Alfvén wave turbulence in coronal loops

Tom Van Doorsselaere

Centre for mathematical Plasma Astrophysics, KU Leuven

26 June 2018

This project has received funding from the ERC (grant agreement No 724326)

Invited Talk

1. Fundamental physical processes and modeling

Turbulence generated by transverse waves in coronal loops

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In the last decade, it has become clear that the solar atmosphere is filled with waves. Of particular interest are transverse waves in coronal loops and plumes, because their observed energy is not too far off the required energy to heat the solar corona.
I will highlight recent modelling efforts that characterise the coronal heating generated by these transverse waves. In many of the 3D simulations of loops that are driven or excited by transverse waves, the simulated coronal loops evolve into turbulence, either through the Kelvin-Helmholtz instability or uniturbulence. The resulting turbulence is an efficient agent to dissipate the wave energy and deposit it into heat.
By using forward modelling, I will discuss the observational consequences of these turbulent models. I will show in which respects the models agree or disagree with the observations.

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Alfvén wave turbulence

Normally, turbulence described with Elsässer variables, define as (e.g. Velli et al. 1989):

$$\vec{z}^- = \vec{v} - \frac{\vec{b}}{\sqrt{\mu\rho}} \qquad \text{upward propagating Alfvén waves}$$

$$\vec{z}^+ = \vec{v} + \frac{\vec{b}}{\sqrt{\mu\rho}} \qquad \text{downward propagating Alfvén waves}$$

Incompressible MHD in homogeneous plasma ($\vec{v}_A = \vec{B}/\sqrt{\mu\rho}$):

$$\frac{\partial \vec{z}^+}{\partial t} - \vec{v}_A \cdot \nabla \vec{z}^+ = -\vec{z}^+ \cdot \nabla \vec{z}^-$$

$$\frac{\partial \vec{z}^-}{\partial t} + \vec{v}_A \cdot \nabla \vec{z}^- = -\vec{z}^- \cdot \nabla \vec{z}^+$$

Only non-linear evolution if both $\vec{z}^+$ and $\vec{z}^-$ are present.

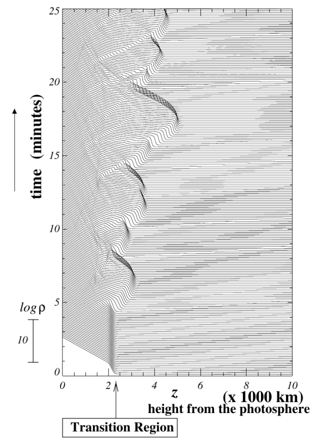
Can extend to compressible MHD (Marsch & Mangeney 1987).

Importance of turbulence for coronal heating

- Elsässer representation of MHD: non-linear terms e.g. $\vec{z}^{+} \cdot \nabla \vec{z}^{-}$.
- Assume a driving wave with $\vec{z}^{\pm} \sim \exp\left(i(kz - \omega t)\right)$.
- Non-linear terms $\vec{z}^{+} \cdot \nabla \vec{z}^{-} \sim \exp\left(i(2kz - 2\omega t)\right)$.
- Waves with higher k generated.
- Large scale waves lose energy to smaller scale and higher frequency waves: cascade.
- Turbulence.
- Good for heating: at some point Reynolds number $R = \frac{VL}{\eta} \sim \frac{V}{k\eta} \approx 1 \rightarrow$ easy to dissipate!

