ASSSP, Warwick, 11.00-12.30, 05/09/2012

MHD waves and coronal seismology

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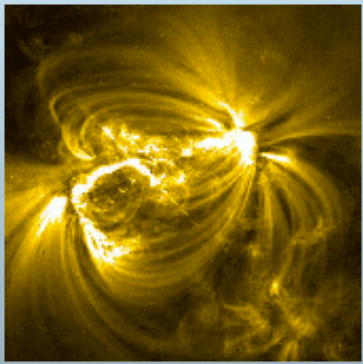
Wave and oscillatory processes in the solar corona:

- Observational evidence of coronal oscillations (or quasi-periodic pulsations) is abundant (major contribution by SOHO,TRACE, NoRH, now Hinode and SDO).
- Possible relevance to coronal heating and solar wind acceleration problems.
- Possible role in the physics of solar flares.
- **Plasma diagnostics.**

(MHD) coronal seismology – diagnostics of solar coronal plasmas with the use of coronal MHD waves and oscillations



- c.f. magneto(spheric)seismology,
- MHD spectroscopy of tokamaks).

Uchida, Y., Diagnosis of coronal magnetic structure by flare-associated hydromagnetic disturbances, PASJ **22**, 34, 1970

Roberts, B., Edwin, P.M, Benz, A.O., On coronal oscillations, ApJ **279**, 857, 1984

Main differences with helioseismology:

- Transparent medium
- Usually only local diagnostics of the oscillating structures and their nearest vicinity (e.g. magnetic field **in** the oscillating loop (c.f. time-distance helioseismology).
- Three wave modes (fast, slow magnetoacoustic and Alfvén) – more constrains and more toys to play with.
- In the majority of cases, oscillations are of **very** poor quality (wavelets rather than waves).

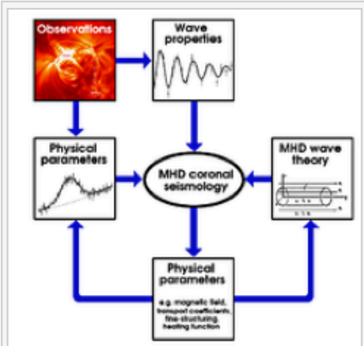
Coronal seismology

From Wikipedia, the free encyclopedia

Coronal seismology is a technique of studying the plasma of the Sun's corona with the use of magnetohydrodynamic (MHD) waves and oscillations. Magnetohydrodynamics studies the dynamics of electrically conducting fluids - in this case the fluid is the coronal plasma. Observed properties of the waves (e.g. period, wavelength, amplitude, temporal and spatial signatures[clarification needed], characteristic scenarios of the wave evolution[clarification needed]), combined with a theoretical modelling of the wave phenomena (dispersion relations, evolutionary equations, etc.), reveal physical parameters of the corona which are not open to direct observations, such as the coronal magnetic field strength and Alfvén velocity [1] and coronal dissipative coefficients.[2] Originally, the method of MHD coronal seismology was suggested by Y. Uchida in 1970[3] for global seismology (standing waves) and B. Roberts et al. in 1984 [4] for local seismology (propagating waves), but was not practically applied until the late 90s due to a lack of necessary observational resolution. Philosophically, coronal seismology is similar to the Earth's seismology, helioseismology, and MHD spectroscopy of laboratory plasma devices. In all these approaches, waves of various kind are used to probe a medium.

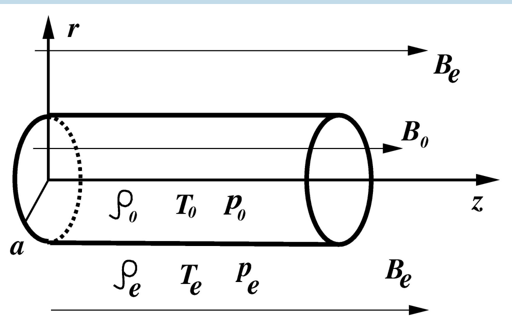
The theoretical foundation of coronal seismology is the dispersion relation of MHD modes of a plasma cylinder: a plasma structure which is nonuniform in the transverse direction and extended along the magnetic field. This model works well for the description of a number of plasma structures observed in the solar corona: e.g. coronal loops, prominence fibrils, plumes, various filaments. Such a structure acts as a waveguide of MHD waves.

This discussion is adapted from Valery M. Nakariakov and Erwin Verwichte, "Coronal Waves and Oscillations", Living Rev. Solar Phys. 2, (2005), (cited on November 26, 2009).



Contents [hide]

Standard theory: interaction of MHD waves with magnetic structures (V. Zaitsev, A. Stepanov, B. Roberts and colleagues, 1975-)



- Magnetohydrodynamic (MHD) equations →
- Equilibrium →
- Linearisation →
- Boundary conditions

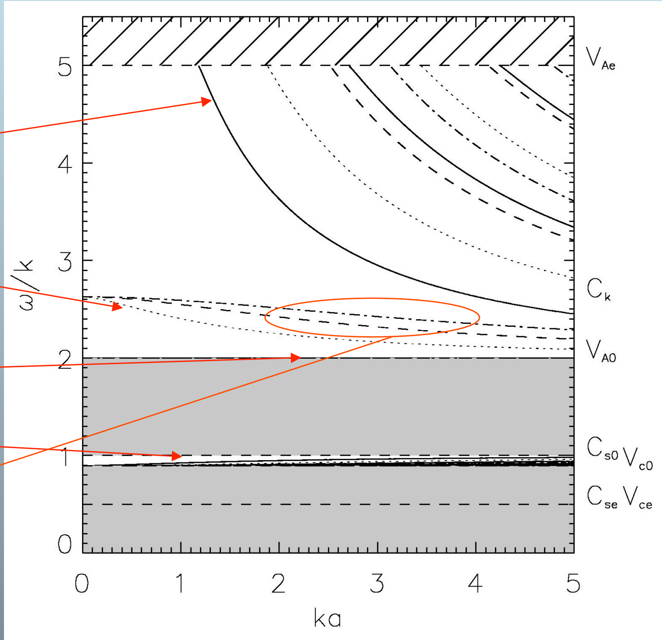
Dispersion relations of MHD modes of **a magnetic flux tube**:

$$\rho_e(\omega^2 - k_z^2 C_{Ae}^2) m_0 \frac{I_m'(m_0 a)}{I_m(m_0 a)} - \rho_0(\omega^2 - k_z^2 C_{A0}^2) m_e \frac{K_m'(m_e a)}{K_m(m_e a)} = 0$$

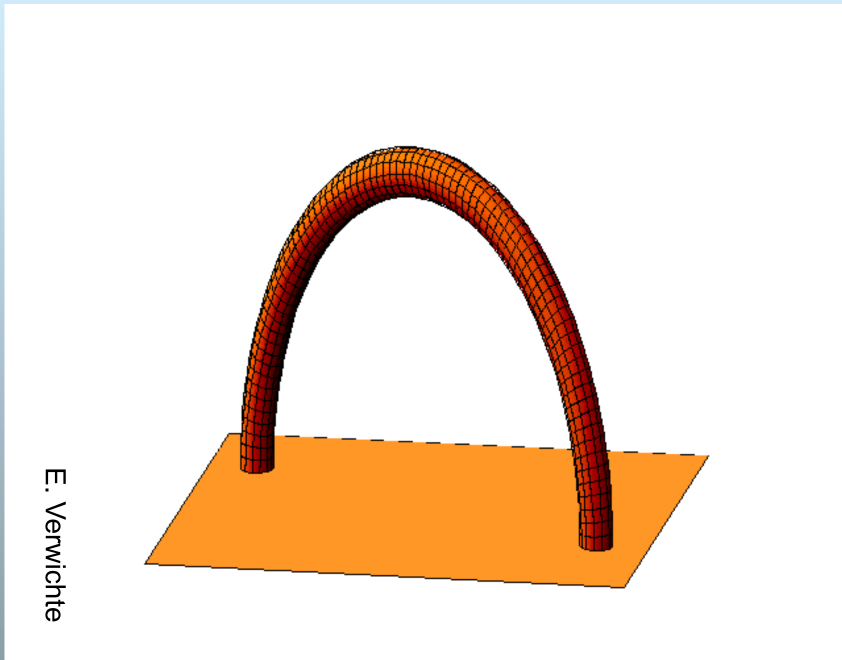
Dispersion curves of coronal loop:

Main MHD modes of coronal structures:

- **sausage** (|B|, r)
- **kink** (almost incompressible)
- **torsional** (incompressible)
- **acoustic** (r, V)
- **ballooning** (|B|, r)

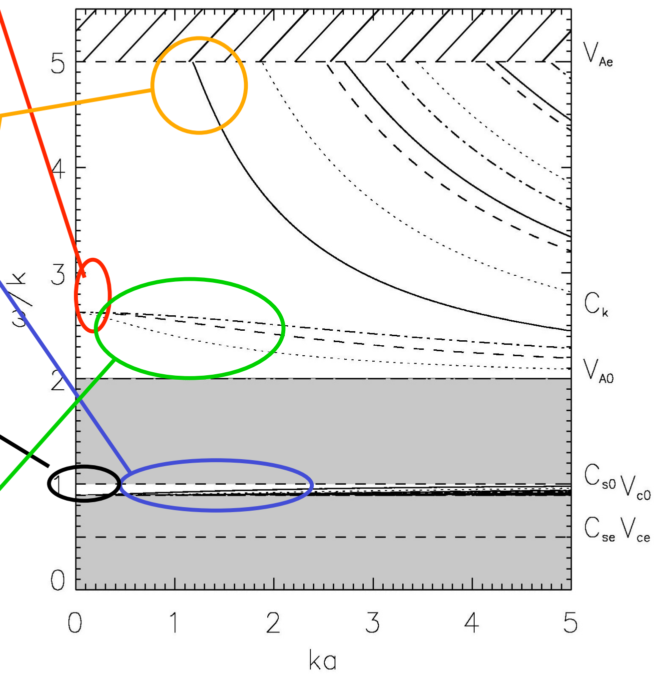


MHD modes of a coronal loop

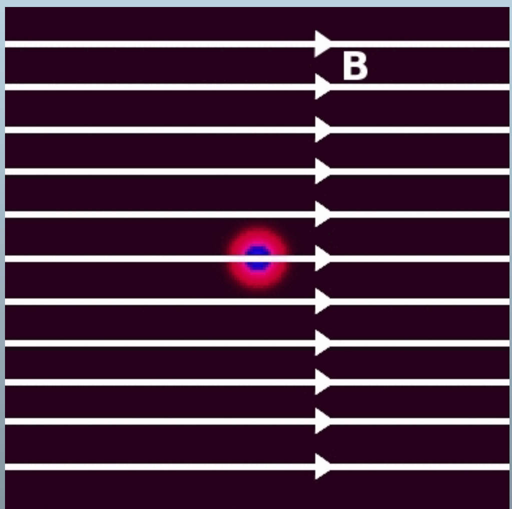


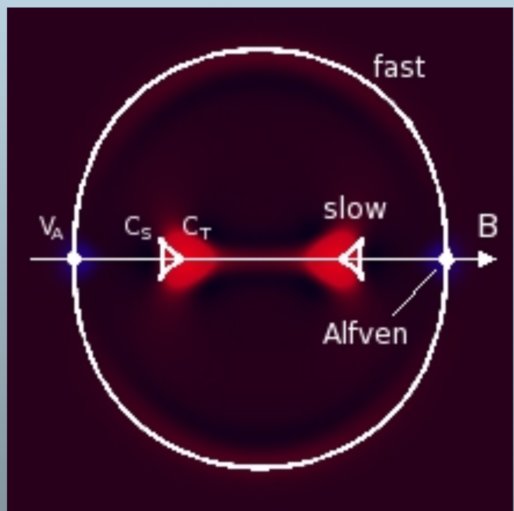
Observed wave phenomena (to September 2012):

1. Kink oscillations of coronal loops (Aschwanden et al. 1999, Nakariakov et al. 1999, and many authors later)
2. Propagating longitudinal waves in polar plumes and near loop footpoints (Berghmans & Clette, 1999; Nakariakov et al. 2000, De Moortel et al. 2000-2004, and many authors later)
3. Standing longitudinal waves in coronal loops (Kliem at al. 2002; Wang & Ofman 2002; and many authors later)
4. Global sausage mode (Nakariakov et al. 2003, Melnikov et al. 2006)
5. Propagating fast waves. (Williams et al. 2001, 2002; Katsiyannis et al. 2003; Verwichte et al. 2005; Tomszyk et al. 2007)



