Oscillations and waves in coronal loops

Recent observations from SOHO and TRACE

Tongjiang Wang

(*Max-Planck-Institut für Sonnensystemforschung)*

Thanks to: Sami K. Solanki
Werner Curdt
Davina E. Innes

MPS

Outline

1. Introduction

2. Standing waves

    a) Kink mode oscillations

    b) Slow mode oscillations

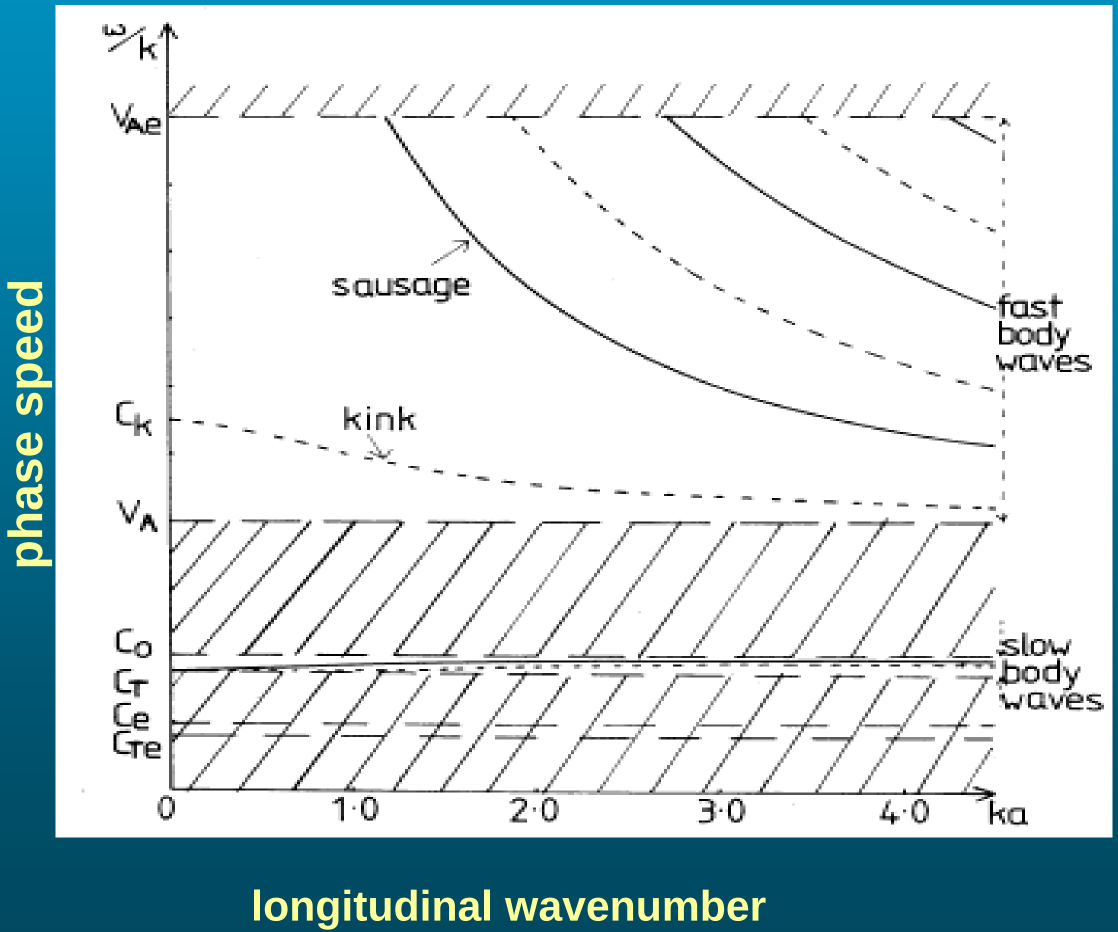
3. Propagating waves

    Slow magnetoacoustic waves

4. Summary and questions

Coronal Seismology: Loop Oscillations

- MHD oscillations in magnetic cylinder
  (Edwin & Roberts 1983; Robert et al. 1984)



- **Expected oscillation periods in coronal loops**

Slow modes: P = 7 –70 min
Kink modes: P = 1.4 – 14 min
Sausage modes: P = 0.1 – 5 s
(Aschwanden 2003)

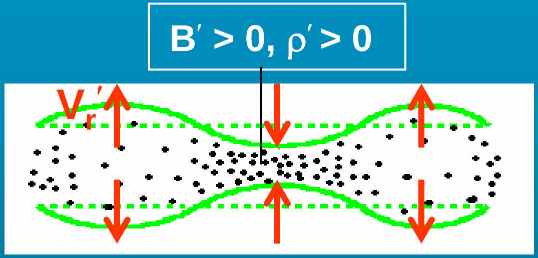
- Coronal seismology ⇒
  (Roberts, 1981;1986)

  Diagnostic of physical parameters of coronal structure, e.g., magnetic field strength, dissipation coefficients, etc.

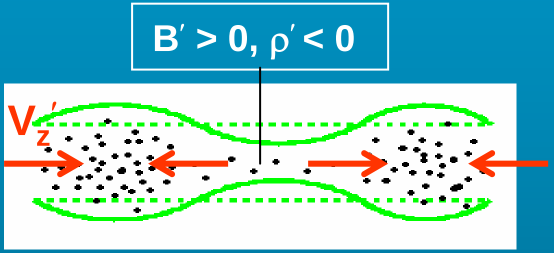
Sketches of oscillation modes

1) Fast modes:

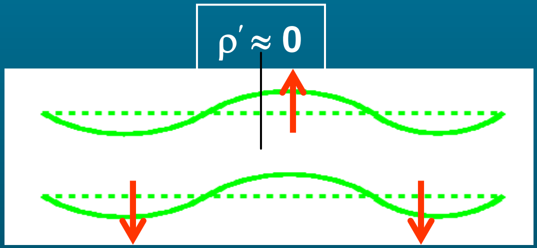
(a) sausage
(symmetric)



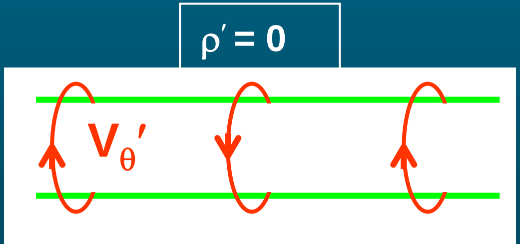
2) Slow (sausage) modes:



(b) kink
(asymmetric)

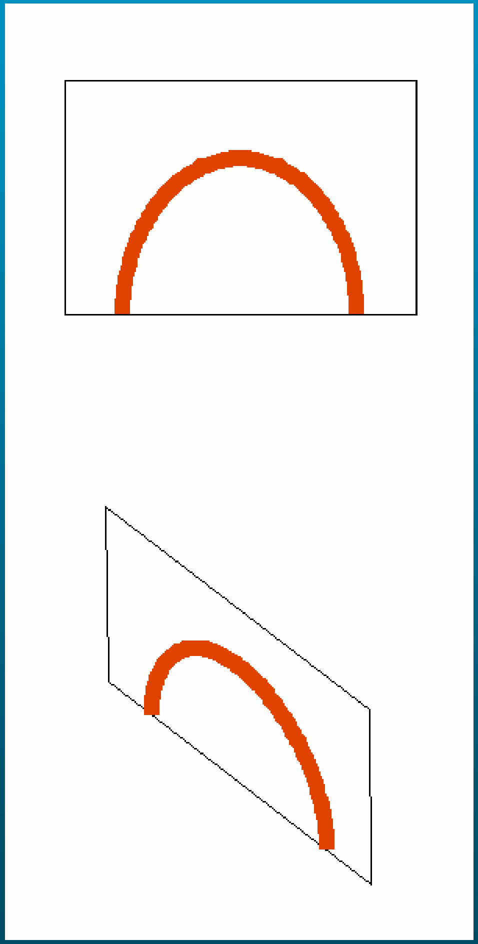


3) Torsional Alfven modes:

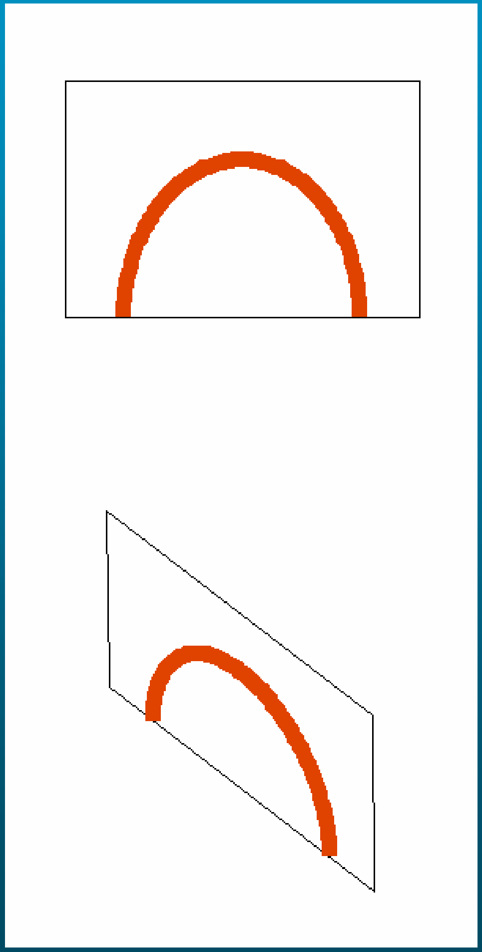


Three types of kink oscillations of a loop

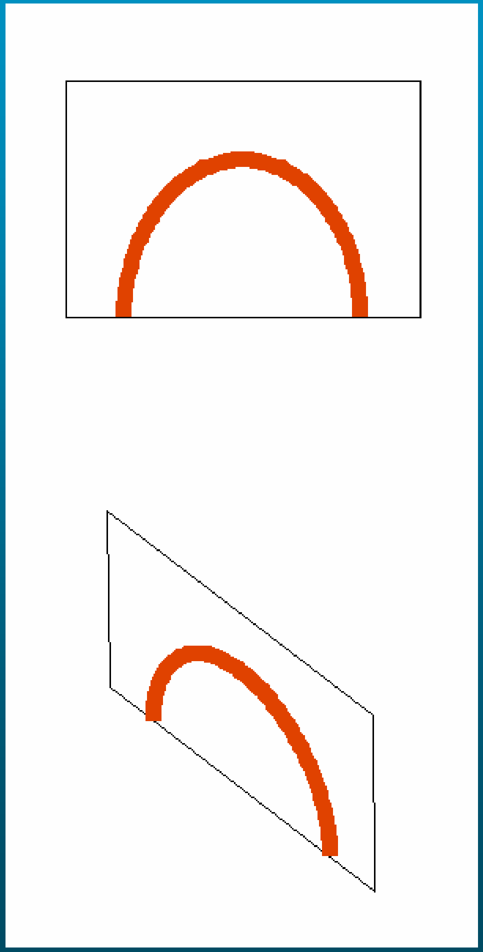
1) Horizontal mode



2) Vertical mode



3) Distortion mode



Observations with SOHO and TRACE in EUV

1) Standing kink-mode oscillations — TRACE

Aschwanden et al. (1999) Nakariakov et al. (1999) Schrijver & Brown (2000)

