From monolithic or multi-stranded loops to turbulent loops using 3D simulations of wave heating

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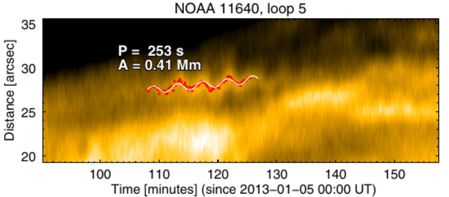
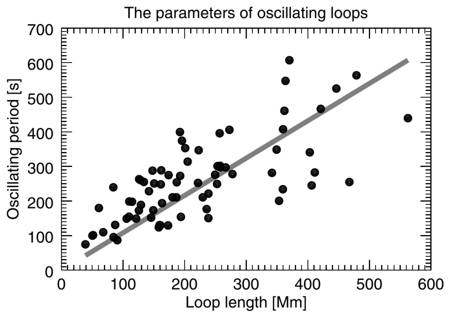
Driven transverse waves

Tomczyk & McIntosh (2009): CoMP propagating waves

Anfinogentov et al. (2015): AIA standing (decayless) waves



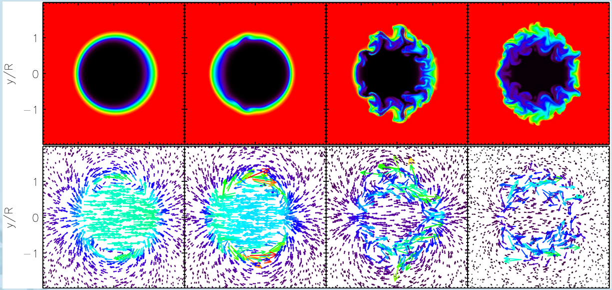


Are decayless waves propagating or standing?
In any case, driven from below?

Non-linear transverse waves

Terradas et al. (2008): large amplitude standing kink waves experience Kelvin-Helmholtz instability

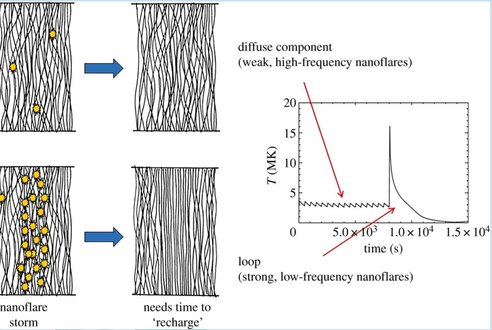
Antolin et al. (2014): perform modelling of impulsively excited waves (cross-sections)

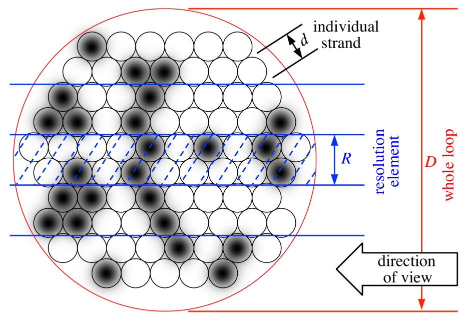


Kelvin-Helmholtz instability forms so-called
Transverse Wave Induced Kelvin-Helmholtz rolls (or TWIKH rolls)

Multi-stranded loop models

- Hypothesis: coronal loops consist of (magnetically decoupled) strands
- Strands heated with nanoflares
- Few to a thousand strands
- Dynamic equilibrium or cooling



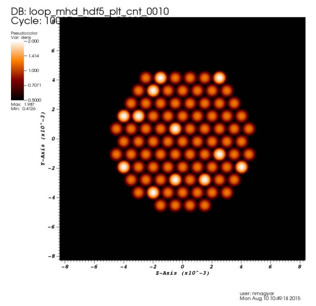


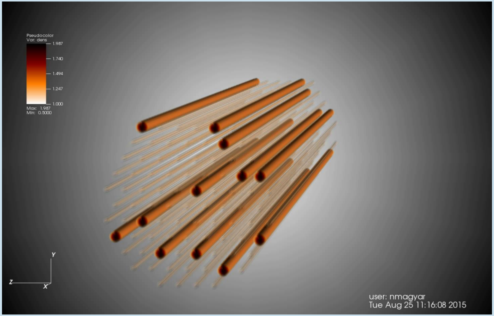
(Klimchuk 2015, Peter et al. 2013)

Simulation setup

Magyar & Van Doorsselaere (2016): simulate honeycomb structure

- Macro-loop with radius $R = .5\mathrm{Mm}$ and length $L = 50\mathrm{Mm}$.
- Strands with radius $R_s = .1R$, touching each other.
- Drive with vertical velocity field (5km/s).





Strands fracture and get mixed.

If loops are oscillating transversally, multistranded loops mix.