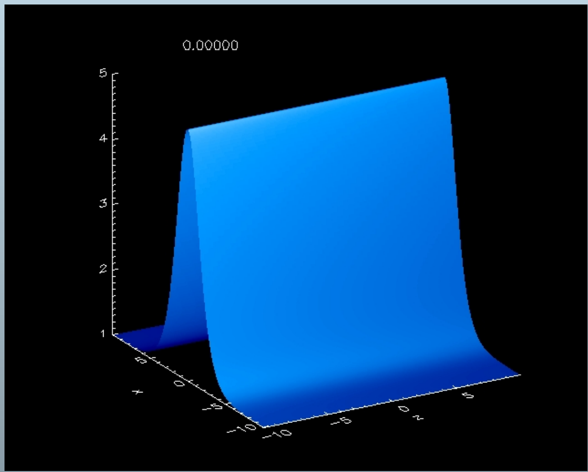
Development of an MHD perturbation in a uniform medium

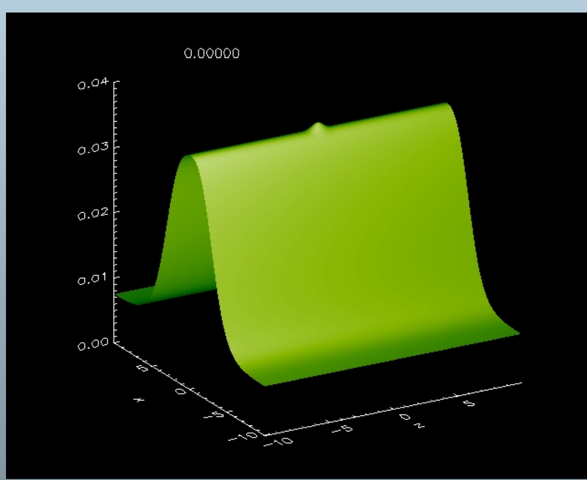




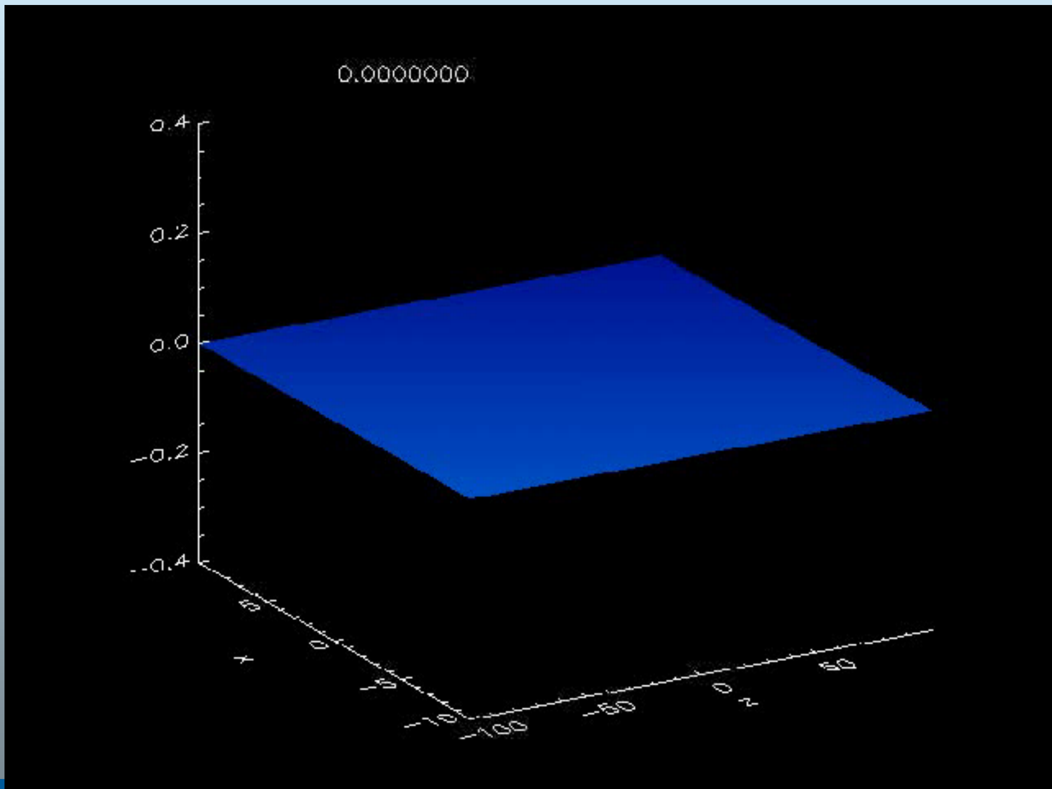
Verwichte, 2006

Dispersive evolution of a magnetoacoustic pulse guided by a field-aligned plasma non-uniformity:

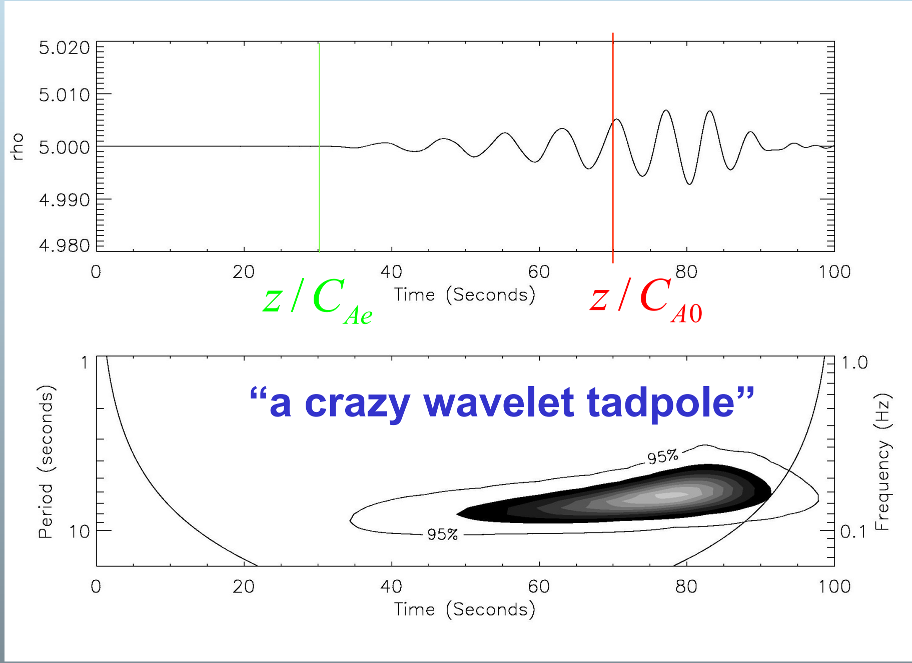




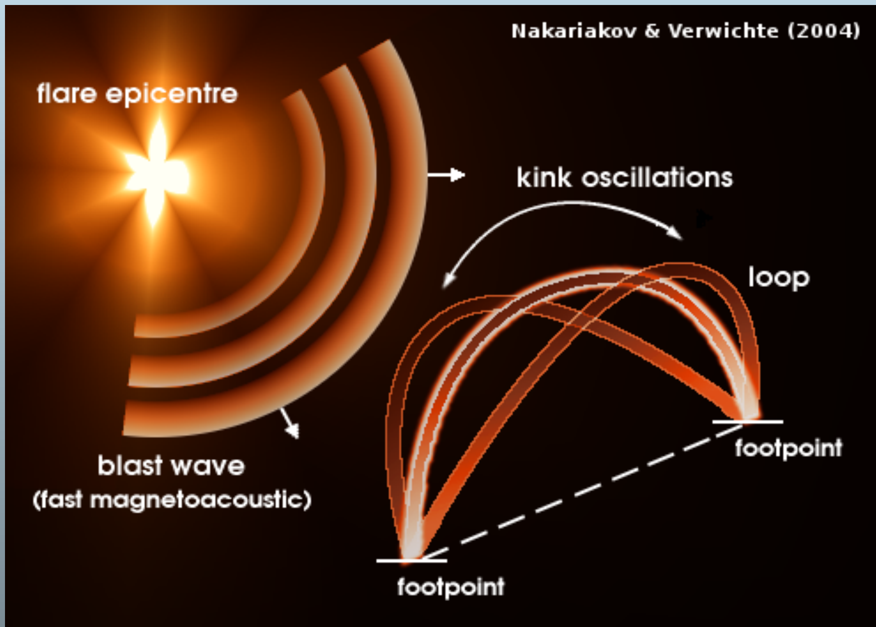
Perturbations of density:



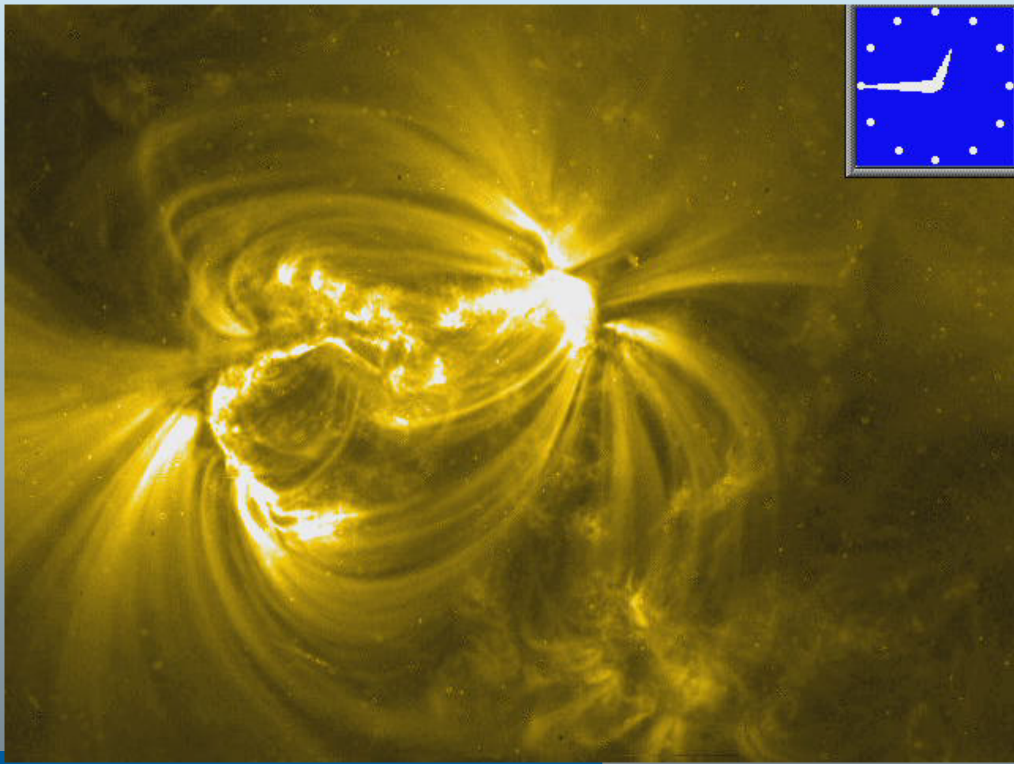
Impulsively excited fast pulse at distance 70 from the source, the density contrast is 5; Alfvén speed ratio is 2.3.



