations of heating.

Decayless transverse waves

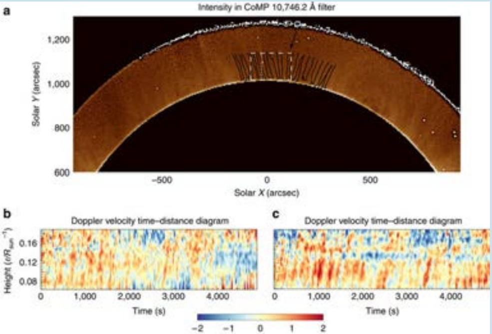
Decayless waves also present in coronal plumes

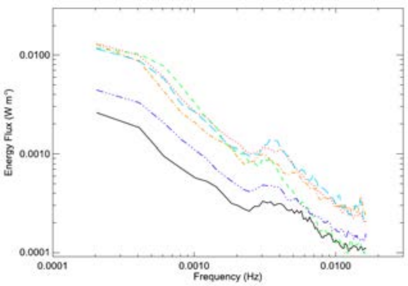


Thurgood et al. (2014)

Decayless transverse waves

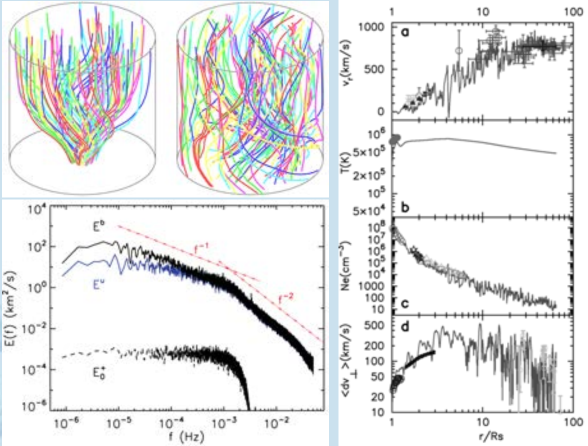
Morton et al. (2015, 2016): measure energy flux in plumes with CoMP





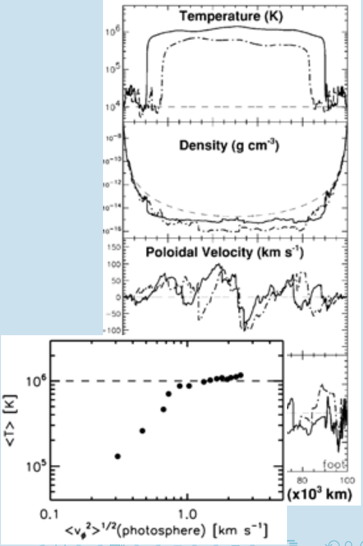
Heating by Alfvén waves

Van Ballegooijen et al. (2011), Verdini et al. (2012), Suzuki & Inutsuka (2005): 1D or R MHD, turbulence from counterpropagating Alfvén waves



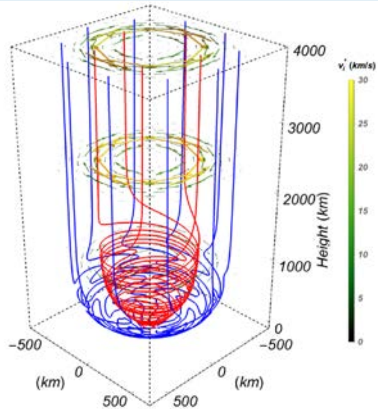
Heating by Alfvén waves

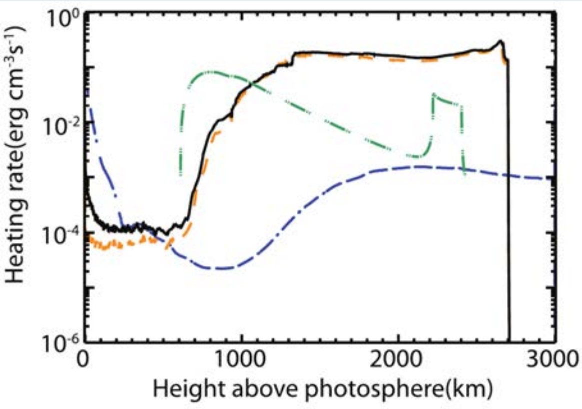
- Moriyasu et al. (2004): Heating with Alfvén driver of RMS amplitude of 2km/s
- Antolin et al. (2008, 2010): Dependence of T on driver amplitude, development of coronal rain
- Buchlin et al. (2007): Extend model to RMHD with 2D shell model