Loop heating model with footpoint driving

- Kudoh & Shibata (1999): 1D loop with rotating footpoints
- Moriyasu et al. (2004): Heating with 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



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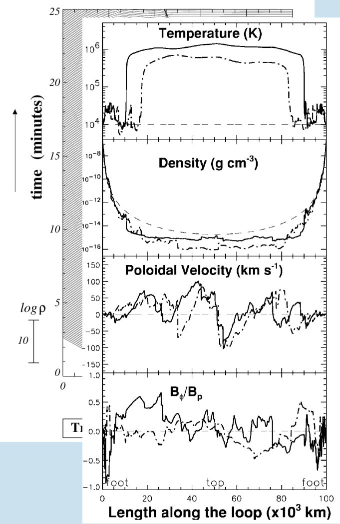

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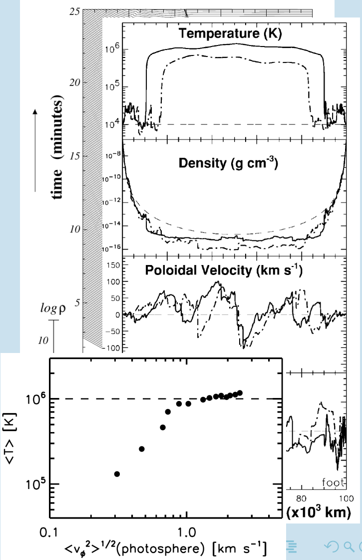
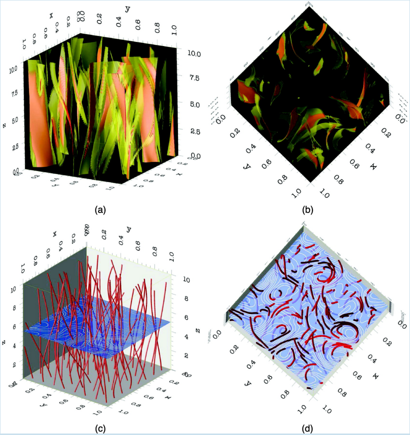


Alfvén wave turbulence

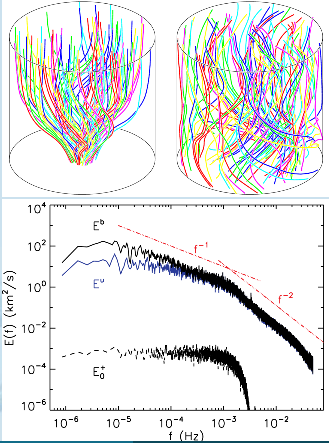
Rappazzo et al. (2008): Alfvén wave turbulence in reduced MHD

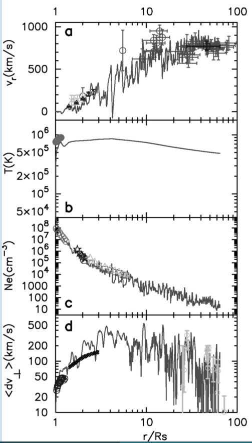


Driving from both ends, formation of small scale current sheets, heating

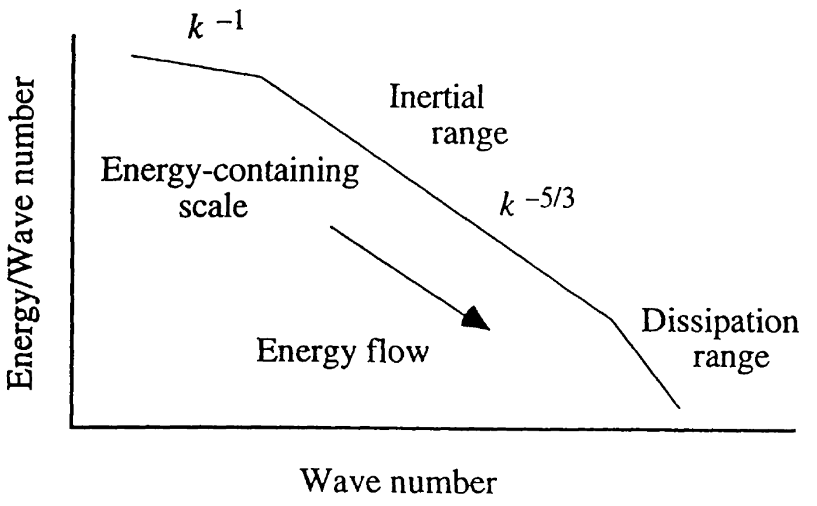
Loop heating model with footpoint driving

Van Ballegooijen et al. (2011), Verdini et al. (2012), Suzuki & Inutsuka (2005): Use Alfvén speed gradients to create counterpropagating waves, heat loops and coronal plumes/solar wind.