1. Coronal Seismology with standing kink modes:

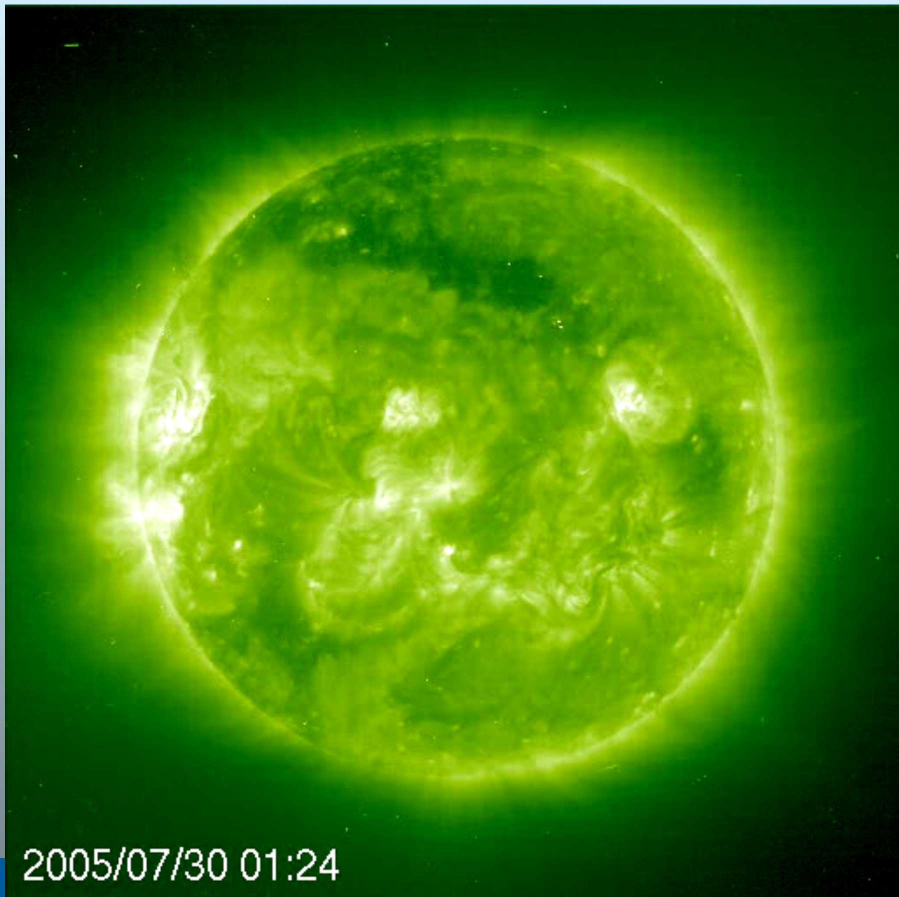


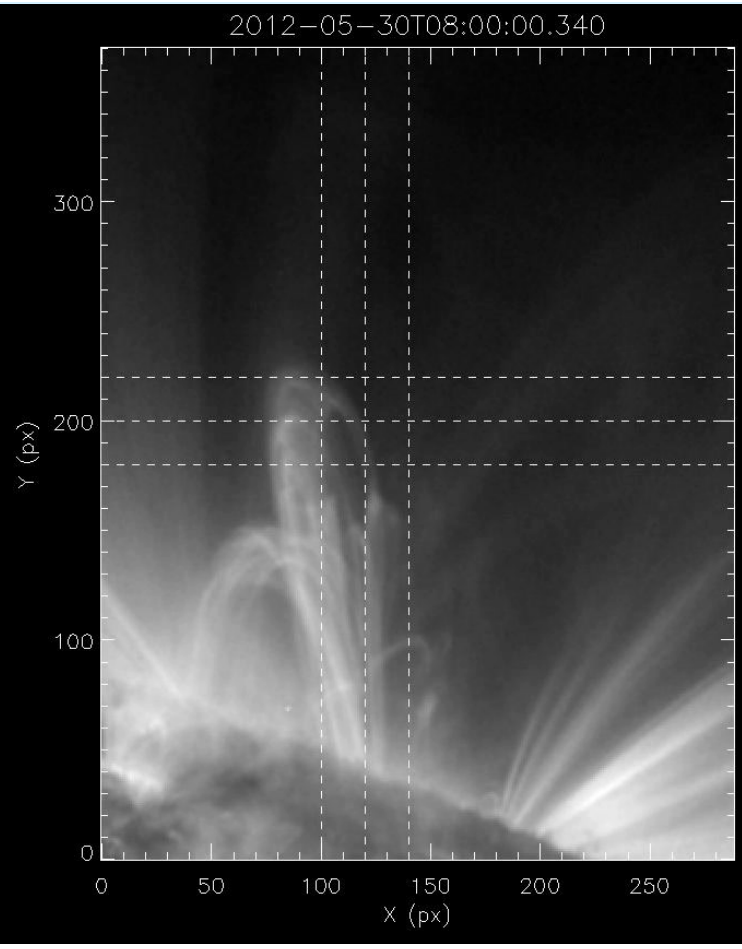
First observation of kink modes of coronal loops (EUV, TRACE):



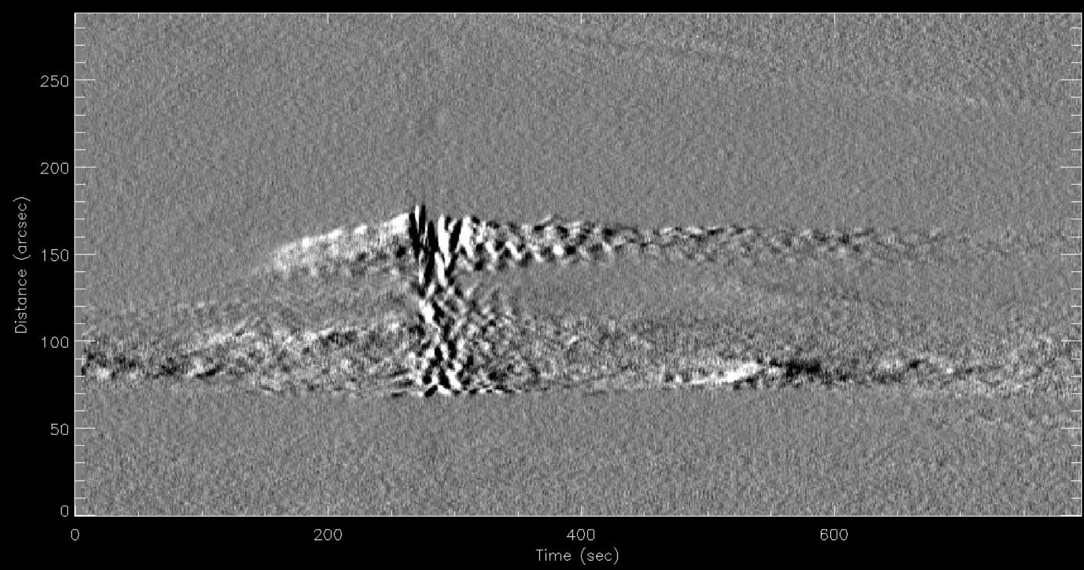
Longest
period kink
oscillation:

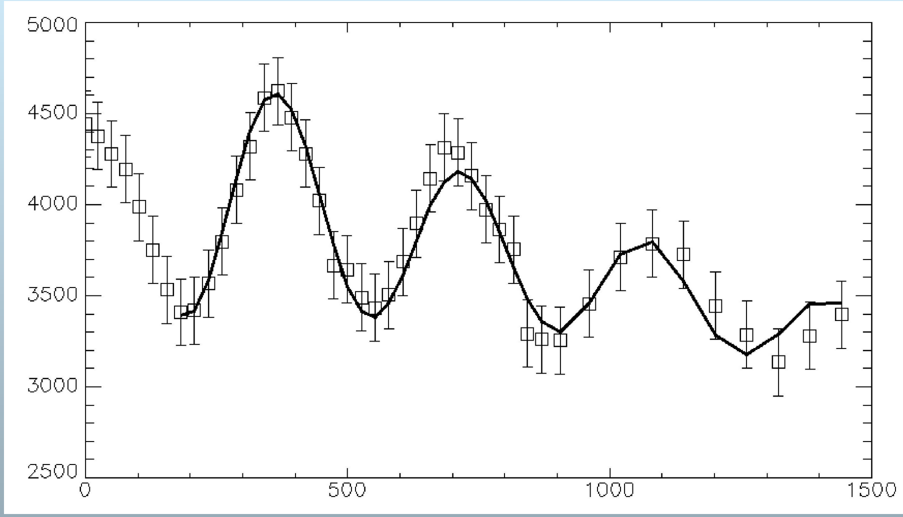
(EUV,
SOHO EIT)





An oscillatory pattern occurs before the onset of the main oscillation:

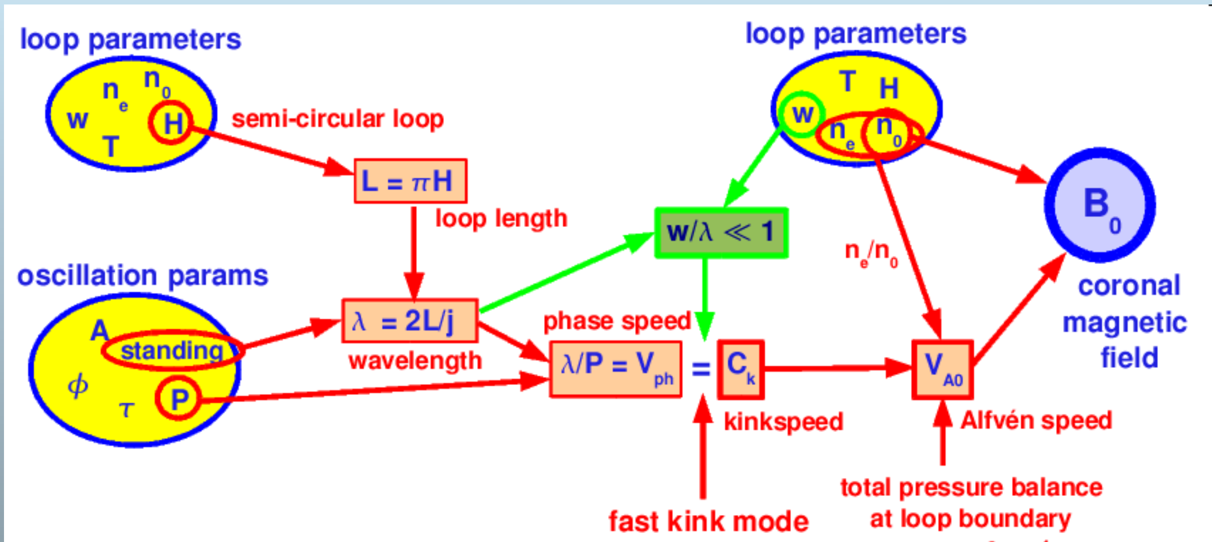




$$\xi_n(t) = A e^{-\gamma_n t^n} cos(\omega t + \phi),$$

- Oscillation period,
- Decay time

Estimation of the magnetic field:



One of the aims of SDO/AIA

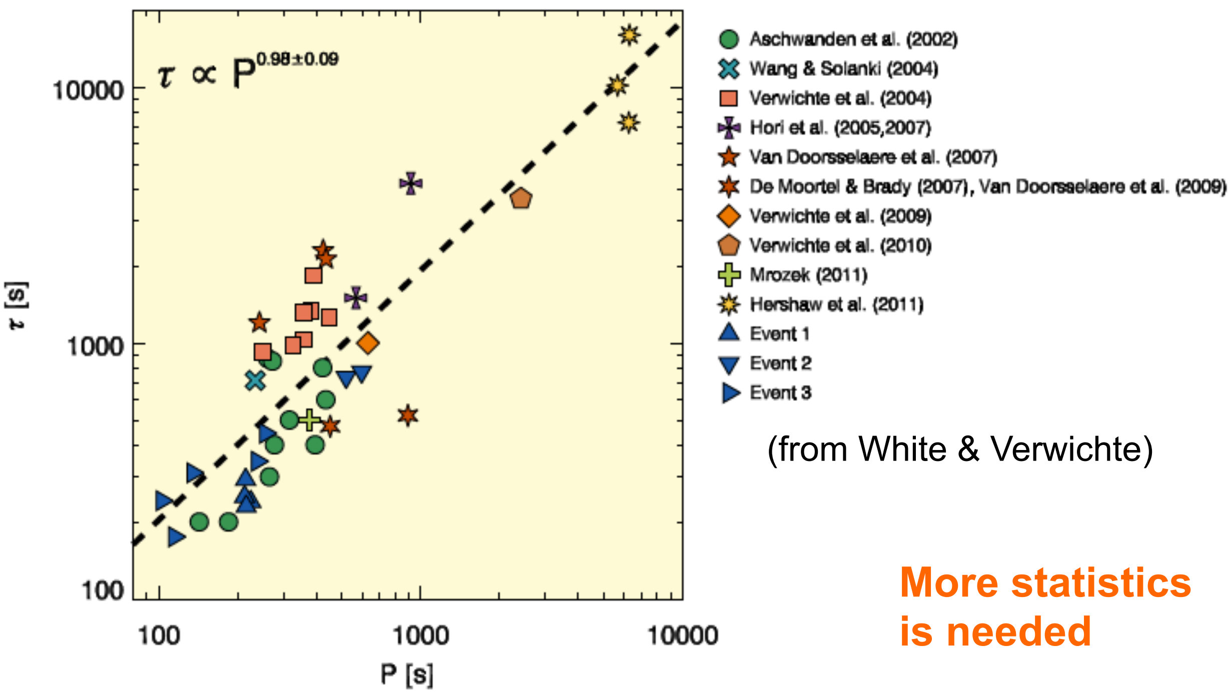
TRANSVERSE OSCILLATIONS IN CORONAL LOOP ARCADE 15

Table IV. Derived physical parameters

Path	C_k (km s^{-1})	V_A (km s^{-1})	B (G)	ν (m^2 s^{-1})	R
A	1250 ± 410	880 - 1000	13 - 36	-	-
B	1090 ± 210	770 - 880	11 - 31	-	-
C	$880 \pm 120^{(a)}$	620 - 700	9 - 25	$0.9 - 1.4 \times 10^8$ [a]	$1.0 - 1.7 \times 10^6$
	970 ± 40	690 - 790	10 - 28	$0.6 - 1.0 \times 10^8$	$1.4 - 2.9 \times 10^6$
D	$940 \pm 120^{(a)}$	670 - 760	10 - 27	-	-
	1160 ± 90	820 - 940	12 - 33	$0.3 - 0.4 \times 10^8$	$4.4 - 7.6 \times 10^6$
E	1220 ± 40	860 - 980	13 - 35	$0.8 - 1.5 \times 10^8$	$1.4 - 3.0 \times 10^6$
F	1920 ± 810	1360 - 1550	20 - 55	-	-
G	1320 ± 110	940 - 1070	14 - 38	$1.4 - 2.8 \times 10^8$	$0.8 - 1.8 \times 10^6$
H	1440 ± 200	1020 - 1160	15 - 41	$1.3 - 2.2 \times 10^8$	$1.1 - 2.0 \times 10^6$
I	1320 ± 330	940 - 1070	14 - 38	$0.6 - 0.9 \times 10^8$	$2.6 - 4.1 \times 10^6$

[a] Oscillation is assumed to be a second harmonic.