Heating by Alfvén waves

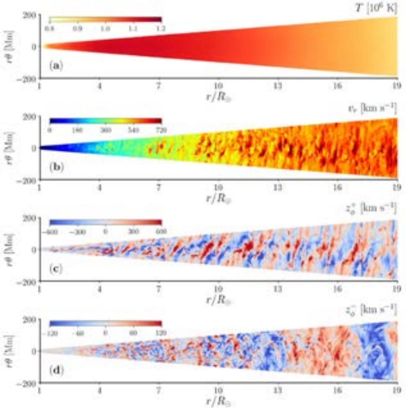
Arber et al. (2016), Soler et al. (2019): Extension of these models to multi-fluid

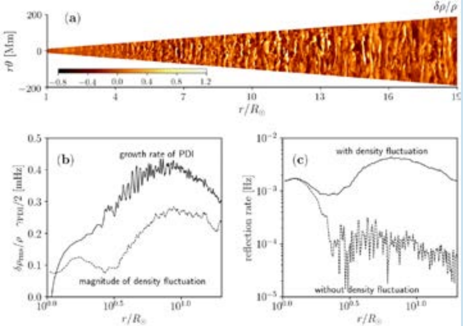




Heating by Alfvén waves

Shoda et al. (2019): Extending models of (e.g.) Rappazzo et al. (2008) to compressible MHD

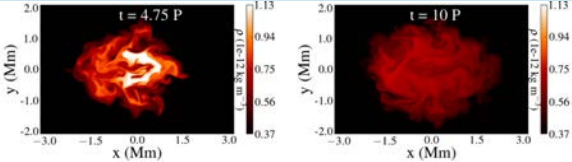


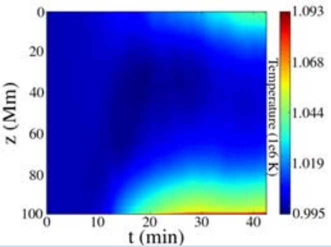


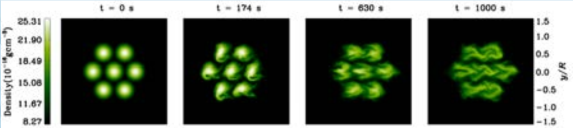
Ponderomotive force (a.k.a. parametric decay instability) plays key role

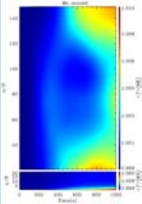
Turbulence heating models

Karampelas et al. (2017, 2019), Guo et al. (2019a,b):
Heating by decayless waves through KHI





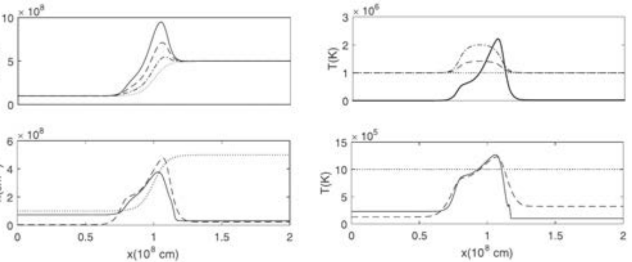


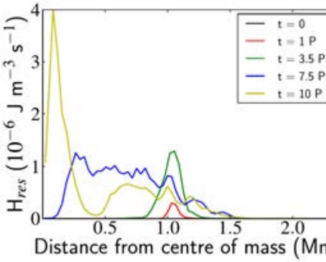


Driver energy cascaded to small scales and dissipated
Heating up to few $10^5 K$, easier with multiple strands/modes

Turbulence heating models

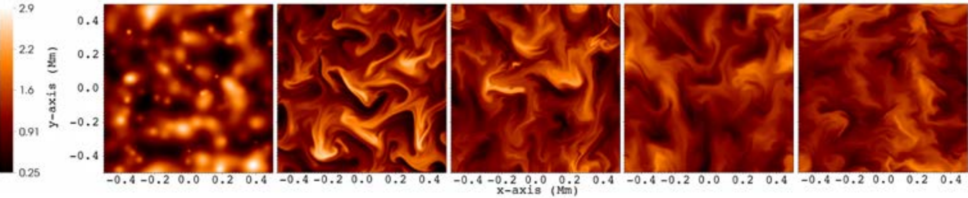
Cargill et al. (2016): Wave heating in wrong location
Karampelas et al. (2018): Heating spread over loop cross-section due to turbulence





Uniturbulence

Magyar et al. (2017, 2019): Simulated driven waves in plumes → medium becomes turbulent, too.