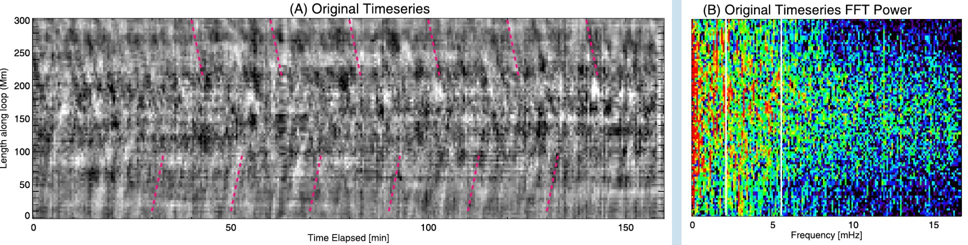




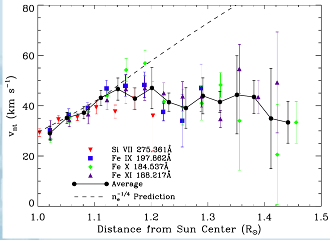
Heating via Alfvén wave turbulence



Observational evidence



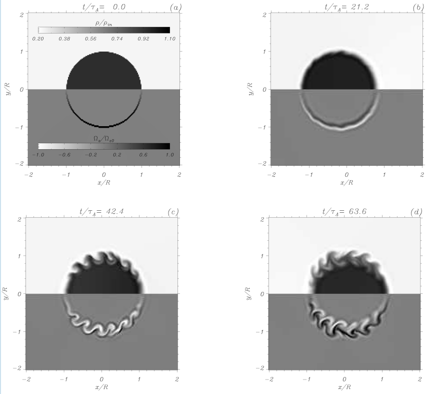
De Moortel et al. (2014): Use CoMP data to show that higher frequency concentrated in loop top → cascade?



Hahn & Savin (2013): additional damping above $1.15R_\odot$. Due to turbulence?

Overview of recent results

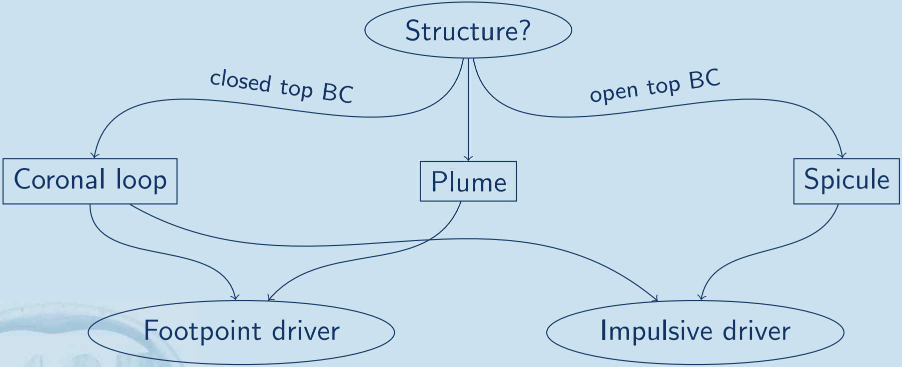
Terradas et al. (2008): transverse waves in coronal loops unstable to Kelvin-Helmholtz instability