Decay time vs **Period**:

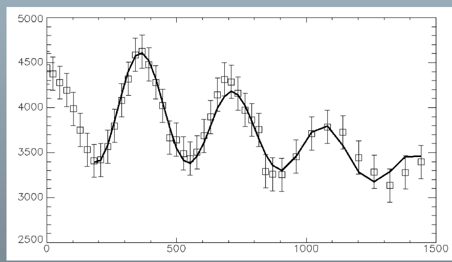


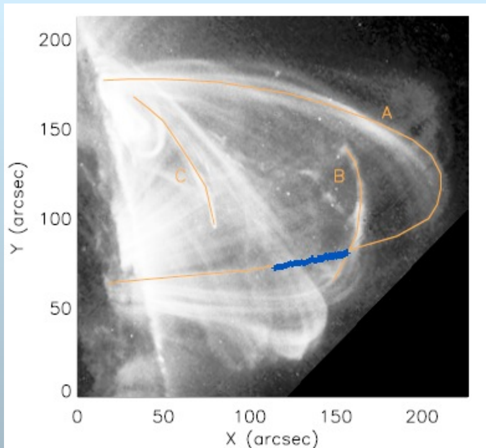
(from White & Verwichte)

More statistics is needed

Fashionable topics:

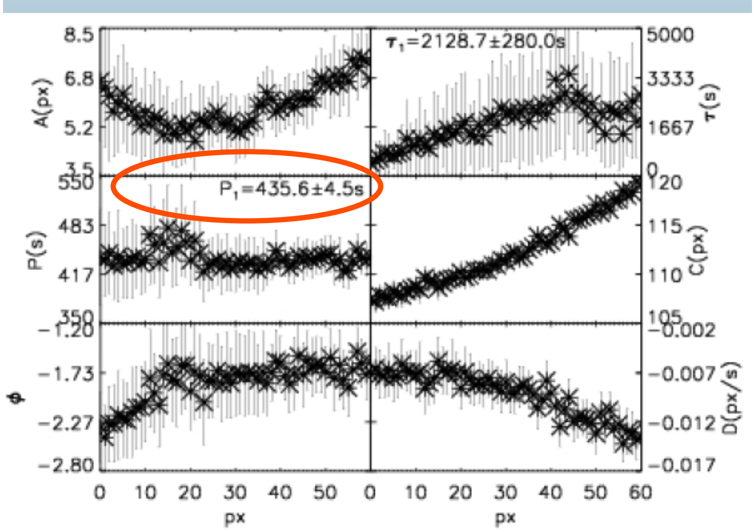
- statistical minimisation of the errors
- effects of curvature and stratification
- P1/2P2 ratio





Minimisation of the errors in the estimation of the period:

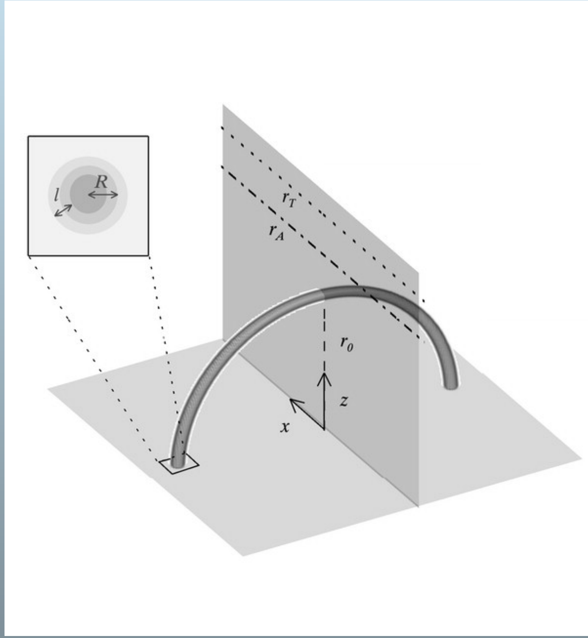
E.g. Van Doorsselaere et al. 2007:



- Edge-sharpening algorithms
- Pattern-recognition with elements of AI
- Bayesian statistics

Effects of curvature and stratification

$$(\lambda > R; \quad R \approx H)$$

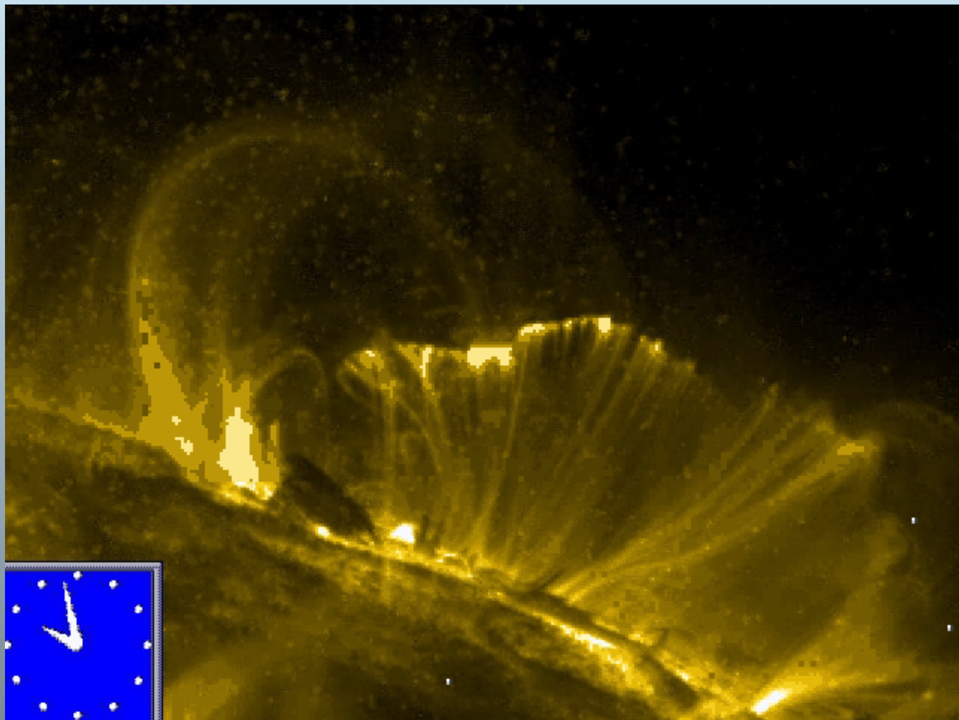


Van Doorsselaere et al. 2004

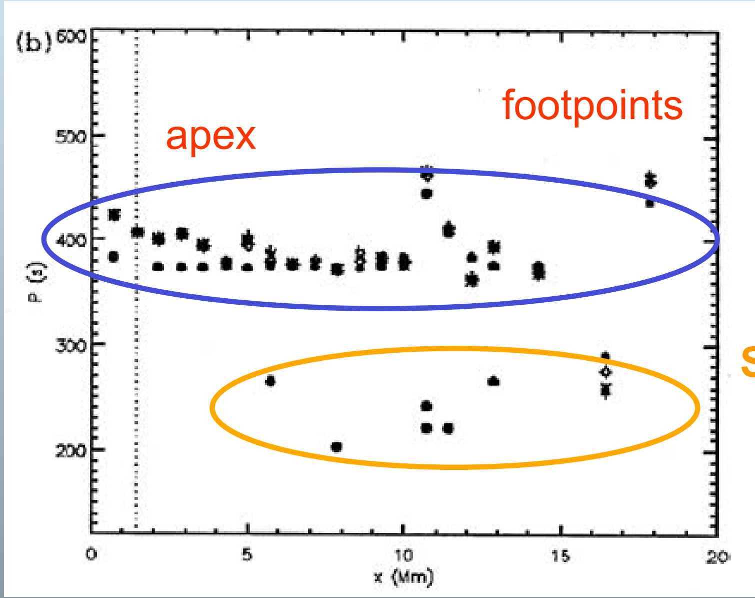
Terradas et al., 2006:

Resonant periods are weakly affected by the curvature.

P1/2P2 ratio: The Harmonica event (Apr 15, 2001)



Higher spatial harmonics:



Verwichte et al. 2004

along loop

Another example: 2nd harmonics of kink modes:

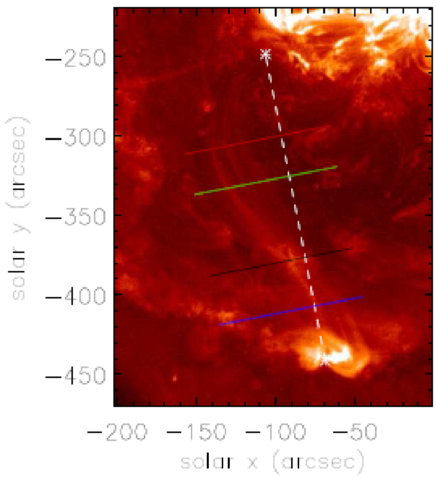


FIG. 1.— TRACE 171 Å image of the oscillation loop at 03.41 UT. Overplotted are the cross-sections 'upper1' (red), 'upper2' (green), 'central' (black) and 'lower' (blue).

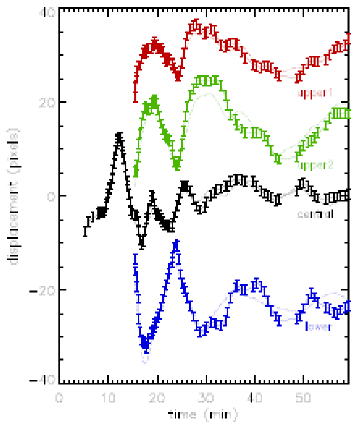
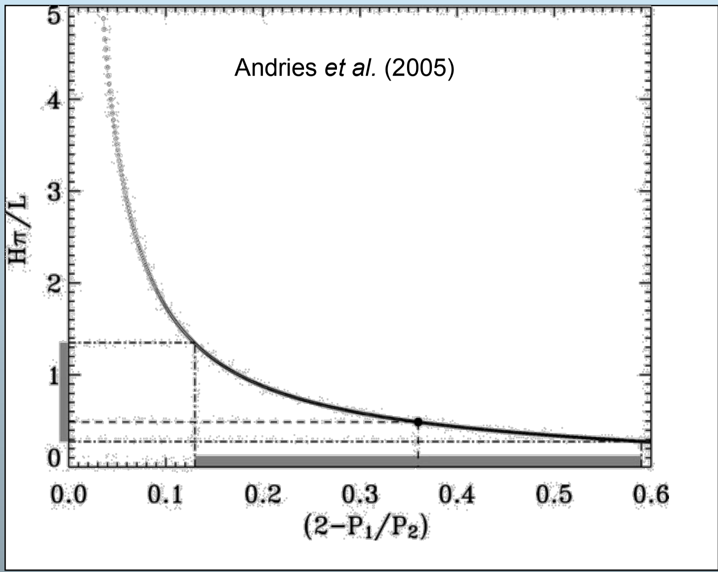


FIG. 2.— Loop displacement at the four cuts across the loop, as a function of time where dot-dashed lines show the corresponding fits. Note that the displacements have been shifted by arbitrary constants.

(De Moortel & Brady, 2007)

$P_1 \neq 2P_2$

- Dispersion (e.g., for the sausage wave P_2 can be even greater than P_1!) – but, just a few % for kink mode.
- Variation of the speed **along** the loop.



Estimation of the density scale height (heating function?)

Example: Van Doorsselaere et al. 2007 :

$$\frac{P_1}{P_2} = 1.795 \pm 0.051$$

Loop length $L \approx 400$ Mm.