Aschwanden et al. (2002) Schrijver et al. (2002) Wang & Solanki (2004)

Verwichte et al. (2004)

2) Standing slow-mode oscillations — SOHO/SUMER

Kliem et al. (2002) Wang et al. (2002) Wang et al. (2003a)

Wang et al. (2003b) Wang et al. (2005)

3) Propagating slow mode waves — SOHO/EIT and TRACE

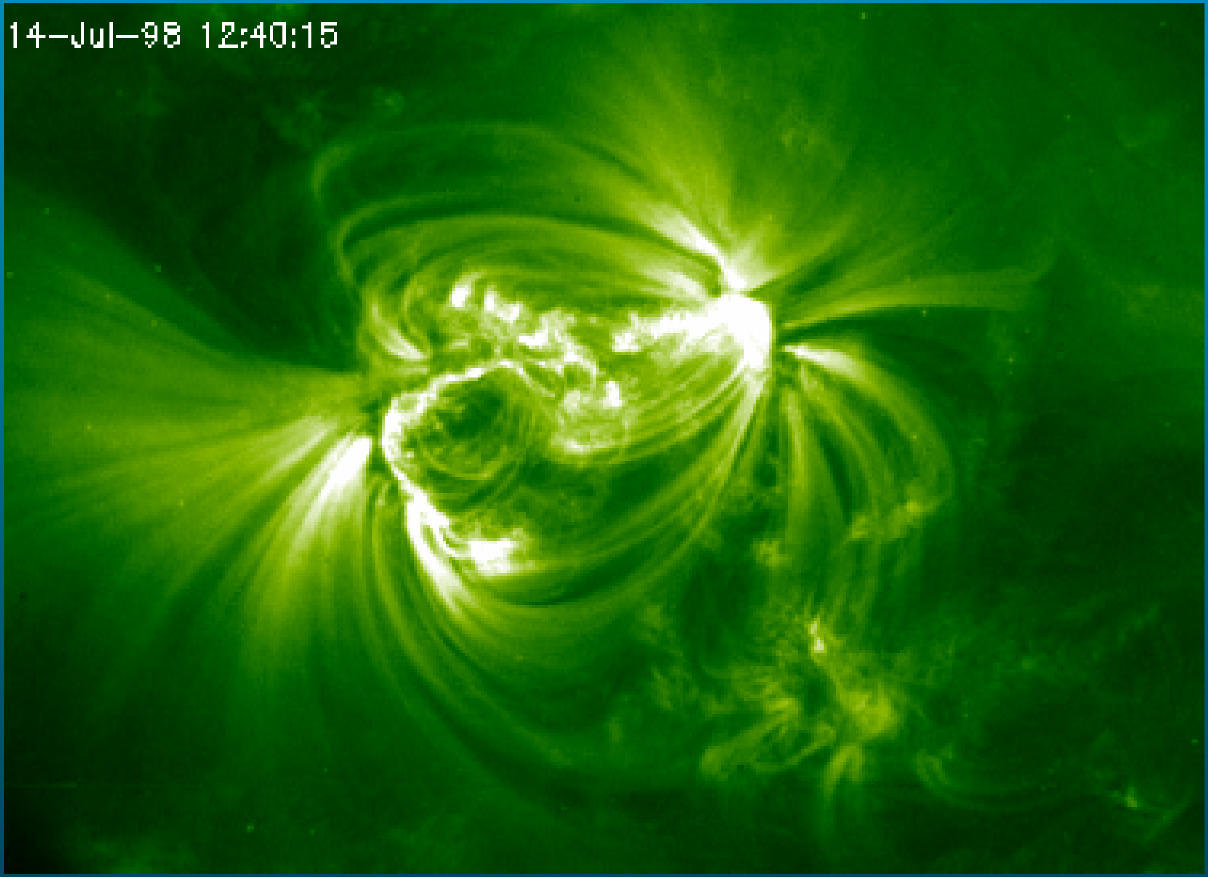
Berghmans & Clette (1999) De Moortel et al. (2000)

Robbrecht et al. (2001) De Moortel et al. (2002a,b,c)

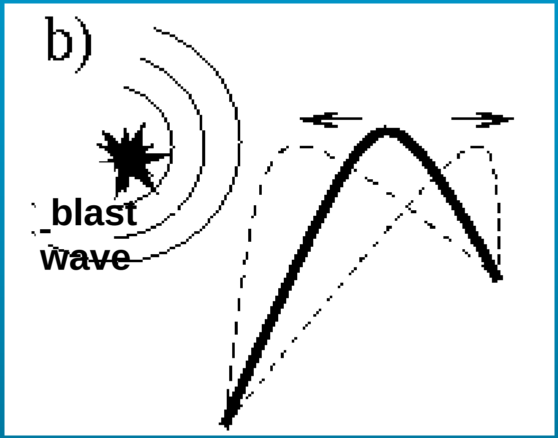
King et al. (2003) Marsh et al. (2003)

Horizontal loop oscillations observed by TRACE

- Loop oscillations are triggered by a M-class flare (Aschwanden et al. 1999)



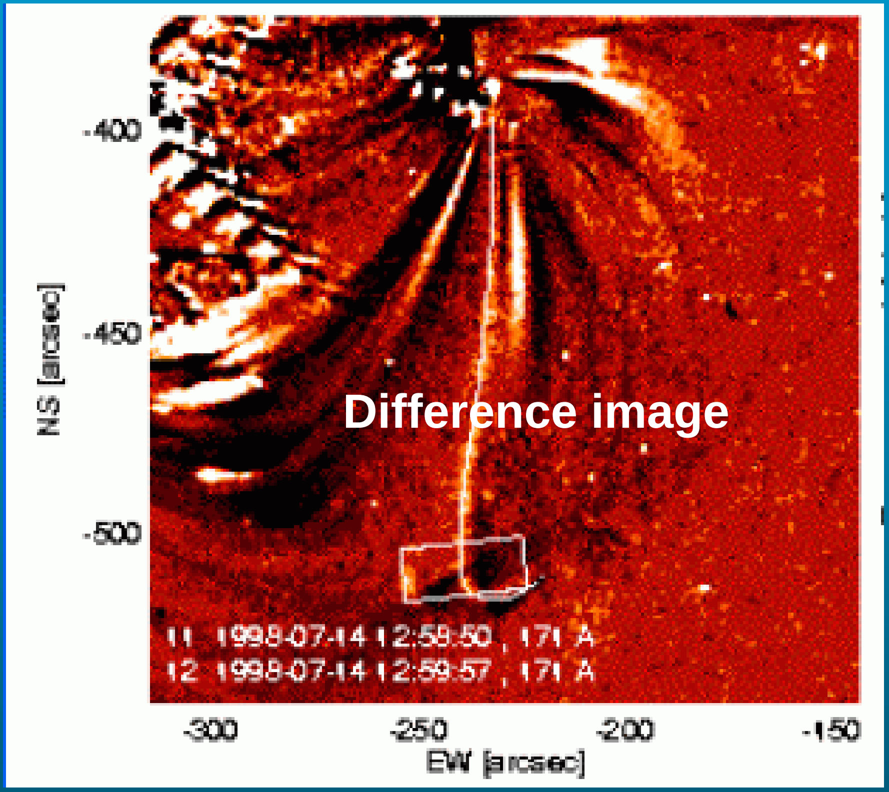
Movie in 171 A

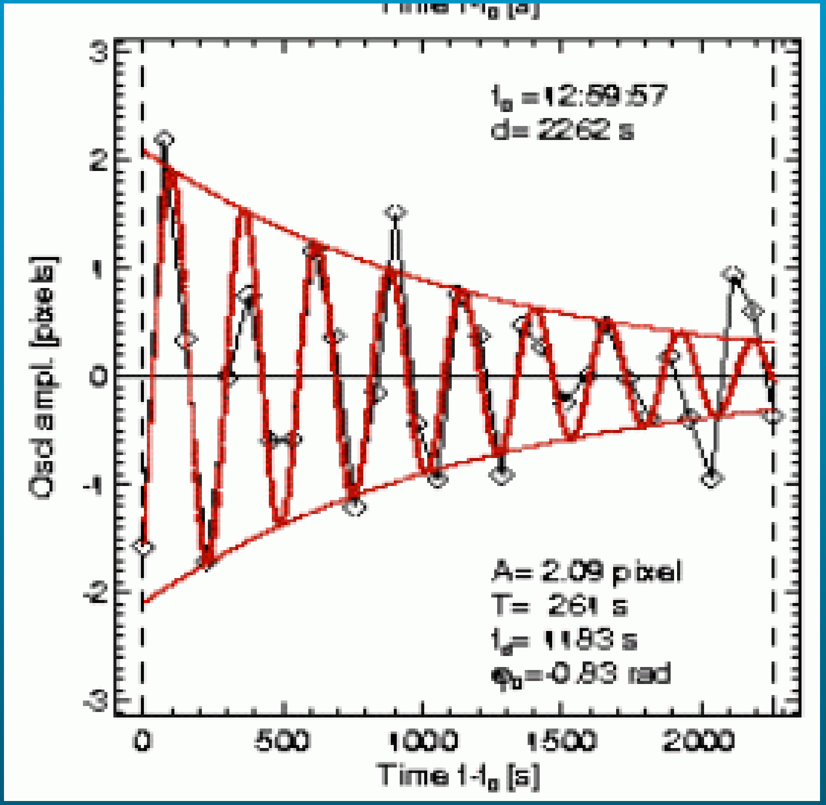


Transverse oscillations are excited by a flare blast wave indicated by initial motions away from the flare source

- 12/28 cases associated with metric type II bursts; 24/28 associated with CMEs (Hudson & Warmuth 2004)