Tomczyk et al. (2007): lots of transverse waves in the corona

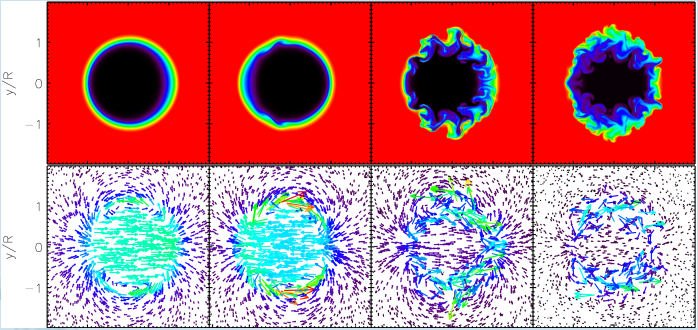
$\rightarrow$ Many models from Leuven, St. Andrews, Tokyo

Overview of recent results



loop: closed BC + impulsive driver

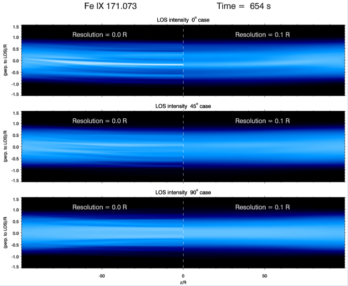
Antolin et al. (2014, 2015, 2016): loop or prominence thread with velocity pulse

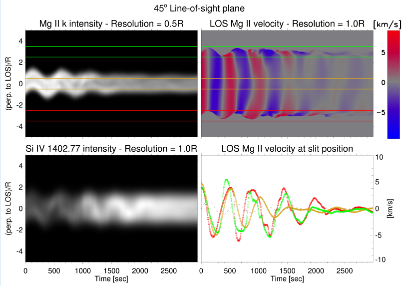


Turbulence due to Kelvin-Helmholtz at loop edge: TWIKH rolls (Transverse Wave Induced Kelvin-Helmholtz rolls)

loop: closed BC + impulsive driver

Antolin et al. (2014, 2015, 2016)



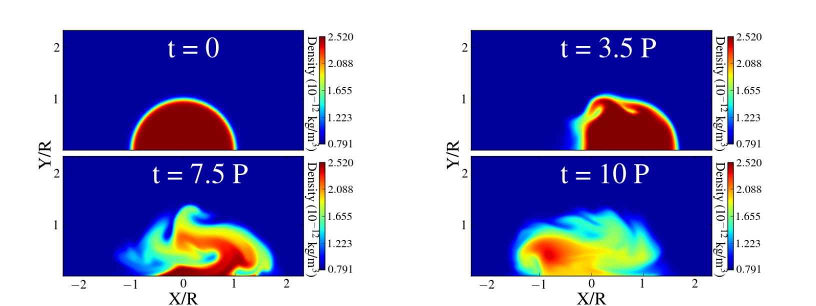


Observability:

- strands,
- apparent decayless oscillations (as observed by e.g. Anfinogentov et al. 2015),
- phase shift of 180° between displacement and velocity → observed with IRIS! (Okamoto et al. 2015)
- different periods in different filters/lines

loop: closed BC + footpoint driver

Karampelas et al. (2017), Karampelas & Van Doorsselaere (2018): loop with footpoint driver becomes fully turbulent (KHI)



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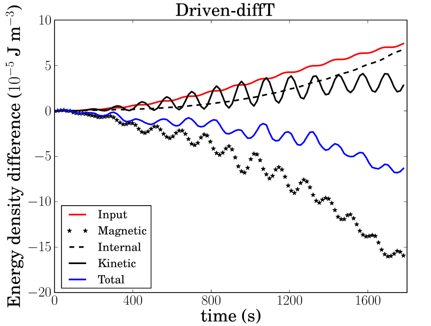
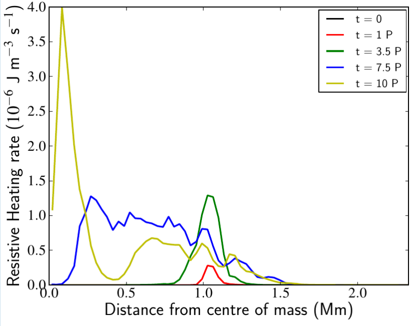
Karampelas et al. (2017), Karampelas & Van Doorsselaere (2018)