- Andries et al. (2005), McEwan et al. (2006): $H = 109^{+31}_{-21}$ Mm
- Dymova et al. (2006): $H = 109^{+22}_{-31}$ Mm because of non-semi-circularity ($h_a \in [-0.5, 0.5]$)

The hydrostatic estimation: H = 50 Mm

(c.f. Aschwanden et al. 2000: "**over-dense loops**")

Oscillations in the vertical plane?

Wang & Solanki, 2004

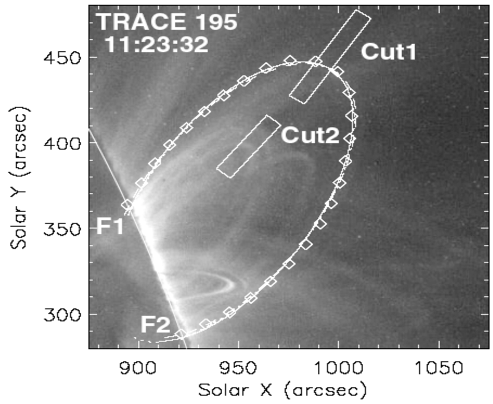
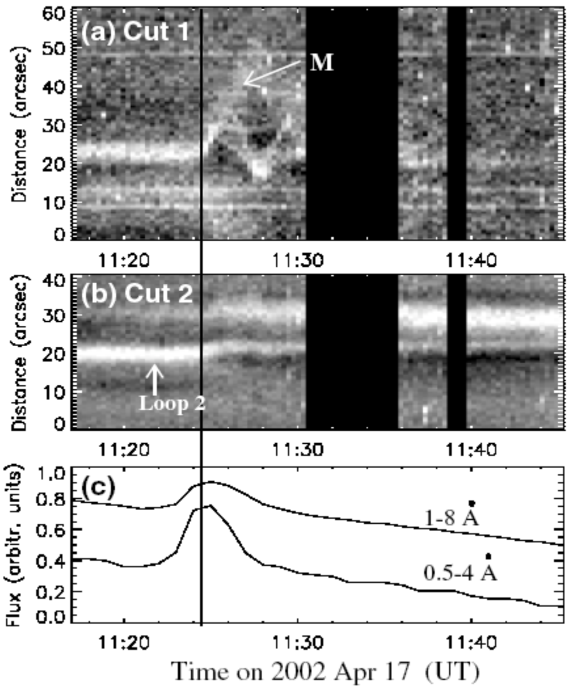


Fig. 1. A TRACE image containing the analyzed coronal loop (outlined by the *diamonds*), which is fit assuming three loop geometries: circular loop (solid curve), fat (dotted curve) and thin (dashed curve) elliptical loops. Both footpoints of the loop are located behind the solar limb. The boxes mark the locations of two cuts shown in Fig. 2.



Confirmation is still needed

Transverse oscillations in a shrinking loop

Li & Gan, 2006

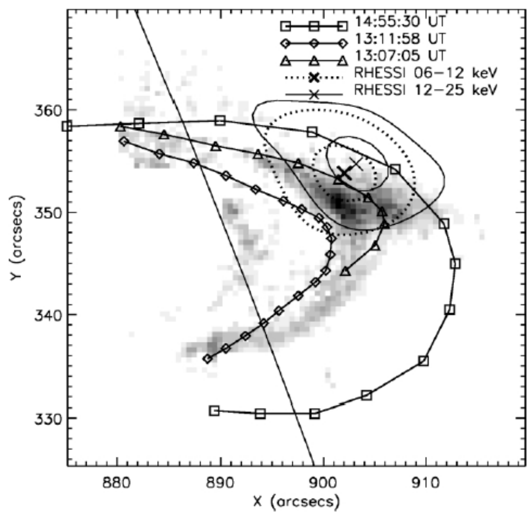
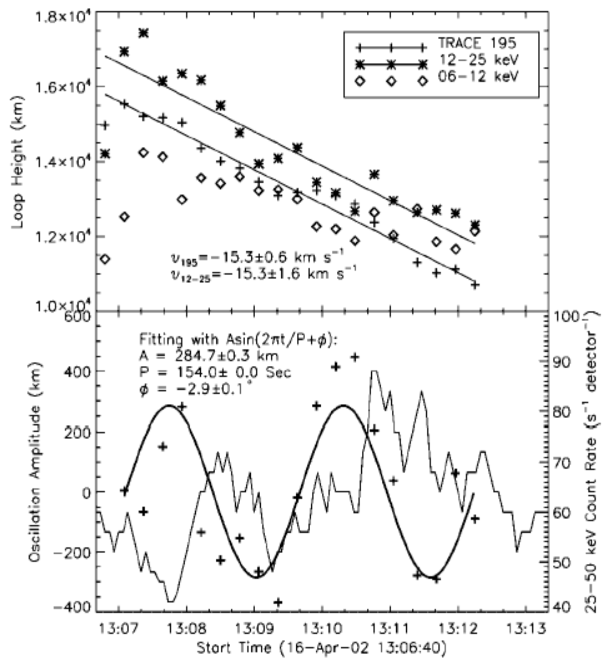
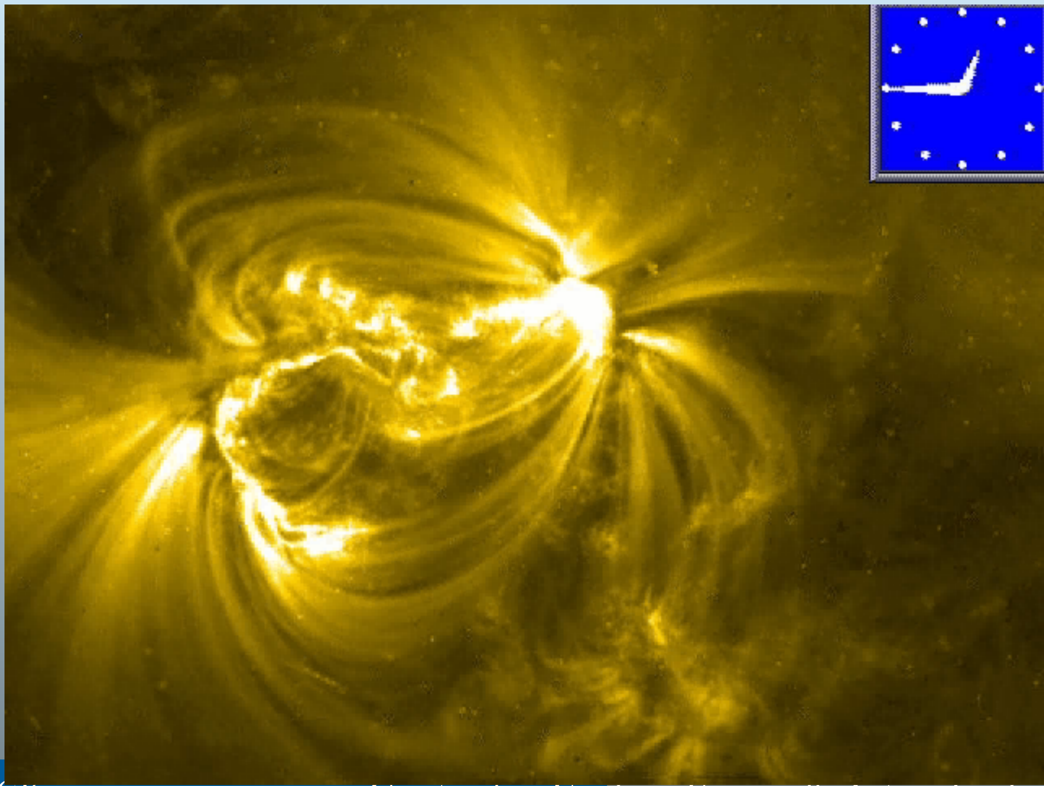


FIG. 2.—*TRACE* 195 Å running difference image (black and white reversed) at 13:09:21 UT, overlaid on the 60% and 90% contours of *RHESSI* 6–12 and 12–25 keV images at 13:09:20 UT, as well as the loops seen at 13:07:05 and 13:11:58 UT from *TRACE* running difference images, and at 14:55:30 UT (postflare loop) from original image of *TRACE*. The crosses represent the centroids of *RHESSI* 90% contours.



Automated detection techniques:



Periodmapping of coronal imaging data cubes:

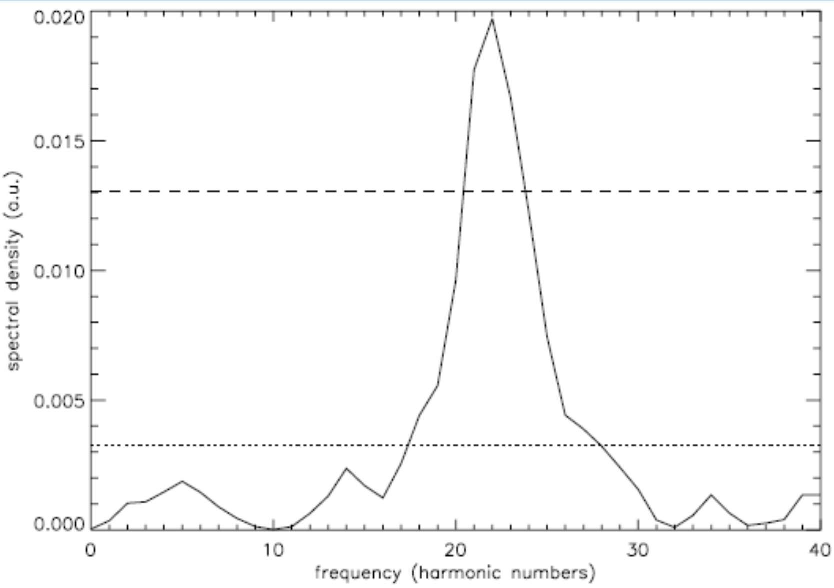
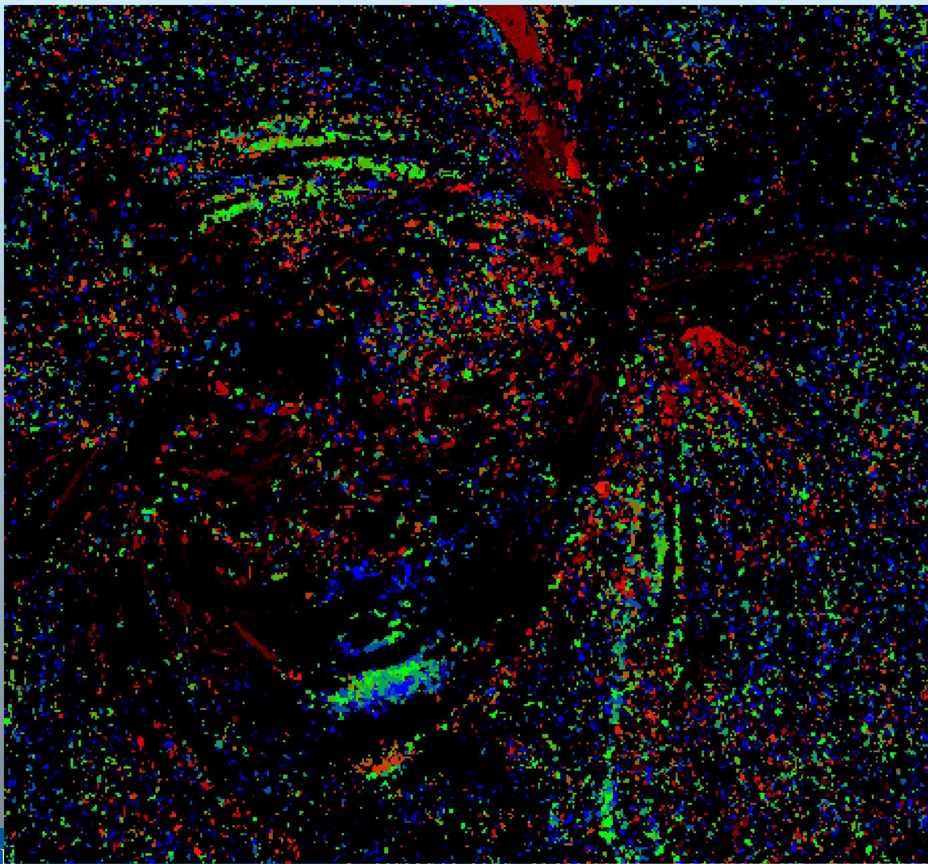


Figure 4 A power spectrum of an EUV signal from a TRACE image pixel. The dotted line corresponds to the mean value of the function, and the dashed line to the mean value multiplied by a factor of 4, which is a prescribed periodicity detection criterion.

“Periodomap” of the active region, 171 A



What about different instruments?