• **Physical parameters of the transverse oscillations**



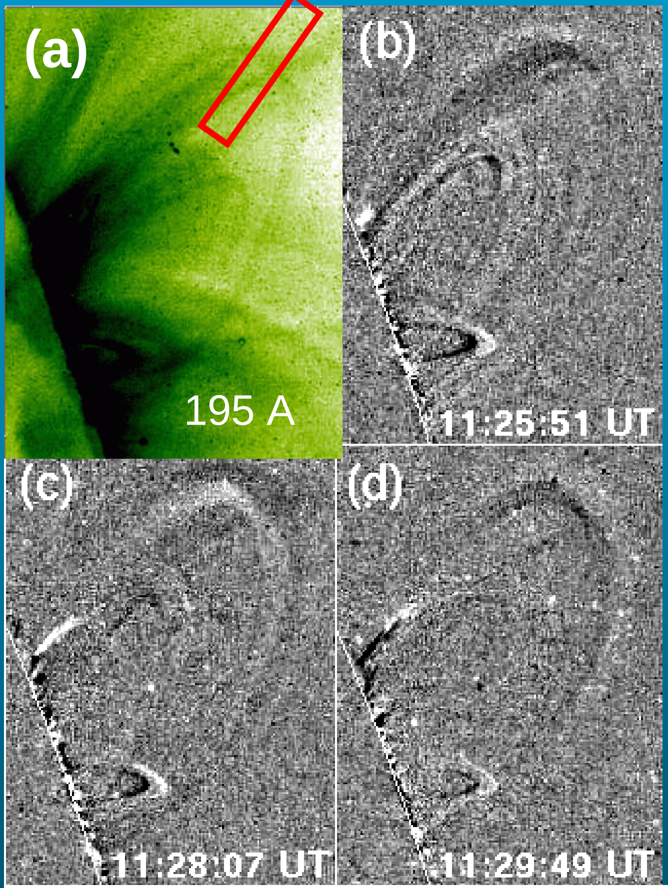


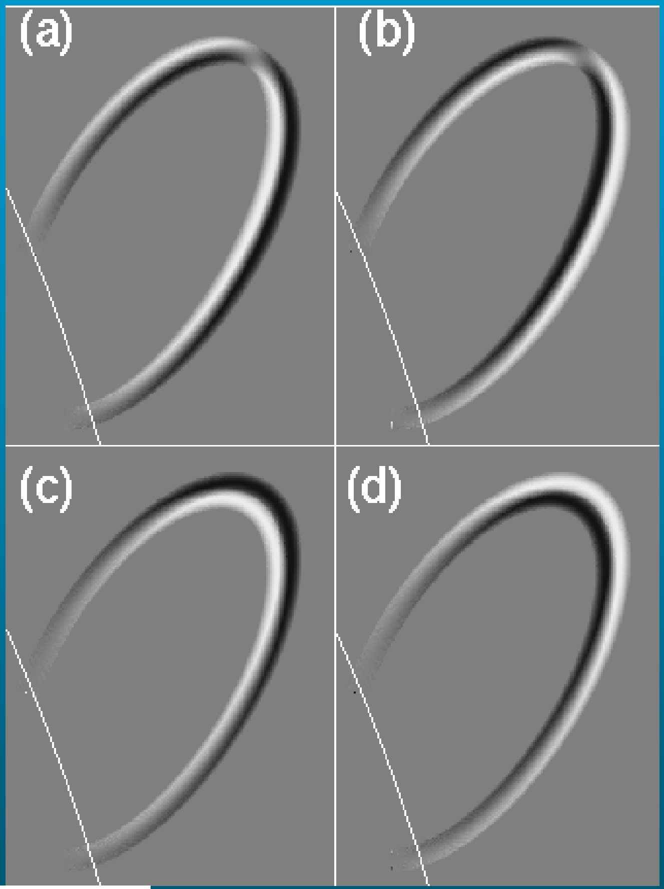
For 26 oscillating loops, (Aschwanden et al. 2002, Sol. Phys.)

P=5.4 ± 2.3 min **T_{decay}=9.7 ± 6.4 min**

A=2.2 ± 2.8 Mm **V_{max}=42 ± 53 km/s**

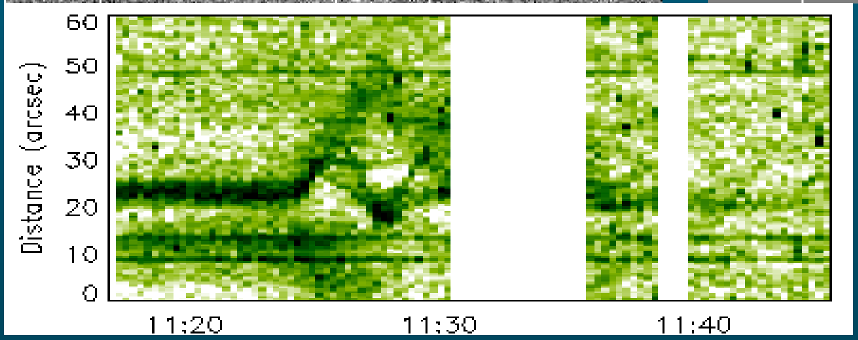
Vertical oscillations of a coronal loop observed by TRACE





(a)-(b): simulated horizontal loop oscillation

(c)-(d): simulated vertical loop oscillation consistent with the observations



Period P=4 min,

Decay time T_d=12 min

(Wang & Solanki 2004, A&AL)

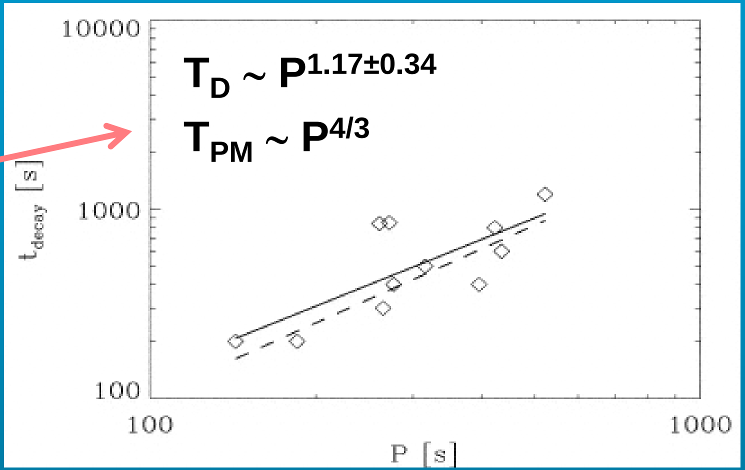
Wave damping mechanisms

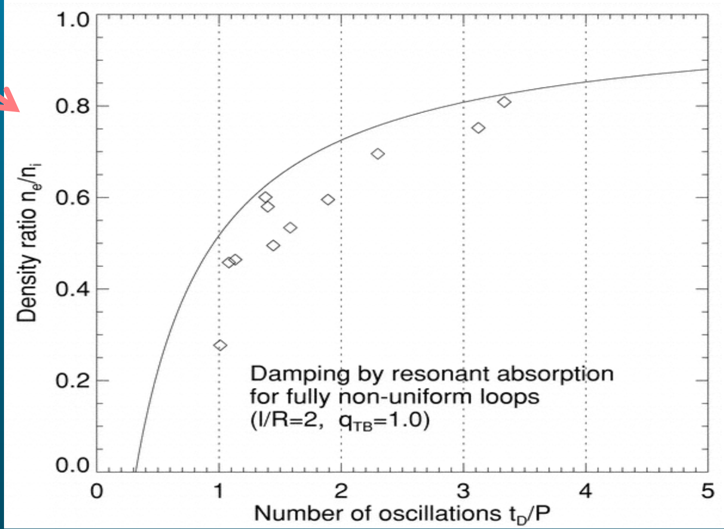
- Phase mixing
  (Nakariakov et al. 1999, sci.)
  (Ofman & Aschwanden 2002, ApJL) Obs,
  viscosity $\nu = 10^{8-9}\, \nu_{class}$

- Resonant Absorption
  (Ruderman & Roberts, 2002, ApJ) Theory
  (Goossens et al. 2002, A&AL) 1D MHD
  (Aschwanden et al. 2003, ApJ) Obs.
  (Van Doorsselaere et al. 2004, ApJ) 1D MHD

- Effect of loop curvature
  (Van Doorsselaere et al. 2004, A&A) Theory
  (Brady & Arber 2005, A&A) 2D MHD
  (Selwa et al. 2005, A&A) 2D MHD
  (Murawski et al. 2005, A&A) 2D MHD

- Stratification effect
  (Miyagoshi et al. 2004, PASJ) 3D MHD
  (Andries et al. 2005, A&A) Theory & 2D MHD
  (Del Zanna et al. 2005, A&A) 2.5D MHD

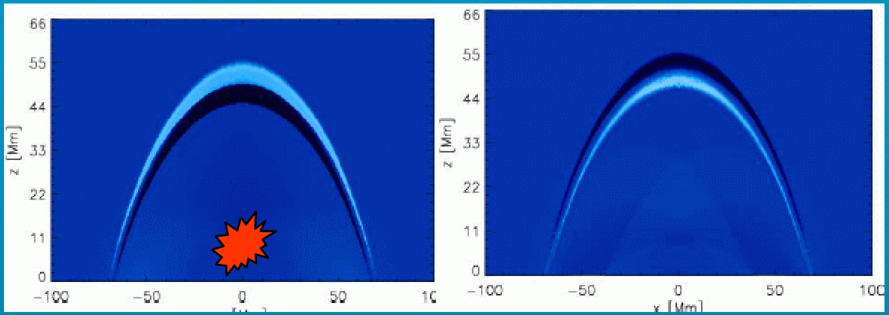




Excitation of loop transverse oscillations

- **1D MHD modeling**

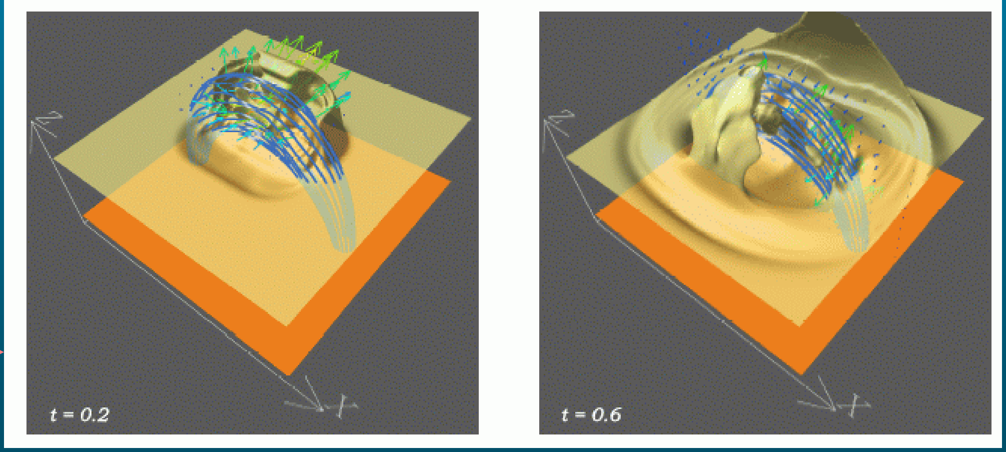
  (Terradas, Oliver & Ballester, 2005 ApJL) in a line-tied loop



(A hot pulse in density and pressure)

- **2D MHD modeling**

(Selwa et al. 2005, A&A) 2D MHD
(Murawski et al. 2005, A&A) 2D MHD
(Del Znna et al. 2005, A&A) 2.5D MHD