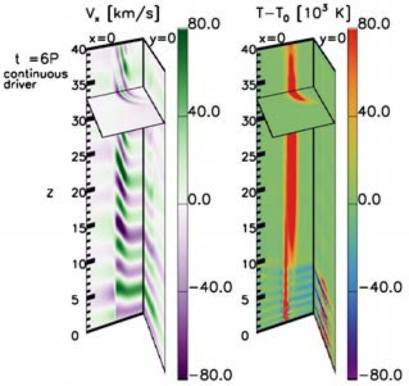
Propagating waves (in one direction) form turbulent medium: uniturbulence (= turbulence from unidirectional waves)

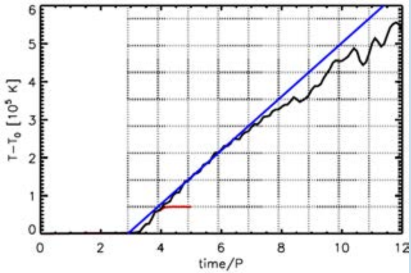
$$(\omega + \omega_A)\vec{z}_\perp^+ = (\omega - \omega_A)\vec{z}_\perp^-$$

What is the heating?

Phase mixing models

Pagano et al. (2017): Heating with phase mixing, putting high resistivity

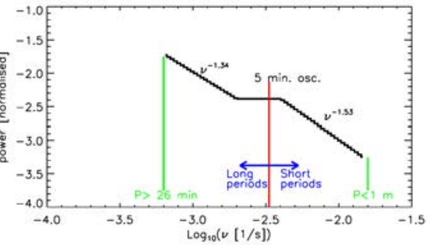


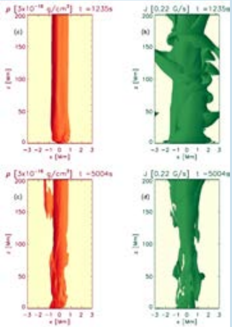


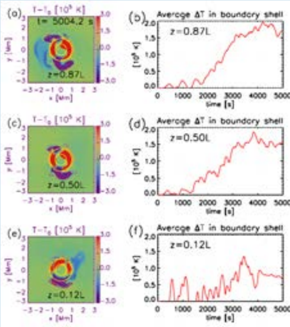
High temperature increase,
but only enough to compensate radiation if very high resistivity

Phase mixing models

Pagano et al. (2018): Driving with multi-modes







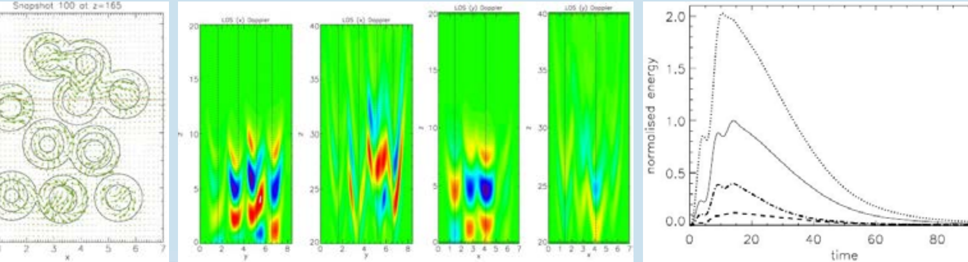
Whole length of loop is heated

Heating and cooling

Critical assessment

All models (beyond 1D) do not have enough heating.

De Moortel & Pascoe (2012): forward model propagating kink modes in bundle of loops



Only a fraction of kinetic energy is observed in (LOS integrated) Doppler shift. Observed energy is underestimated.

Van Doorsselaere et al. (2014): Observed energy flux should be multiplied with filling factor. Lower than thought.

Structure of review

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