The optically thin gyrosynchrotron emission intensity I_f at a frequency f can be estimated as

$$I_f \approx \frac{BN}{2\pi} \times 3.3 \times 10^{-24} \times 10^{-0.52\delta} (\sin\theta)^{-0.43+0.65\delta} \left(\frac{f}{f_B}\right)^{1.22-0.90\delta}$$

Kink mode: $\theta(t)$ → modulation $I_f(t)$

The power law spectral index of nonthermal electrons δ>3-4

Hence: amplification

But, emission requires fast electrons

Open questions connected with kink modes:

- **Excitation mechanism**. *Options are: a flare-generated coronal blast (fast) wave; a chromospheric wave exciting loop footpoints.*

- **Decay mechanisms.** Improved period – decay time scaling is needed; evidence of mode conversion if any.

- **Selectivity of the excitation**: *why some loops respond to the excitation while others do not?*

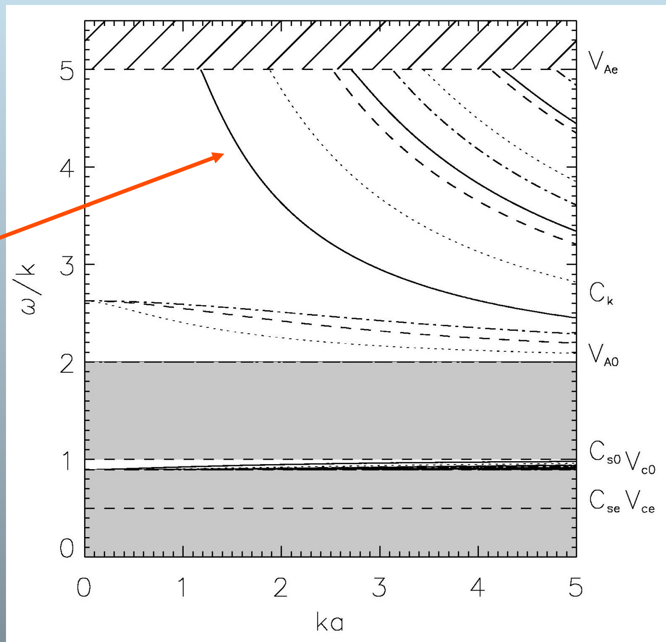
- The role of **nonlinear effects** *(the displacement is greater than the loop width).* Do the oscillations change the loop cross-section shape?

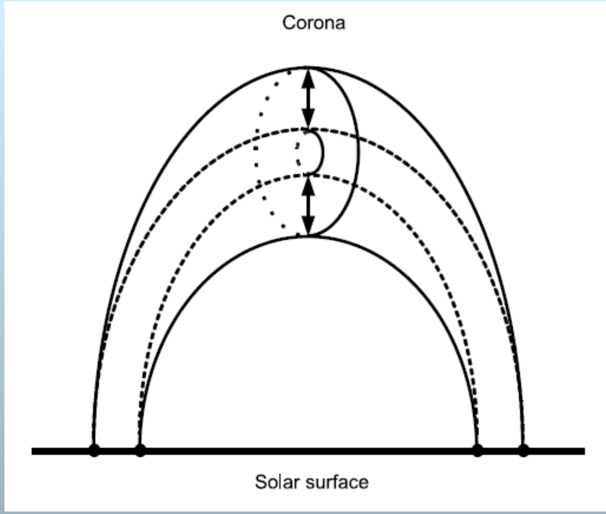
- Coupling of oscillations of **neighbouring loops**, oscillations of AR.

Spectral information is crucial (EIS).
Broader temperature coverage is crucial (AIA, XRT).
Better spatial resolution (ARKA with 0.18” pixel, 2016?)

2. Coronal Seismology with sausage modes:

m=0 mode





Sausage modes are essentially compressible and can **modulate X-ray** directly,

and radio emission (directly, through |B| or through the modulation of the mirror ratio)

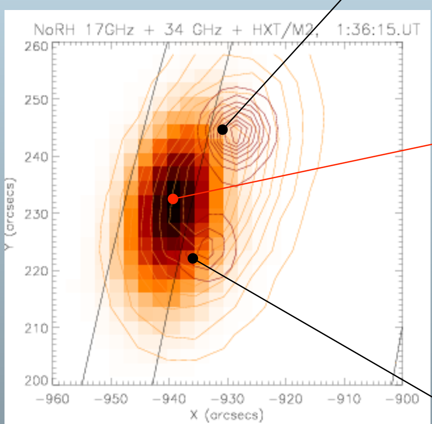
$$P_{GSM} = 2L / C_P, \quad C_{A0} < C_P < C_{Ae}$$

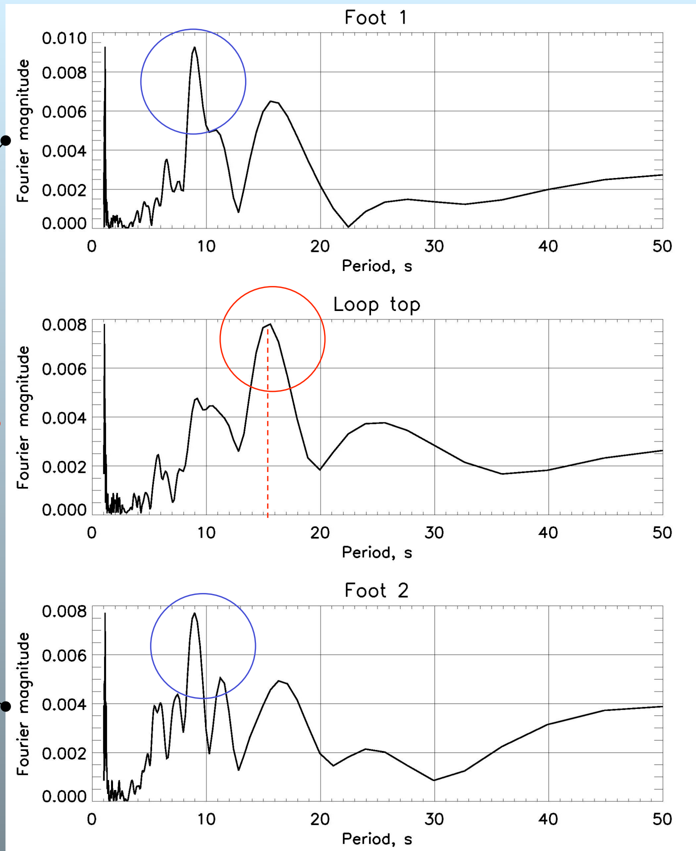
$$P < \frac{2\pi a}{j_0 C_{A0}} \approx \frac{2.62a}{C_{A0}}$$

In solar corona:

P = 10-120 s

Spectra at different parts of the loop:





Melnikov, et al. 2003-2008

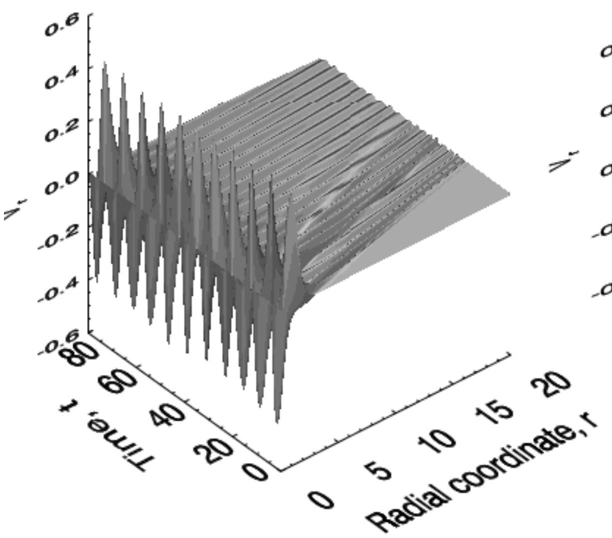
$$C_p = \frac{2L}{P} \approx 3,200 \text{ km/s}, \text{ and it must be} < C_{Ae}$$

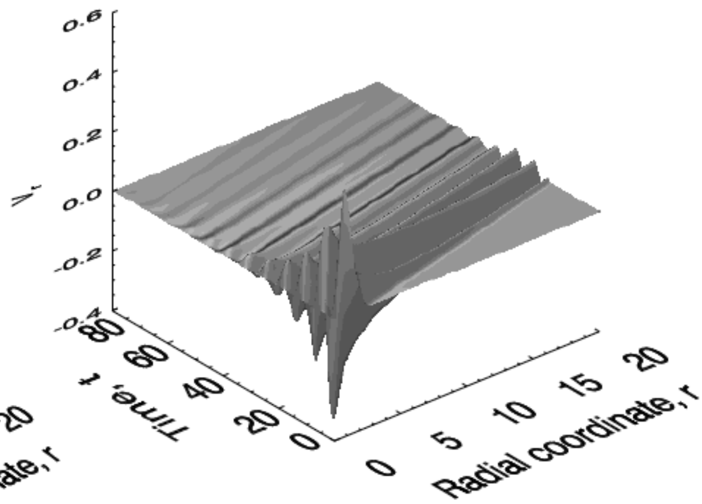
$$P < \frac{2.62a}{C_{A0}} \quad \Rightarrow \quad C_{A0} < \frac{2.62a}{P} \approx \frac{2.62 \times 3}{15} \approx 524 \text{ km/s.}$$

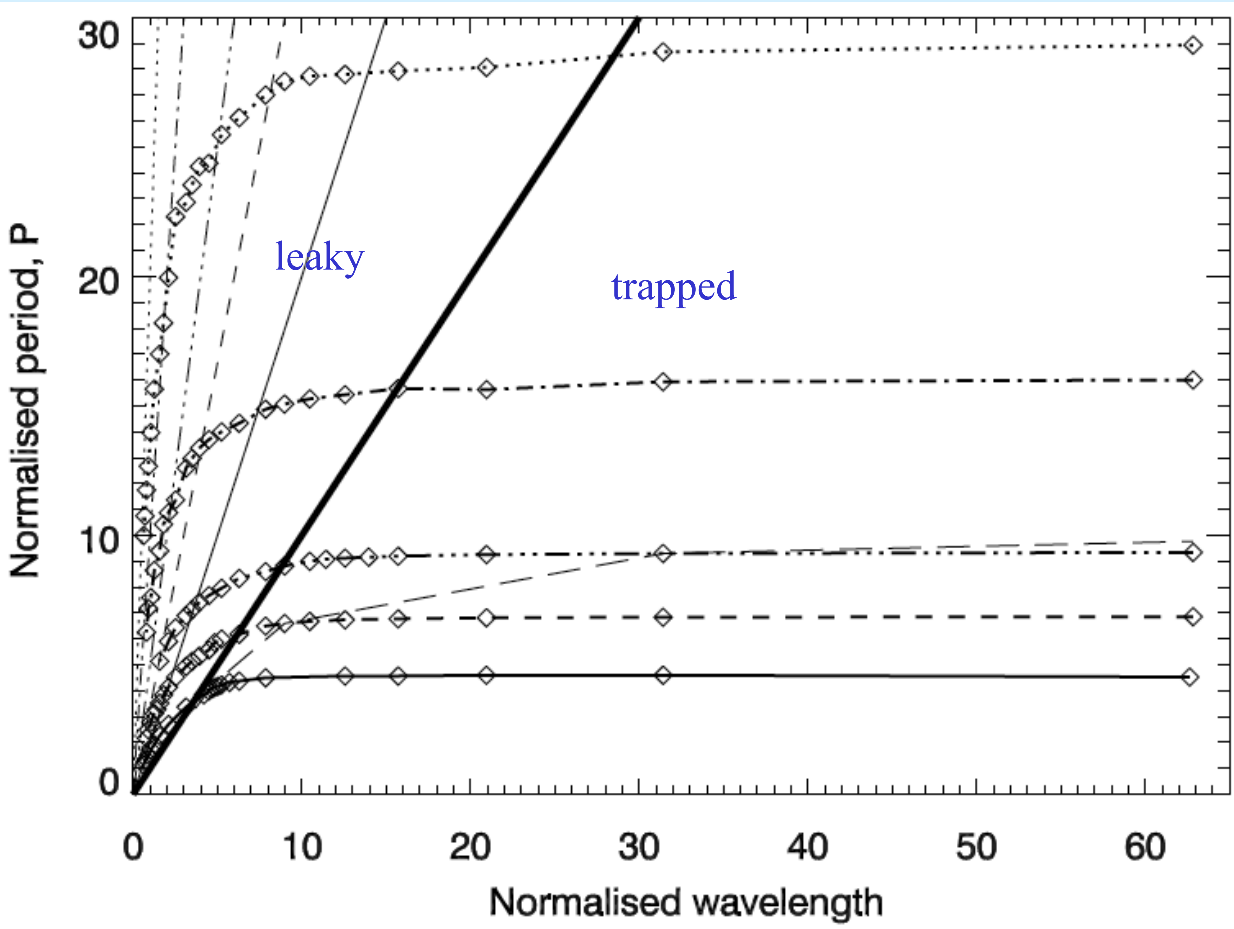
$$\therefore \quad C_{Ae} > 3,200 \text{ km/s}; \quad C_{A0} < 524 \text{ km/s}$$