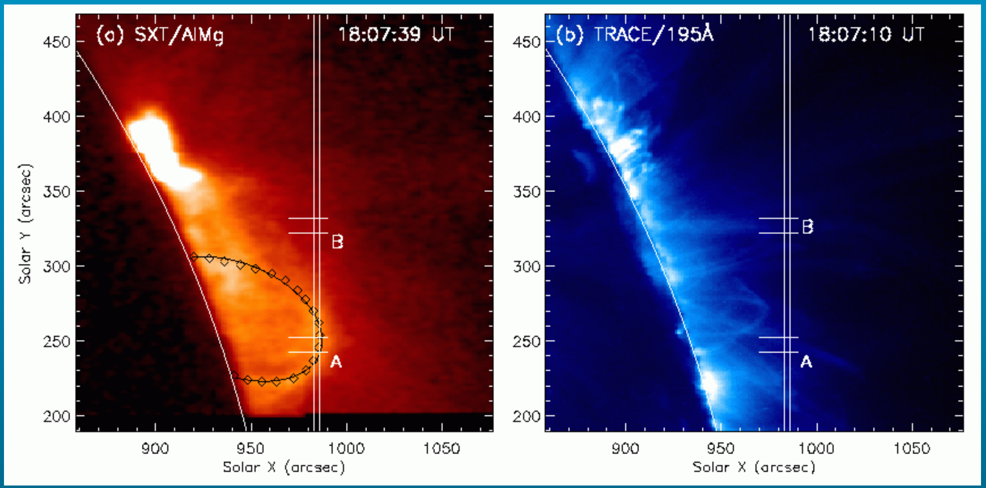
- **3D MHD modeling**

(Miyagoshi et al. 2004, PASJ) 3D MHD

(set an initial velocity at the loop top)

Standing Slow mode oscillations observed by SUMER

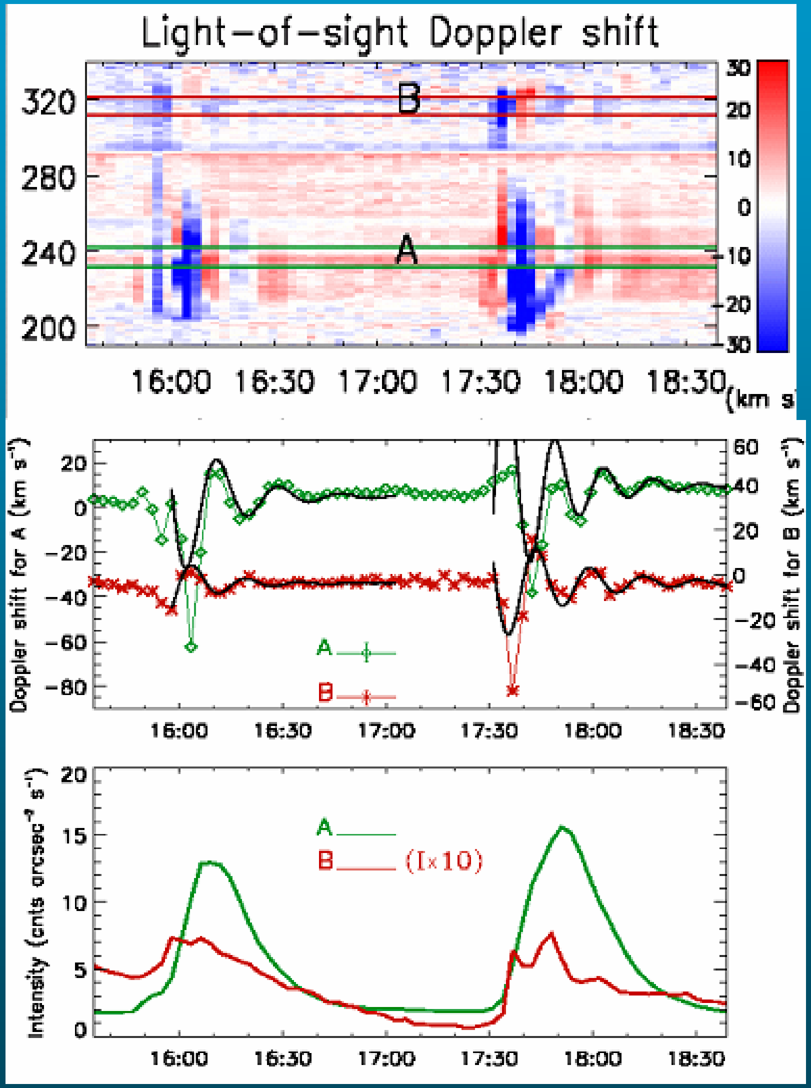
1) Hot loop oscillations



Periods: P=14 – 18 min,
Decay time: T_d=12 – 19 min

Phase speed V_p = 2L/P = 240 – 380 km/s

Sound speed: C_s = 380 km/s
at T = 6.3 MK

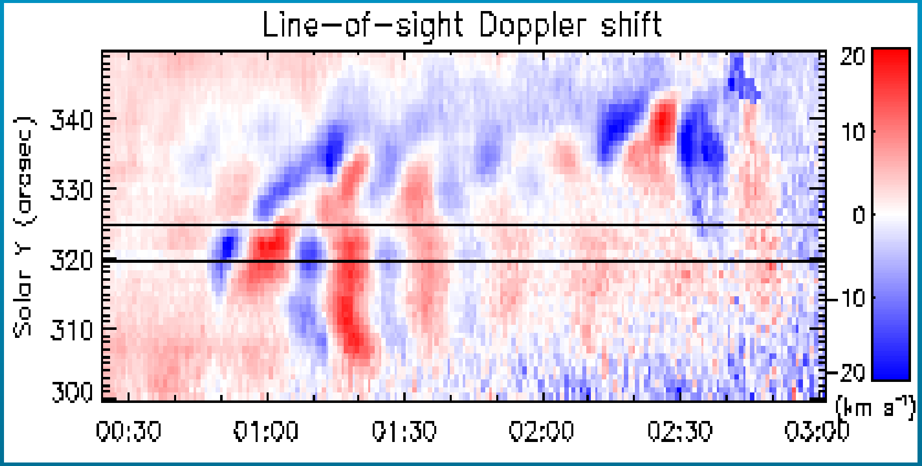


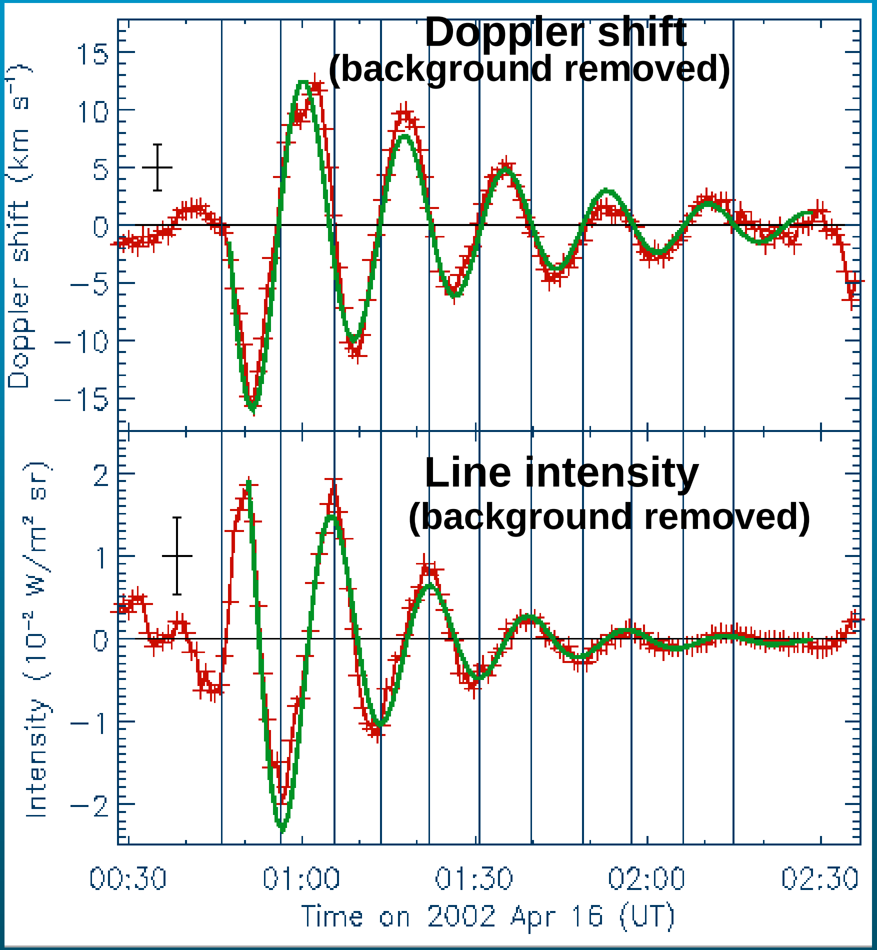
(Wang et al. 2002, ApJL)

2) Evidence for standing slow mode

(Wang et al. 2003b, A&A, 402, L17)

Doppler shift time series in Fe XIX line





a) Doppler shift oscillations

P = 17.6 min

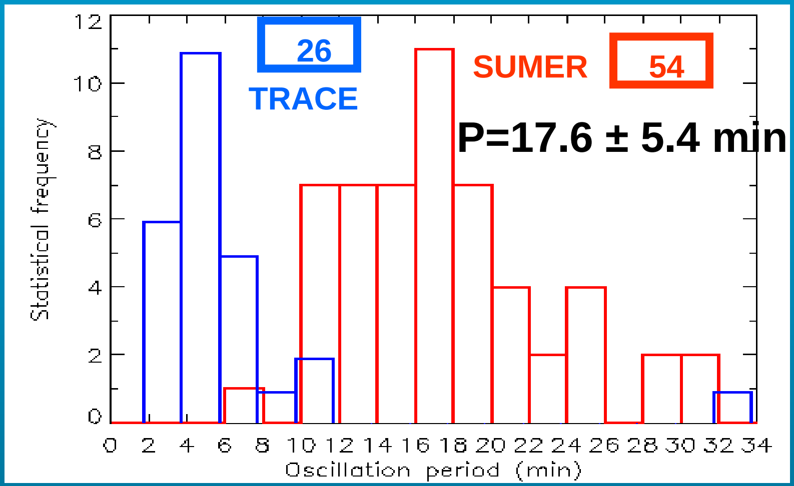
Line intensity oscillations

P = 17.1 min

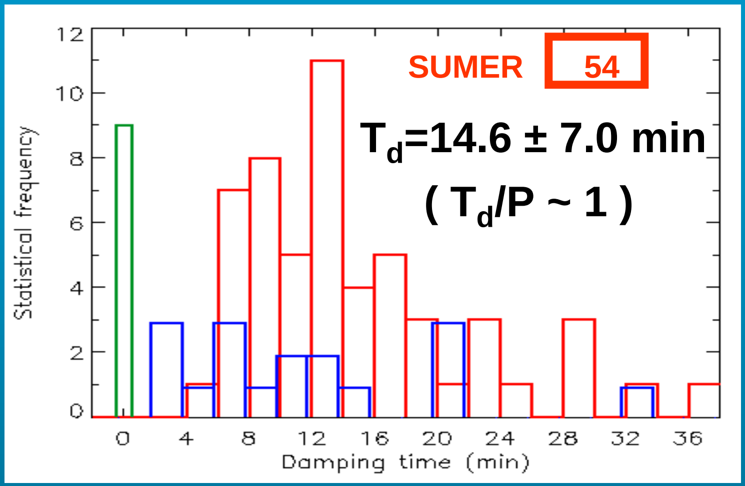
b) 1/4-period phase difference between velocity and intensity