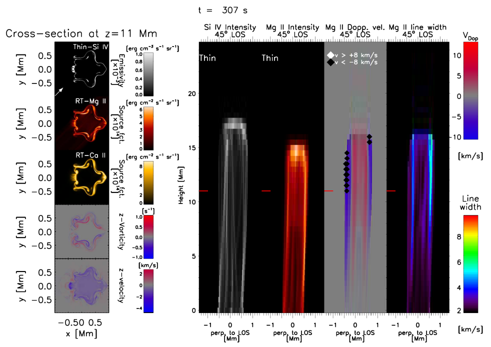




1. Input energy drives waves (kinetic energy)
2. Wave energy cascades to small scales
3. Kinetic energy dissipated in turbulent layer
4. Loop amplitude increases until KHI dissipation balances energy input: DECAYLESS REGIME

spicule: open BC + impulsive driver

Antolin et al. (2018): spicule with impulsive excitation
→ forward modelling of IRIS spectral lines

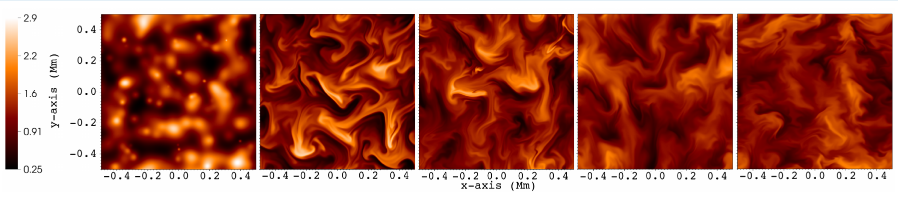


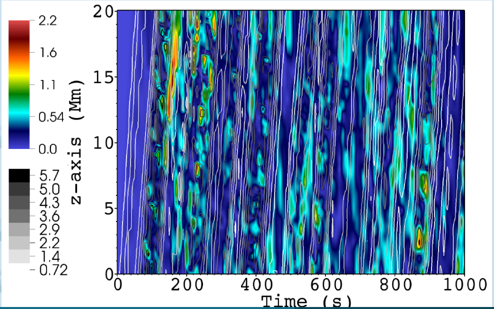
Observability:

- Collective behaviour between neighbouring spicules
- Propagating twisting features

plume: open BC + footpoint driver

Magyar et al. (2017): Multi-stranded plume (without stratification) with footpoint driver

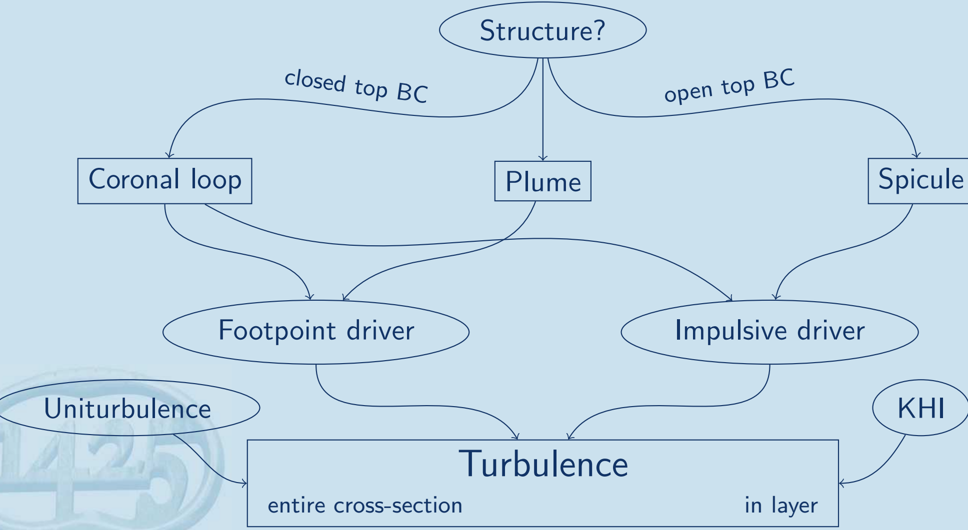




- Only upward "Alfvén" wave
- No reflection from $\nabla_{\parallel} v_A$
- Co-propagating z^+ and z^-
- Due to perpendicular structuring
- Formation of turbulence