A good tool for the estimation of the external (inter-loop) magnetic field

What about leaky modes? Full MHD simulations:

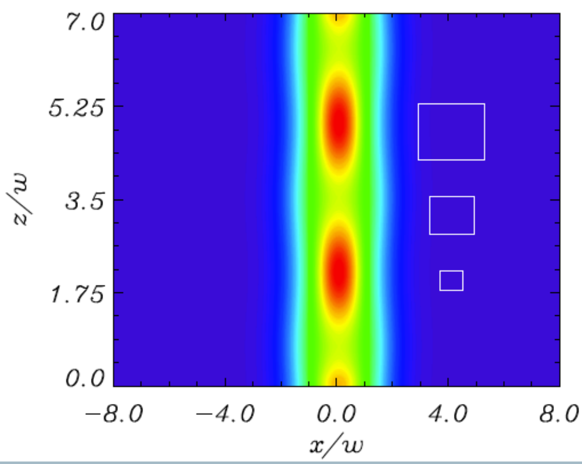


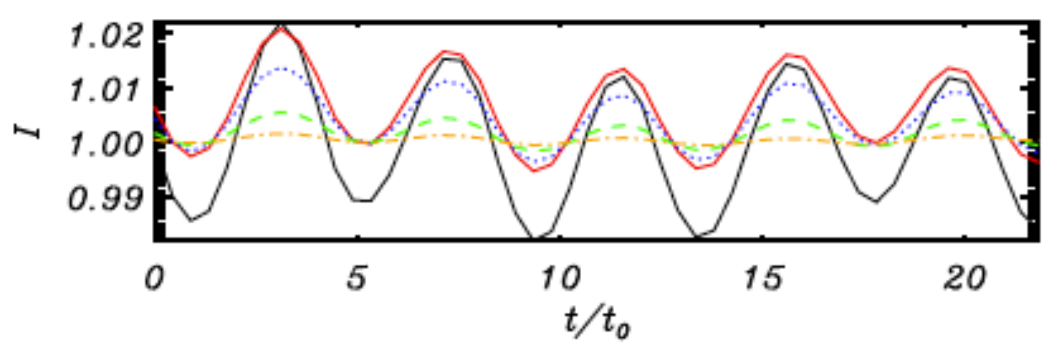




Effect of LOS integration:

$$\mathcal{I}(t) = \int_{(\mathrm{LOS})} \varrho^2(\mathbf{r}, t)\, dx.$$

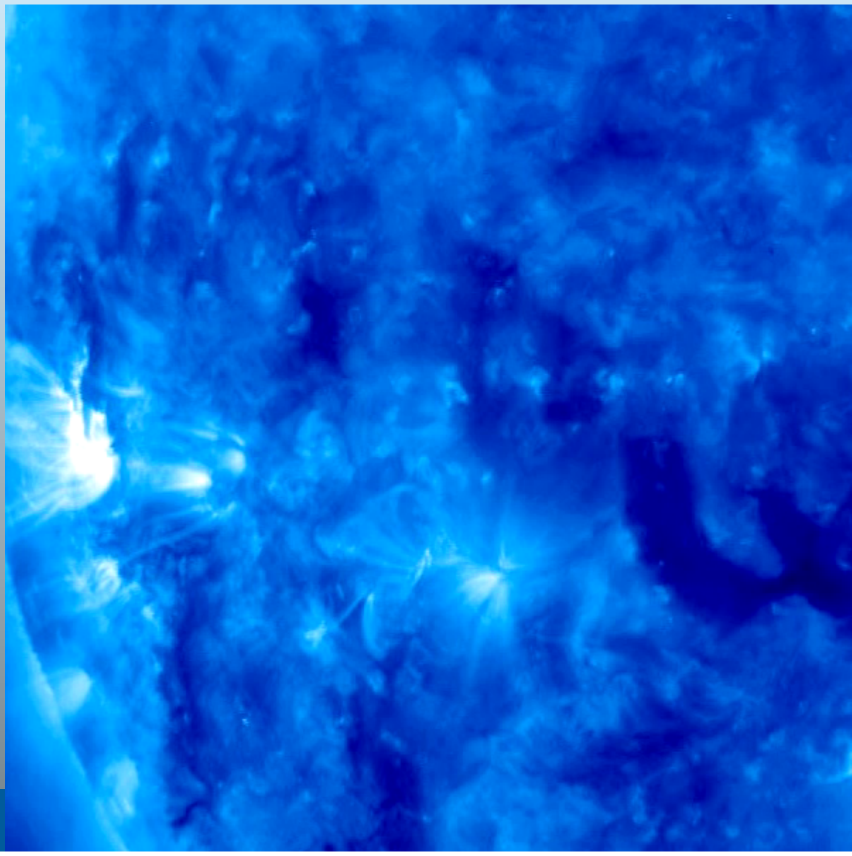




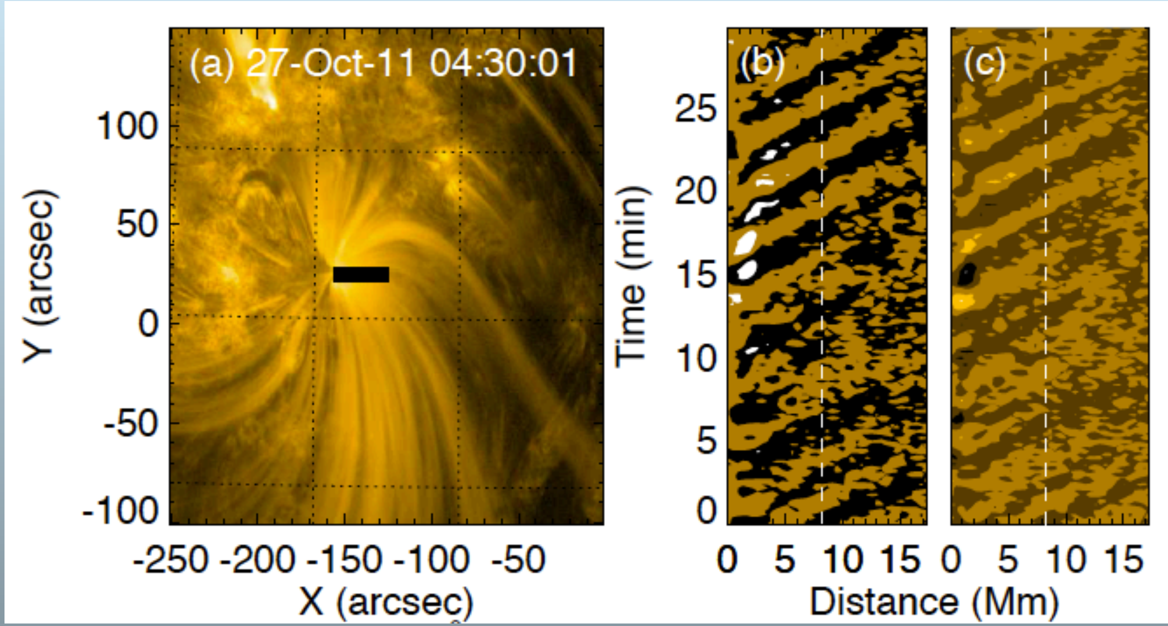
Open questions connected with sausage modes:

- **Why are the almost decayless oscillations not commonly observed?**
- **The role of wave-particle interaction.**
- Are quasi-periodic pulsations in solar and stellar flares connected with the sausage mode?

3. Coronal Seismology with Propagating Slow Waves:



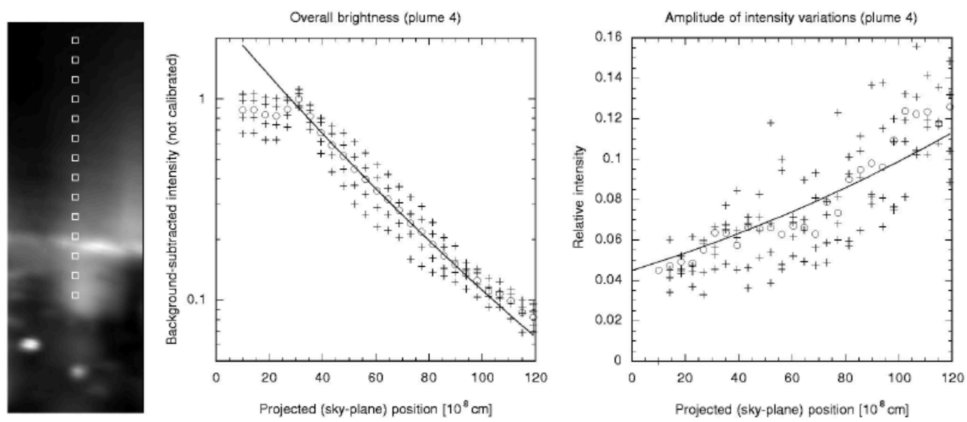
Standard analysis: time-distance plot



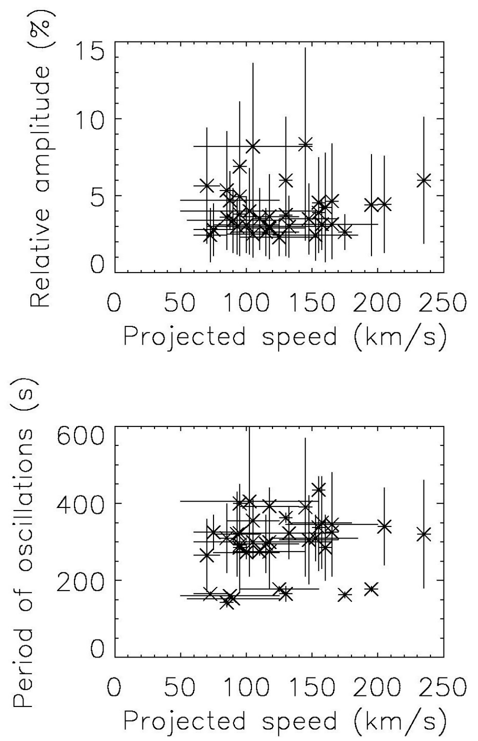
(Yuan & Nakariakov, 543, id.A9, 2012)

Also:

- In coronal holes: (Ofman et al. 1997; Banerjee et al. SSR 158, 267, 2011)
- In non-sunspot loops: (Berghmans & Clette, 1998; De Moortel et al. 2000)
- In polar plumes: (De Forest & Gurman, 1998; Ofman et al. 1999, 2000)



Correlations of observables (based upon De Moortel et al. 2003):



No apparent correlation of the amplitude, period and speed.

Typically observed near in legs of loops and in plumes:

- Upwardly propagating perturbations of EUV emission intensity.
- With constant speed about 25-165 km/s. (Gupta et al. 2010: some evidence of acceleration).
- Amplitude is <12% in intensity (< 6% in density),
- The periods are about 130-1200 s.
- No manifestation of downward propagation.
- A number of examples.
- No correlation between the amplitudes, periods and speeds.

Main mechanisms affecting the vertical dependence of the amplitude:

• Stratification (can be estimated, relative density change is needed),

• Thermal conduction (can be estimated if temperature is known),

• Magnetic flux tube divergence (can be estimated from images)

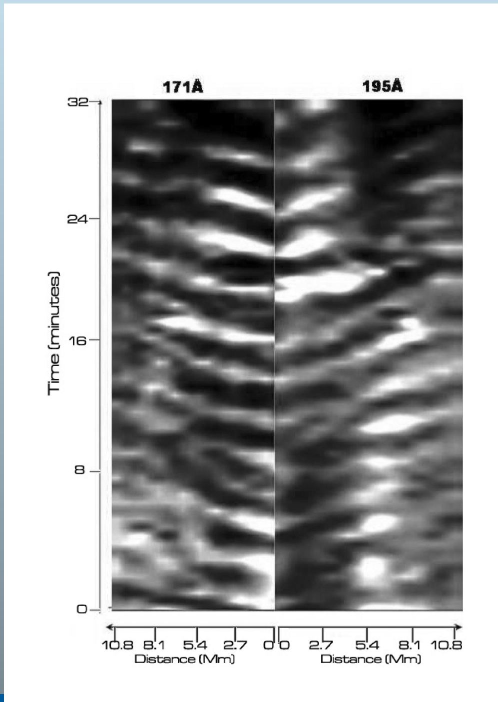
• Radiative damping (can be estimated if temperature is known, e.g. RTV approximation),

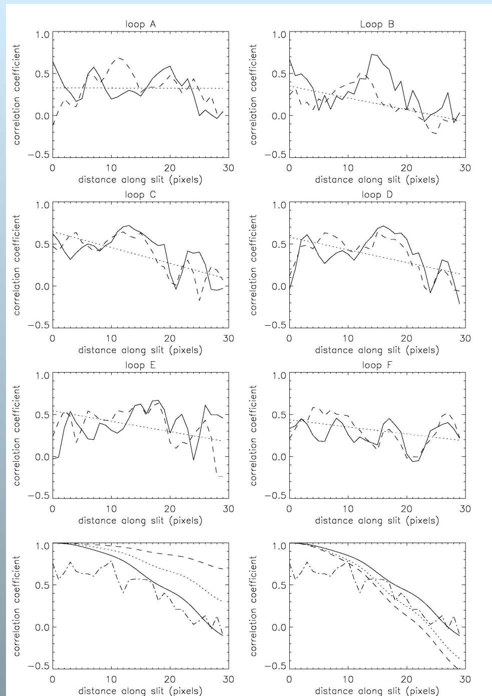
• Unknown **coronal heating function**.