3) Overview of measured physical parameters

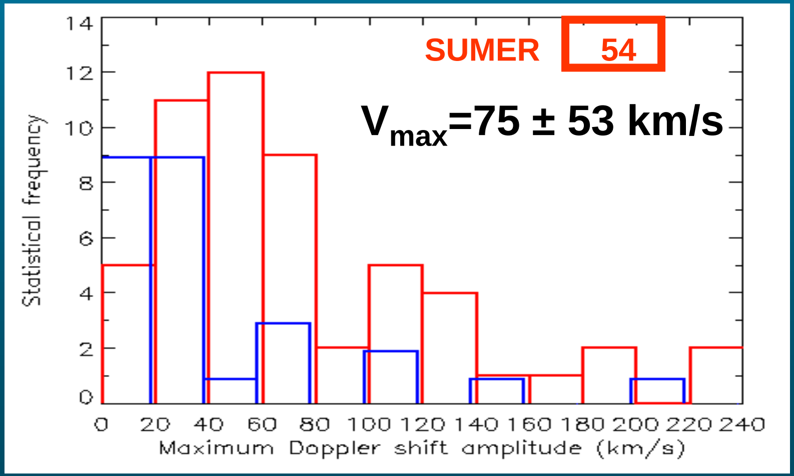
Comparison with TRACE result (Wang et al. 2003b, A&A)



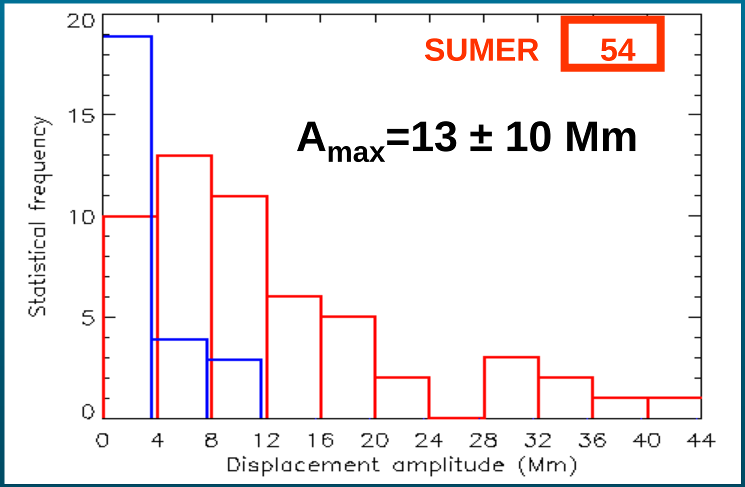
Period



Decay time

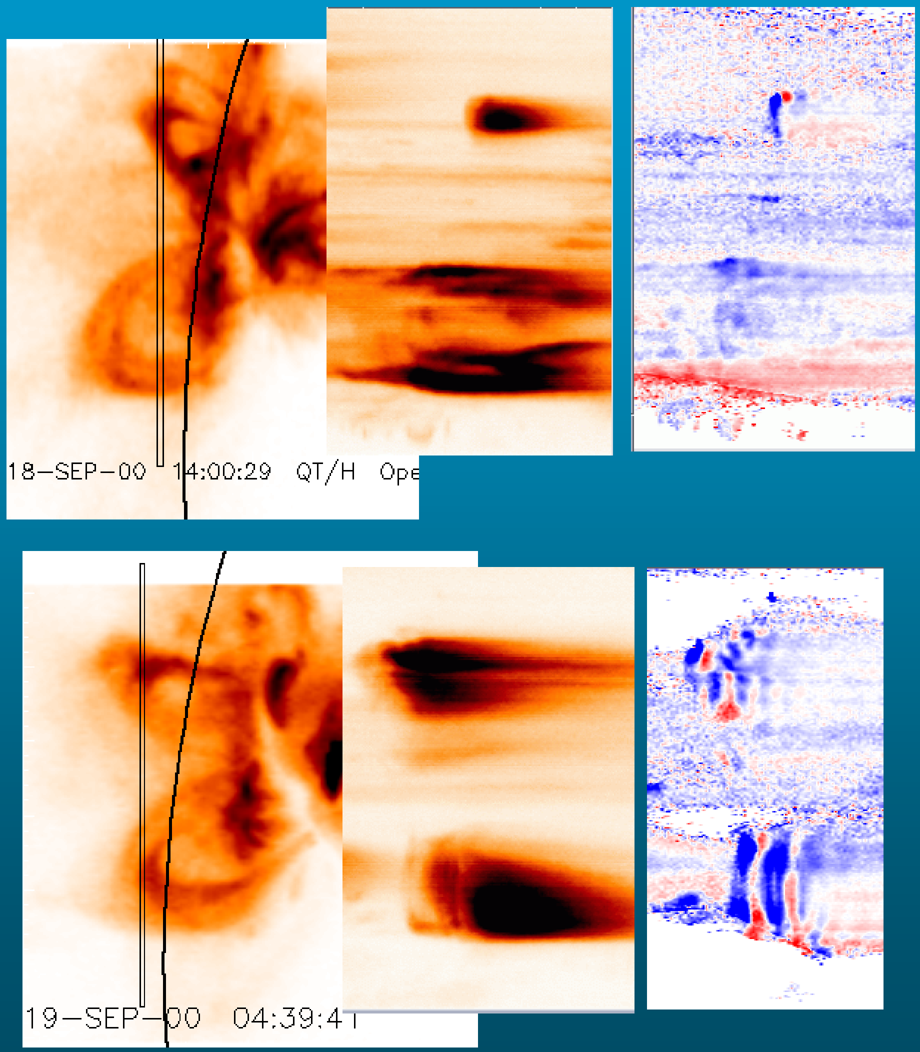


Maximum Doppler velocity



Displacement ampliitude

4) Observation of oscillations at different parts of the loop



SXT

FeXIX intensity

FeXIX Doppler shift

Oscillations are clearly seen at the apex of the loop, but not at the legs.

This result supports the fundamental mode.

5) Measurements of coronal magnetic field strength

a) For a global standing kink mode,

$$C_k = \frac{2L}{P}, \quad \text{and } C_k = V_A \left(\frac{2}{1 + n_e / n_i} \right)^{1/2}$$

Robert, Edwin & Benz, (1984)

$$B = 18 \left(\frac{L}{100 \text{ Mm}} \right) \left(\frac{P}{300 \ s} \right)^{-1} \sqrt{\frac{n_{\text{loop}}}{10^9 \text{ cm}^{-3}}} \ [G] \ .$$

For loop length: 2L=200 Mm,
osci. period: P = 5 min,
loop density n_{loop}=10^9 cm,
in 26 coronal loops

Obtain: mean: B = 18 G
range: B = 3 – 30 G

Aschwanden et al . (2002): B = 3 – 30 G for 26 cases

Nakariakov & Ofman (2001): B = 4 – 30 G for 2 cases

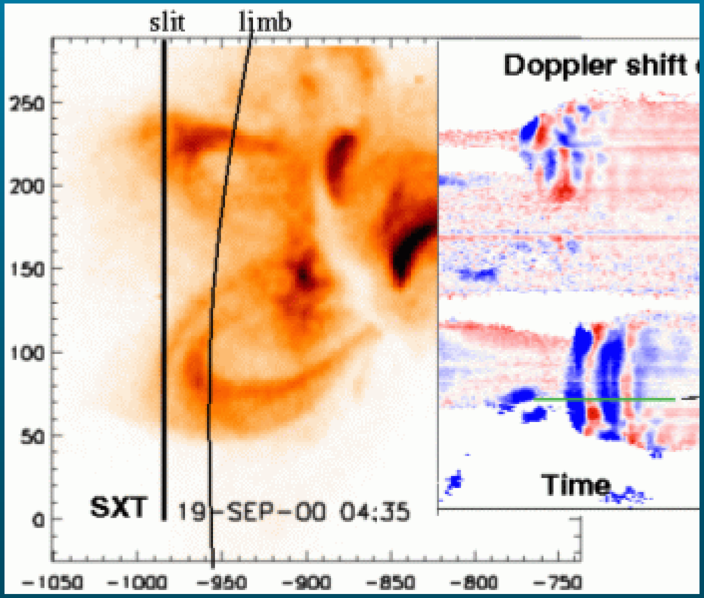
5) Measurements of coronal magnetic field strength

b) For a global standing slow mode,

$$P = \frac{2L}{c_t}, \text{ and } c_t = \left(\frac{1}{c_s^2} + \frac{1}{v_A^2} \right)^{-1/2} \longrightarrow V_A \text{ and } \mathbf{B}$$

$$c_s = \left(\frac{\gamma k_B T}{\mu m_p} \right)^{1/2} = 1.52 \times 10^4 T^{1/2}$$

$$V_A = \frac{B}{\sqrt{\mu \rho}} = 2.18 \times 10^{11} B n_e^{-1/2}.$$



For P=17 min and L=200 Mm, obtain C_t=390 km/s.