$\rightarrow$ UNITURBULENCE

Overview of recent results

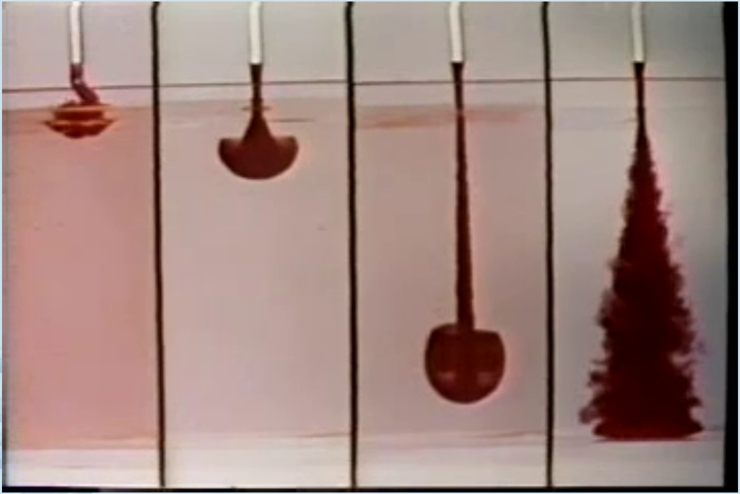


Conclusions

- Transverse waves lead to turbulence (KHI, uniturbulence)
- Turbulence is good for heating: turbulent cascade balances input energy at large scales
- Turbulence is hard (to model, to observe)
- Currently working on:
  - Not enough heating!
  - Superpose other wave modes in driving
  - Multi-frequency driver
  - Include real heating terms (Howson et al. 2017a)
  - Effect of twist (Howson et al. 2017b, Terradas et al. 2018)
  - Stratification
  - Forward modelling to match observations

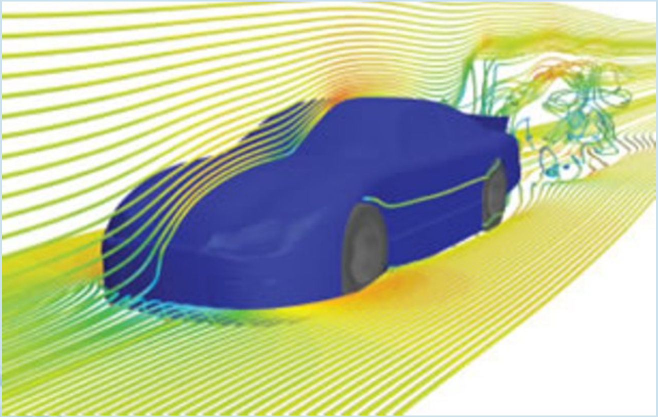
Influence of Reynolds number

$R = 0.05$ $R = 10$ $R = 200$ $R = 3000$



https://www.youtube.com/watch?v=51-6QCJTAjU

Car as a ~~coronal~~ atmospheric heating mechanism



http://www.pro-touring.com/threads/101460-Designing-Aerodynamics-for-Track-Performance

Car as a ~~coronal~~ atmospheric heating mechanism

- Drive all day, end up home
- Heat is all in air
- Heat source: chemical reaction in engine
- How to measure (as an alien, with only remote sensing)
  - Speed car (a.k.a. Doppler shift)?
  - Turbulent tail (a.k.a. line width)?