- can be estimated from slow waves!

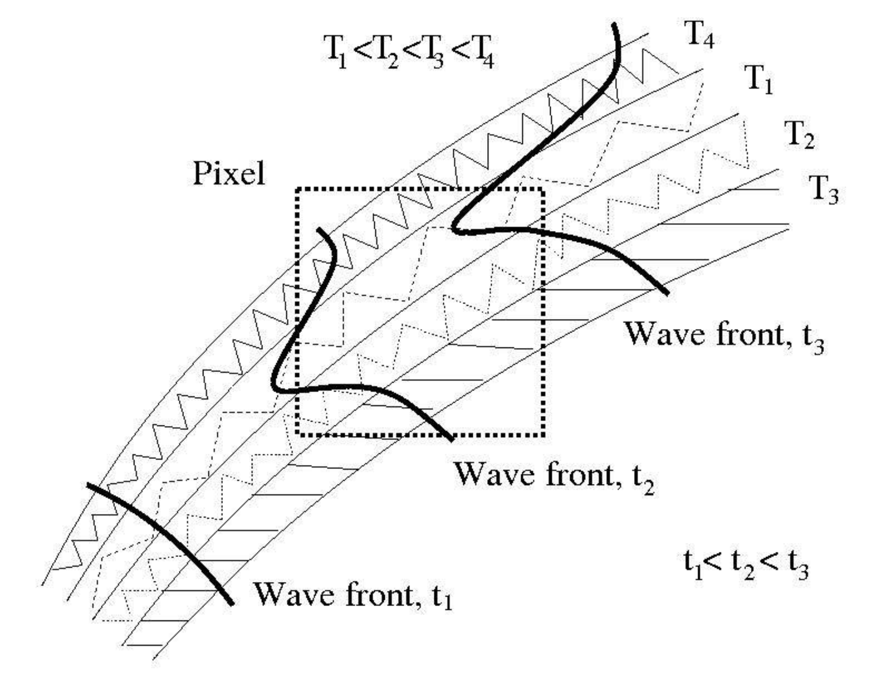
Multi-wavelength observations:

TRACE 171 A and 195 A:

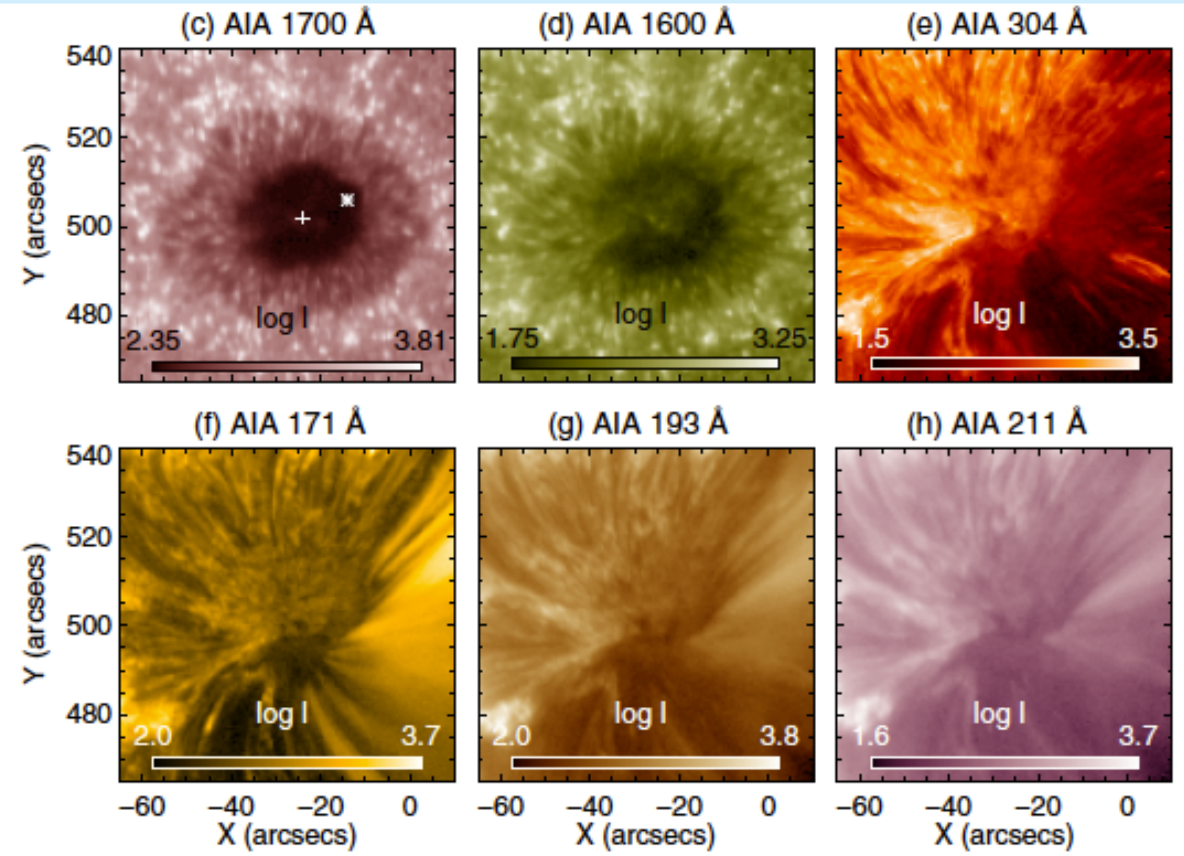




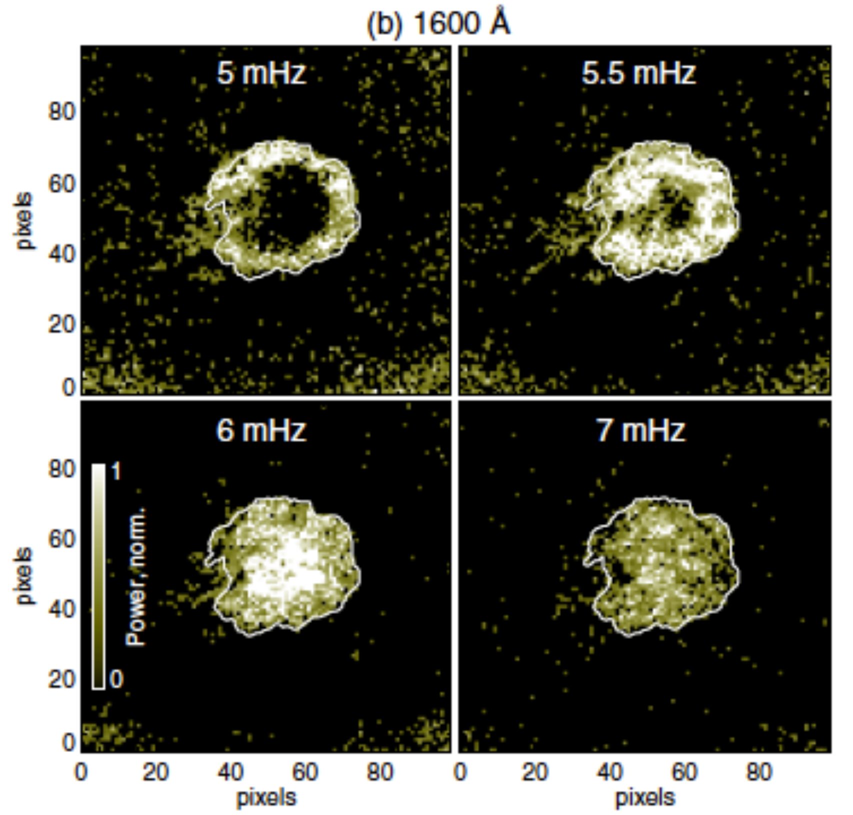
Multi-strand sub-resolution structuring?



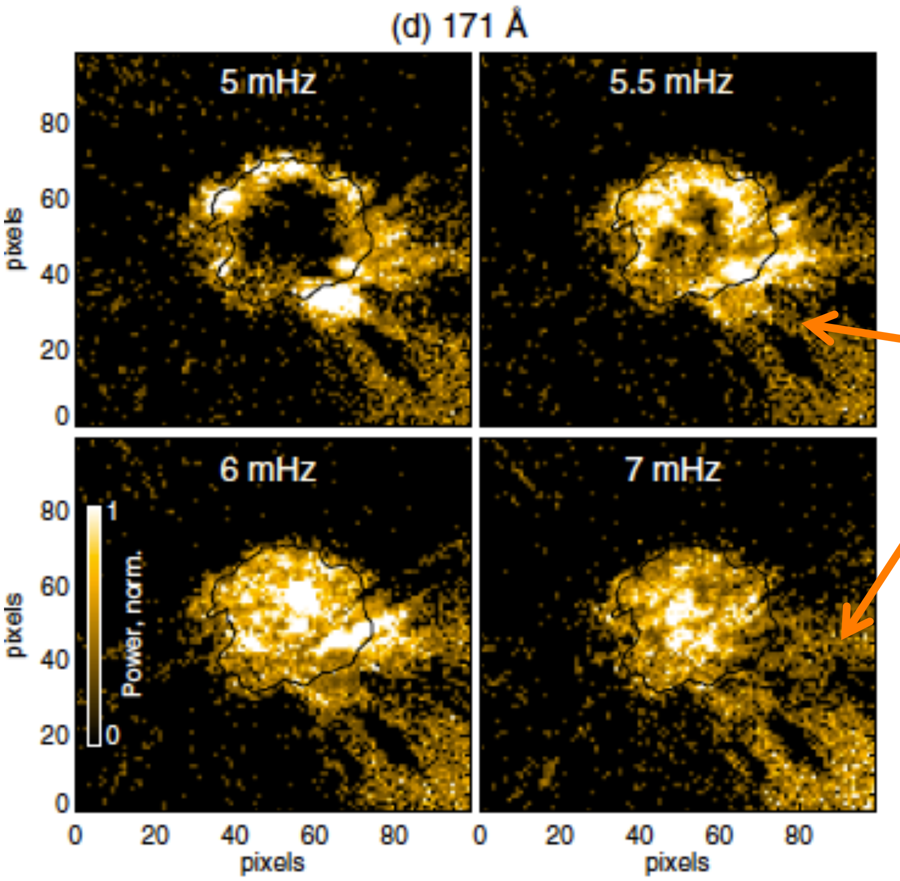
A probe of the sub-resolution structuring of the coronal temperature



Chromosphere



Corona



Slow wave guides

Open questions:

- What is their **origin and driver**? (*Options: thermal overstability, leakage of p-modes and 3-min oscillations, connection with running penumbra waves*).
- What determines the **periodicity and coherency** of propagating waves?
- What is the physical mechanism for the **abrupt disappearance** of the waves at a certain height (*Options: dissipation and density stratification, magnetic field divergence, phase mixing, …*).

Conclusions:

http://www.warwick.ac.uk/go/cfsa

- MHD Coronal Seismology is now a reality.
- Standing kink modes are useful for the remote diagnostics of the **magnetic field** and the **Alfvén speed** inside the loop.
- Interesting perspectives in microwave and X-ray bands (the sausage mode gives the **external magnetic field**).
- Slow waves can give us the **heating function** and an estimate of **sub-resolution structuring**.
- Search for multi-modal events is needed.
- Interesting perspectives with AIA and SO.

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WILEY-VCH

Coronal Seismology

Waves and Oscillations in Stellar Coronae

ISBN-13:
978-3527409945

published on June 4, 2012

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Centre for Fusion, Space & Astrophysics