Al12/Be119 filter ratio shows T≈8 MK, and $n_e \approx 4\times10^9$ cm^{-3}, giving

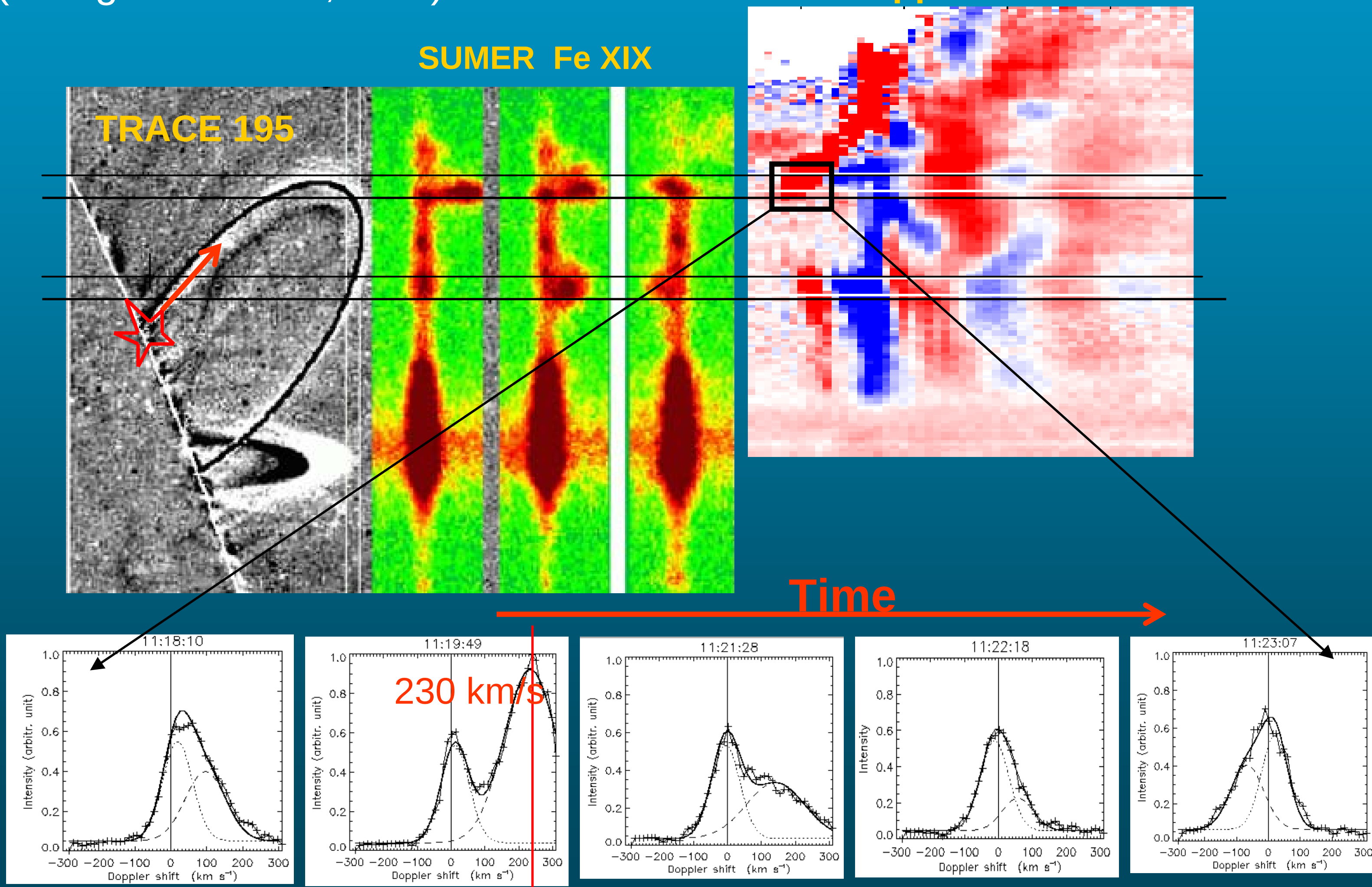
C_s=430 km/s, V_A=926 km/s

$\Rightarrow$ **B = 27 Gauss**

6) Initiation of oscillations: Spectral feature

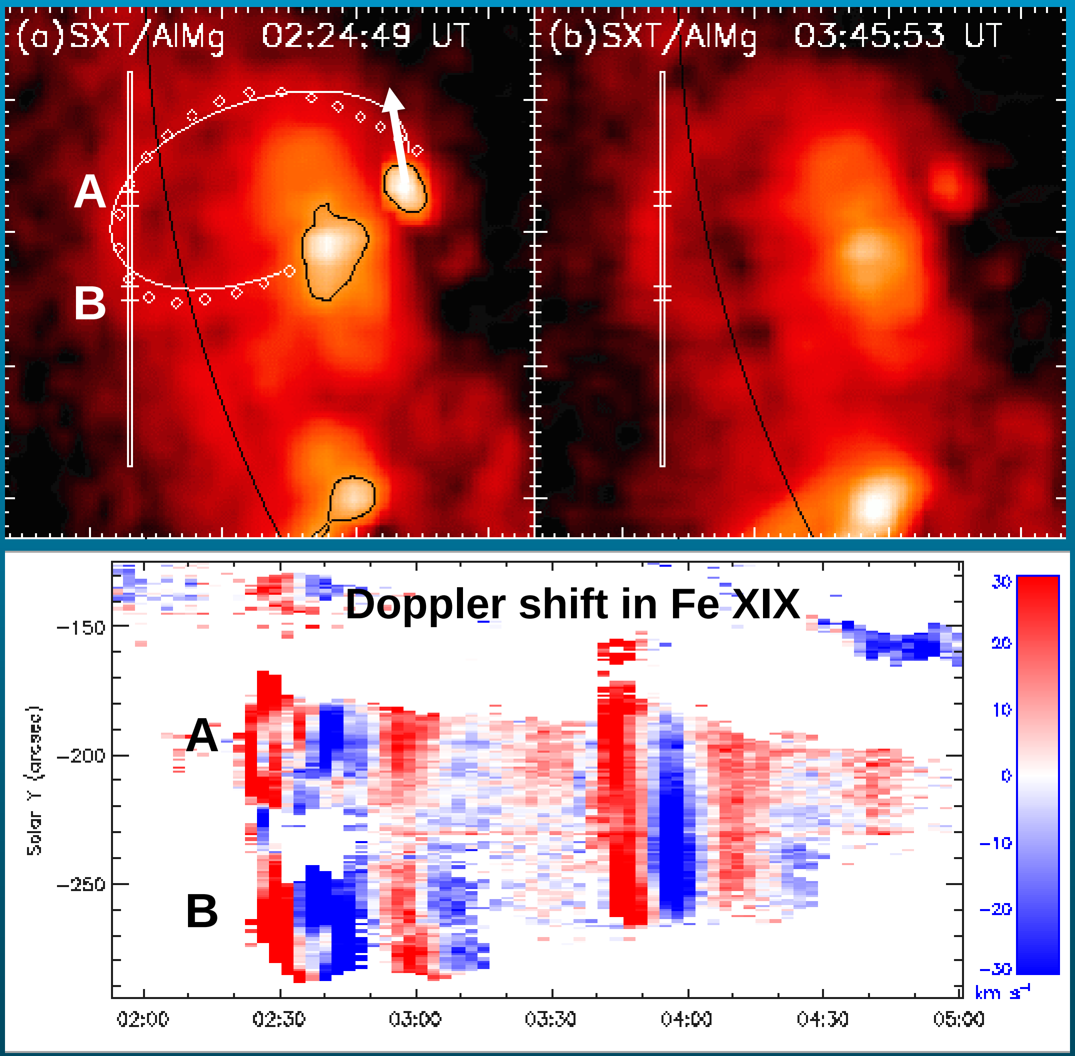
26 out of 54 cases show the presence of two spectral components. The shifted components on the order of 100–300 km/s, suggesting that the oscillations are likely triggered by a pulse of hot plasma injection

(Wang et al. 2005, A&A)



7) Trigger of hot loop oscillations by small or micro- flares

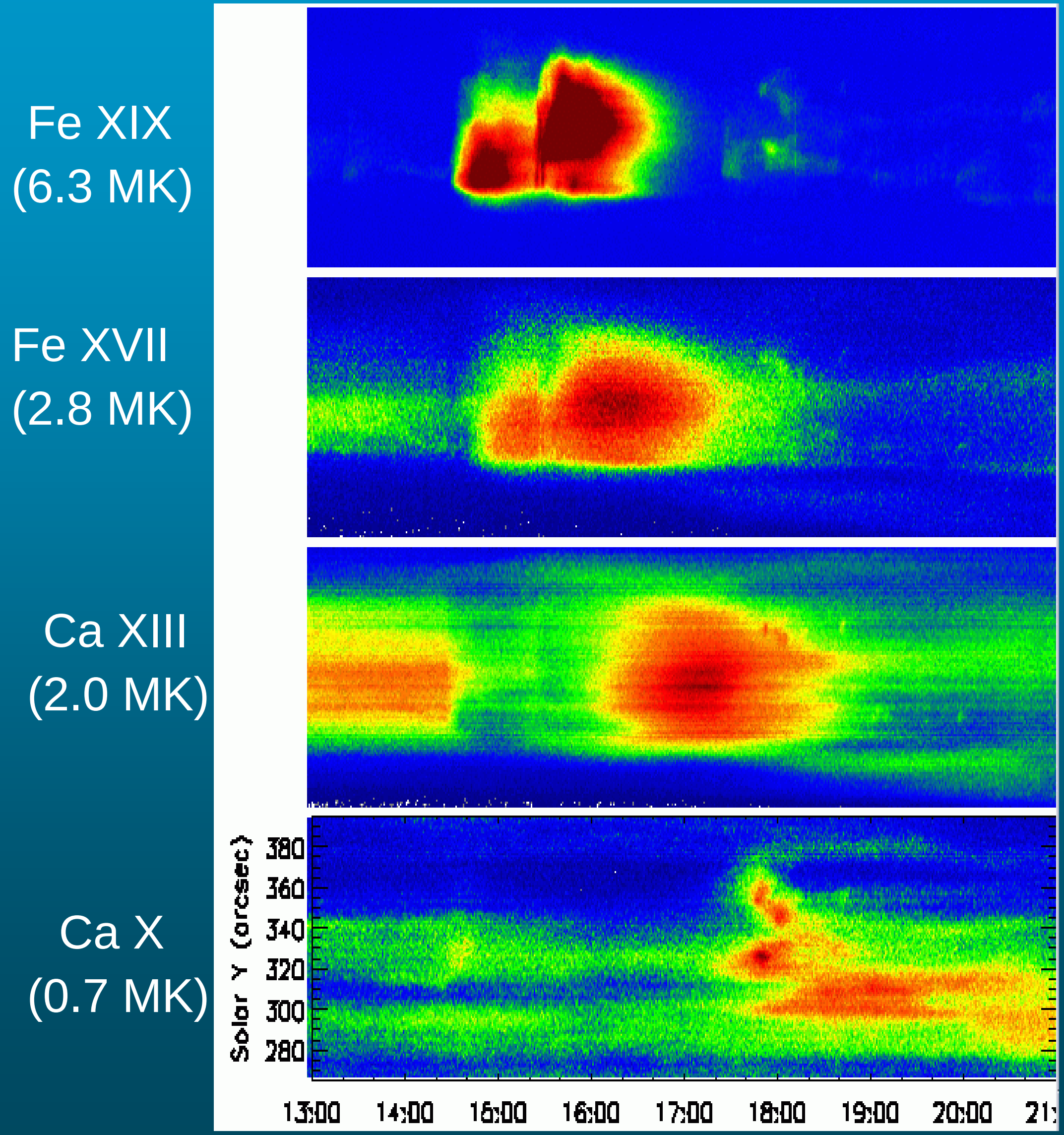
- Case on 2000 September 29 (Wang et al. 2003b, A&A)