Driven transverse waves

Induction equation:

$$\frac{\partial \vec{B}'}{\partial t} = \vec{\nabla} \times (\vec{V}' \times \vec{B}),$$

or (for V'_ϕ and B'_ϕ and $\vec{B} = B\vec{1_z}$)

$$\frac{\partial B'_\phi}{\partial t} = \frac{\partial V'_\phi B}{\partial z}$$

Standing waves in $z \in [0, L]$:

$$V'_\phi \sim \cos(\phi) \sin(\pi z/L) \sin(\omega t) \quad B'_\phi \sim \cos(\phi) \cos(\pi z/L) \cos(\omega t)$$

No stabilising magnetic field for standing waves.
For propagating waves:

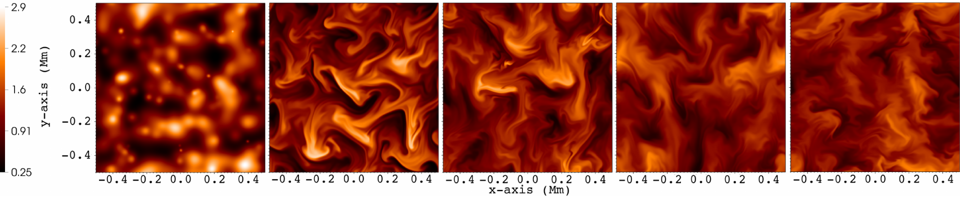
$$V'_\phi \sim \cos(\phi) \sin(\pi z/L - \omega t) \quad B'_\phi \sim \cos(\phi) \sin(\pi z/L - \omega t)$$

Stabilising magnetic field. Kelvin-Helmholtz instability does not work for propagating waves (e.g. Browning & Priest 1984).

Uniturbulence

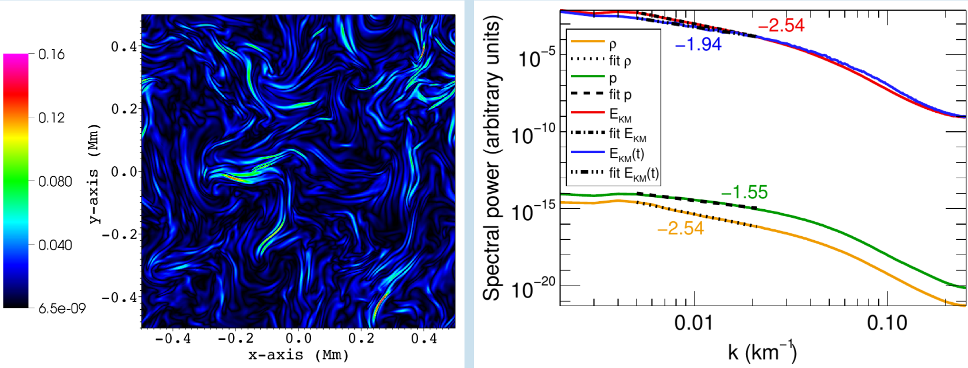
Turbulence? How? Only upward propagating waves!

Magyar et al. (2017, submitted): $B = 5\text{G}, \rho = 2\ 10^{-13}\text{kg}/\text{m}^3$, 250 Gaussian density enhancements, drive with "random motion" with RMS velocity of 12km/s.



Uniturbulence

Magyar et al. (2017, submitted)



Current sheets like turbulence, highly variable power laws

Feed energy on large scales
→ Cascade to small scales
→ Dissipate at small scales

Uniturbulence

Normally, turbulence described with Elsässer variables:

$$\vec{z}^{\pm} = \vec{v} \pm \frac{\vec{b}}{\sqrt{\mu\rho}}$$

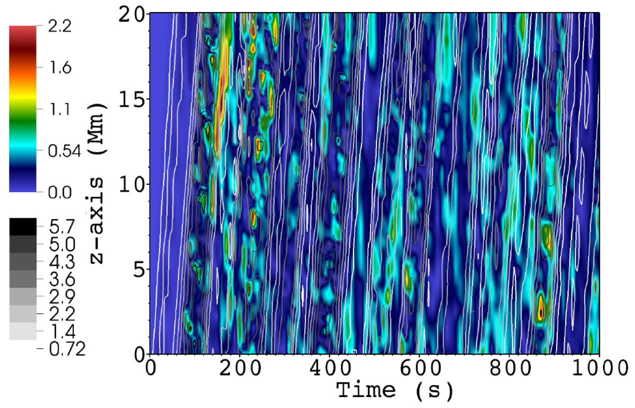
Governing equations:

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

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

Uniturbulence

Magyar et al. (2017, submitted): driving only with $\vec{z}^-$



In-situ generation of $\vec{z}^+$, because of transverse structuring.
Turbulence develops.

Conclusions & Discussion

- Transverse waves → multi-stranded loops mix
- Uniturbulence: z^- and inhomogeneity → in-situ z^+

Conclusions & Discussion

Comparison with nanoflares

	Nanoflares	Uniturbulence
Shape of heating	$\delta(z)$	extended current sheets (+reconnection?)
Time of heating	short	substantial fraction of period
Location of heating	random	footpoints (resistivity) loop top (viscosity)
Dimensionality	1D is enough independent strands	3D needed turbulent transverse mixing
Strands	☑	☑
Broad DEMs	☑	☑
Low filling factors	☑	☑