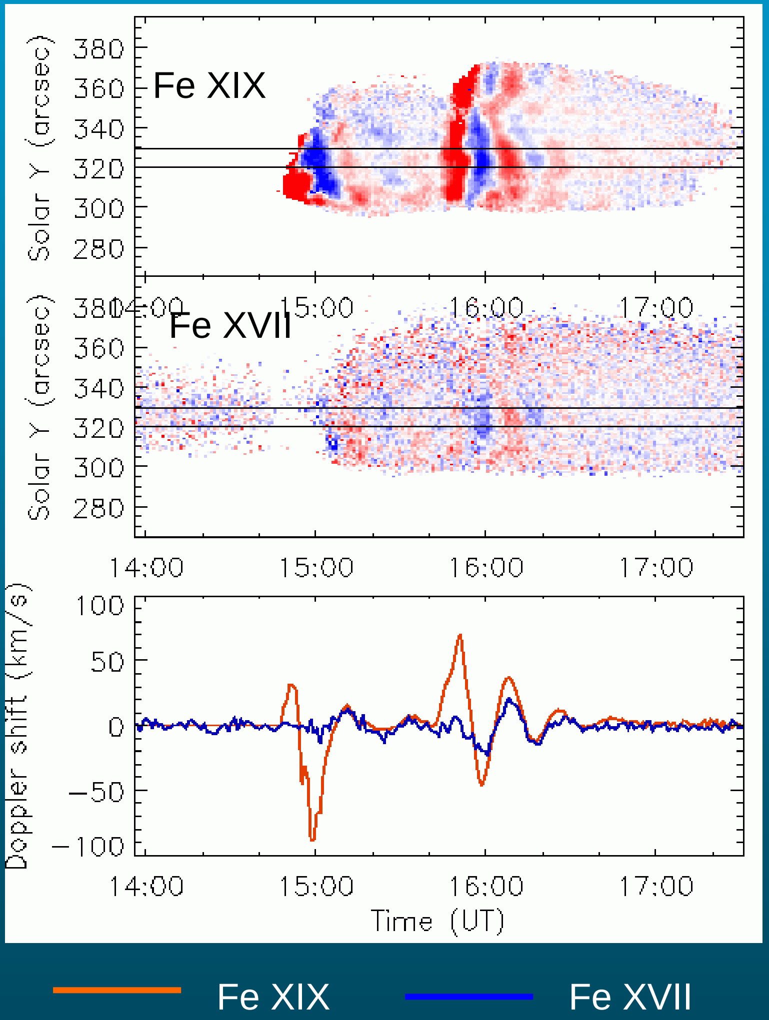
Initiations of two recurring events are associated with a footpoint brightening

8) Cooling of hot oscillating loops

Intensity



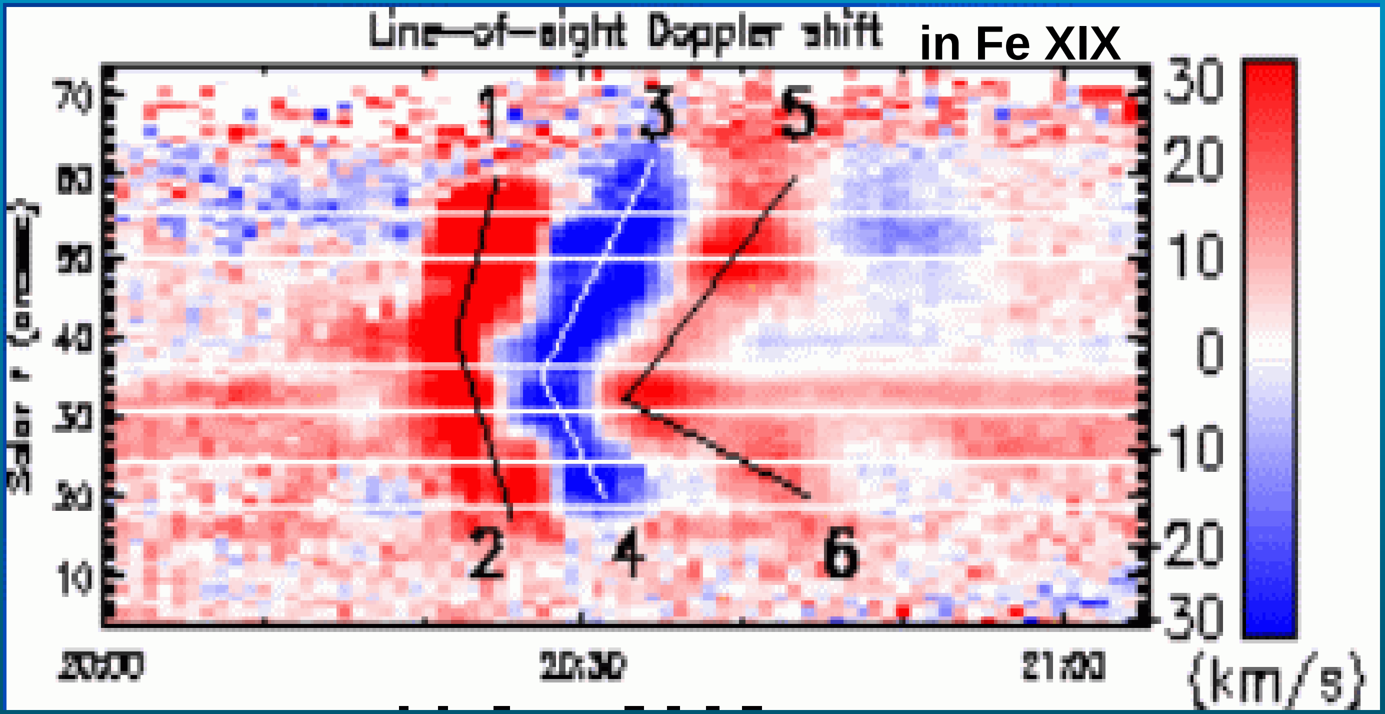
Doppler shift



9) Propagating feature

Case on 11 Apr 2002 (Wang et al. 2003b, A&A)

Along the slit



Time (obseving cadence = 50 s)

Propagating speeds: V = 10 – 100 km/s

10) Main properties of SUMER oscillations

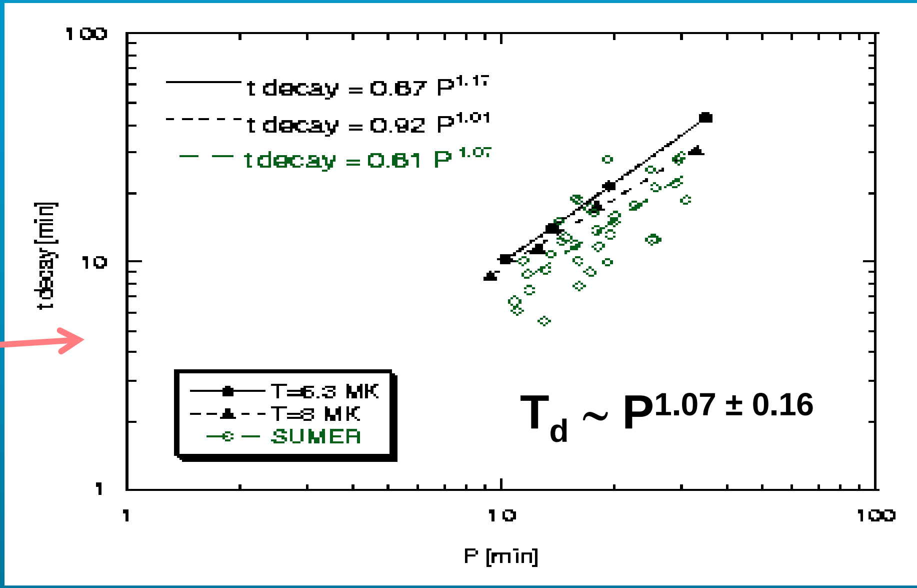
1. Standing waves are set up quickly about a half period after the onset of events.
2. These oscillations are the fundamental mode; No evidence for the 2nd harmonics are found yet.
3. Initial loop temperature is above 2–3 MK, then impulsively heated to a temperature of 6–8 MK.
4. The duration of flarelike brightenings is several times the oscillaion period.
5. Except for strong initial injected flows lasting for about half a wave period, no background flow is present.

11) Wave damping mechanism

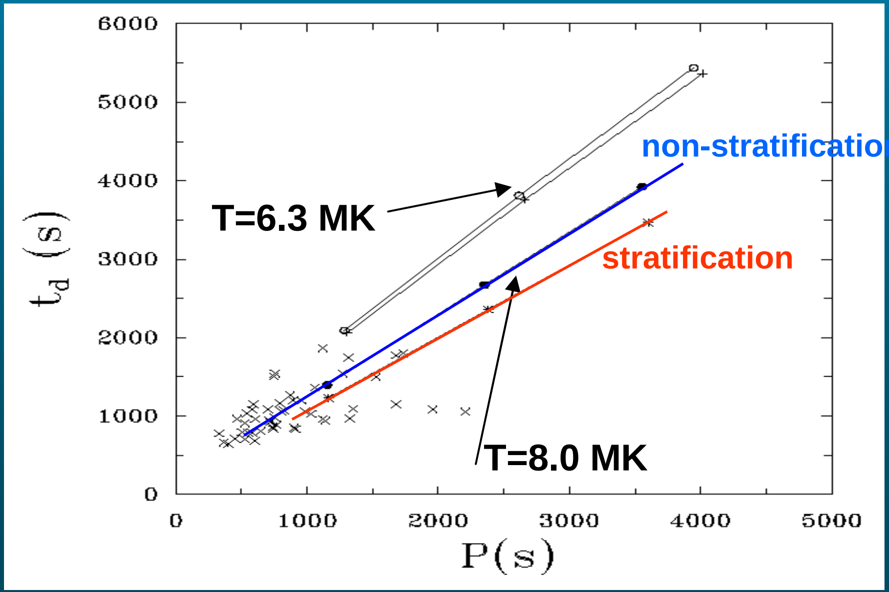
- Slow-mode standing oscillations

Thermal conduction

(Ofman & Wang 2002, ApJL)
(De Moortel & Hood 2003, A&A)



Gravitational stratification
(Mendoza et al. 2003, ApJ)
cause 10–20% reduction of T_d



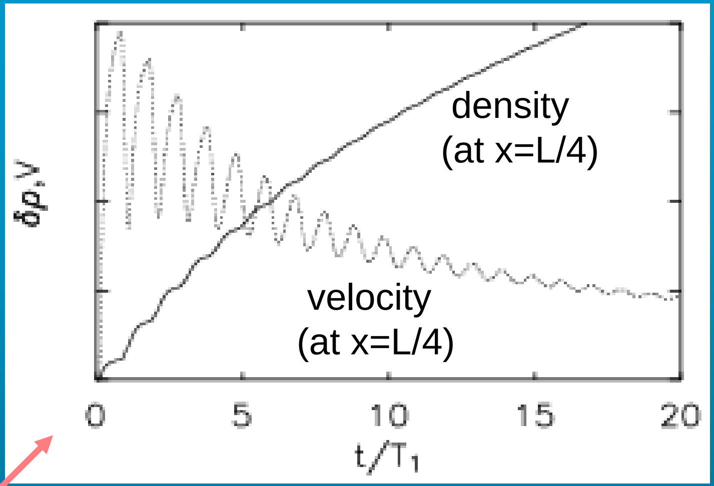
Pressure scale height H=300–400 Mm at T=6–8 MK

>> the height of typical coronal loops (with length L=200 Mm)

12) Excitation of slow-mode stanidng waves

1) The second standing harmonics

of flaring loops (T=30-40 MK) are excited by impulsive energy deposit in the loop apex.
(Nakariakov et al. 2004, A&AL)



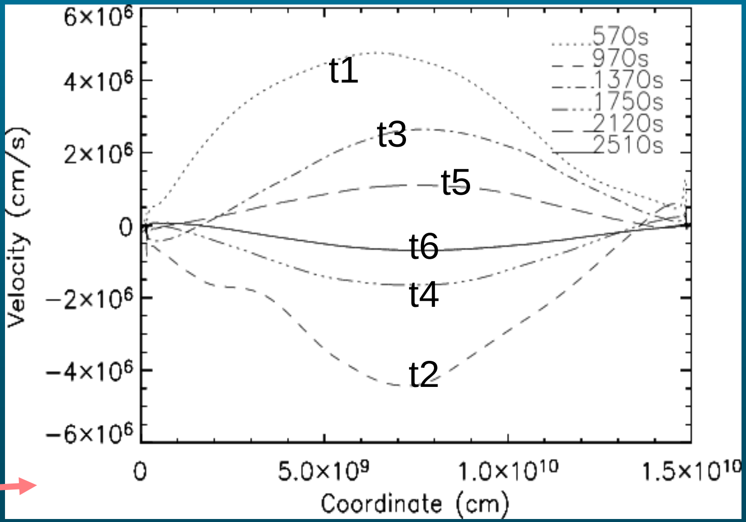
(A hot pulse at a single footpoint)

2) The fundamental mode or the 2nd harmonics

are excited depending on the location of the trigger (simulated as a hot pulse in density and pressure).
Wave excitation time: > 3 periods (parametric study)
(Selwa, Murawski, & Solanki 2005, A&A)

3) The fundamental mode oscillations

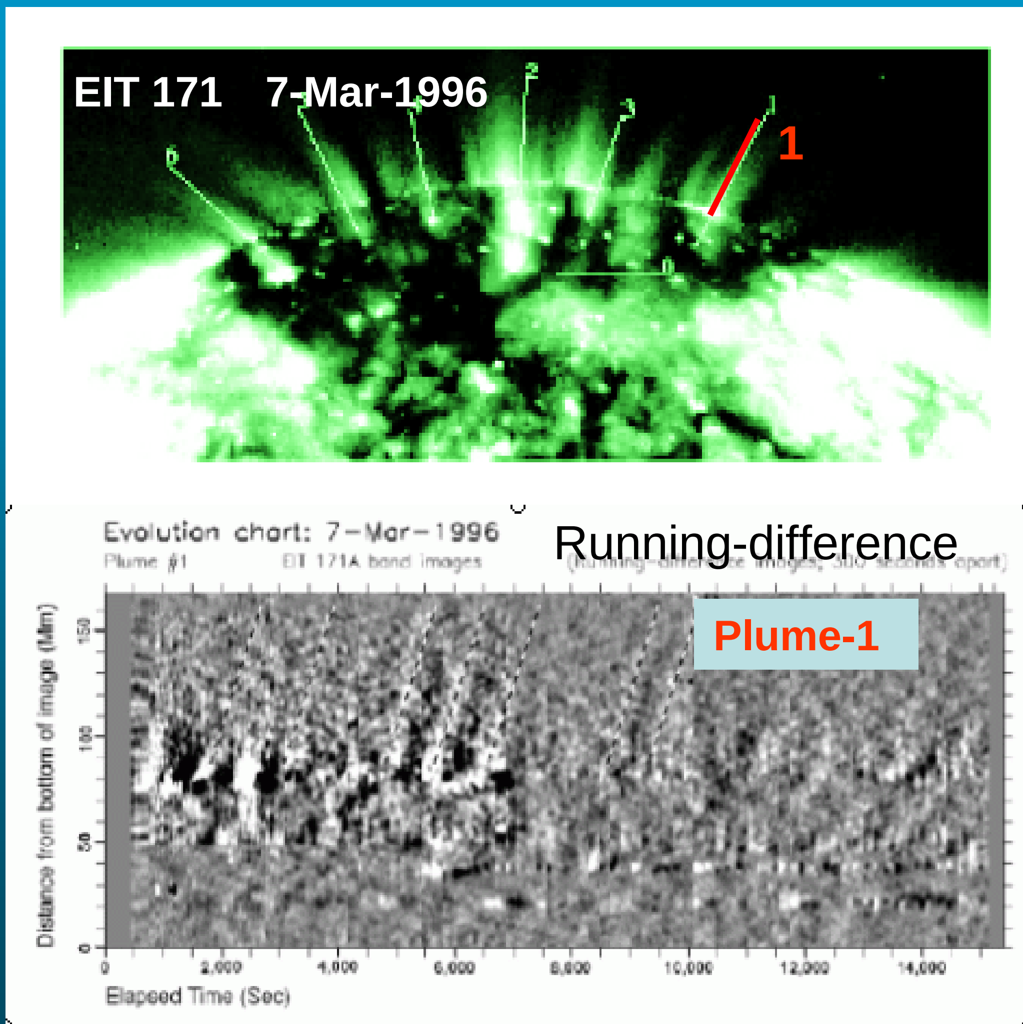
are set up immediately after an impulsive heat deposition at the footpoint of a loop if the duration of the pulse matches the fundamental mode period
(Taroyan et al. 2005, A&A)



(Pulse duration = wave period)

Quasi-periodic compressive waves

1) In solar ploar plumes seen by EIT



Along the plume

Time

DeForest & Gurman (1998, ApJL):

period: P = 10 – 15 min,

propagating speed:

V = 75 – 150 km/s

Quasi-periodic compressive waves

2) In coronal loops seen by EIT

(13 May 1998)

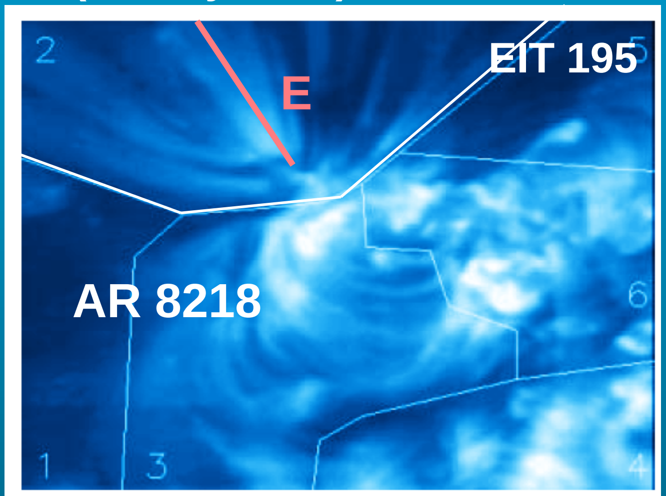


Figure 2. The whole-sequence average image showing the 6 subregions discussed in the text.

Berghmans & Clette (1999, Sol Phys.):

Time evolution of intensity along **Loop E**

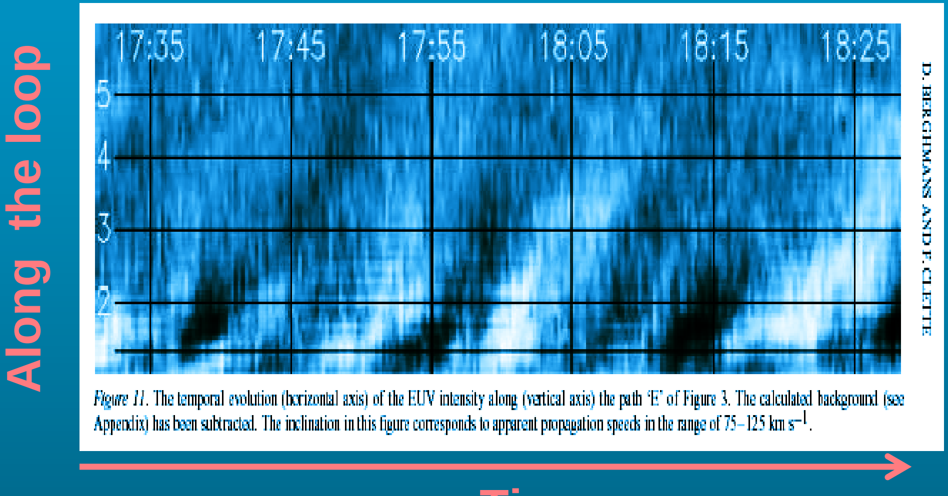
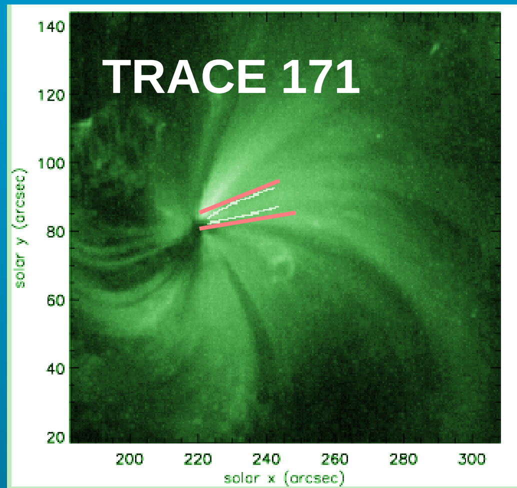


Figure 11. The temporal evolution (horizontal axis) of the EUV intensity along (vertical axis) the path 'E' of Figure 3. The calculated background (see Appendix) has been subtracted. The inclination in this figure corresponds to apparent propagation speeds in the range of 75–125 km s^{-1}.

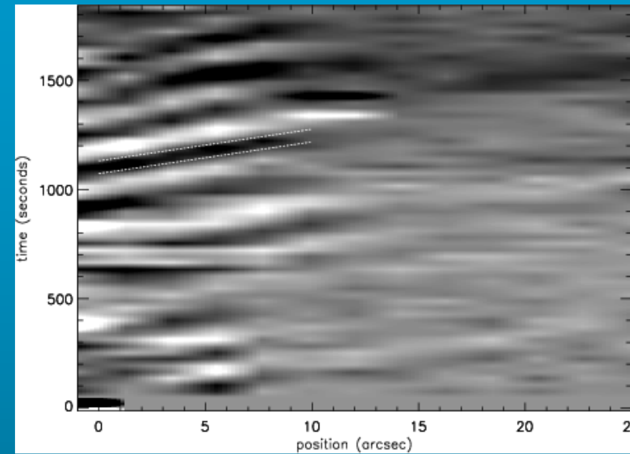
Propagating speed V=75 – 125 km/s

Period P=10 – 15 min

Quasi-periodic compressive waves
in coronal loops seen in EUV



Time



Along the loop

- For 38 examples, (De Moortel et al. 2002, A&AL):
  (1) 10 loops above Sunspots: P=2.9 ± 0.5 min (3-min umbral osci)
  (2) 25 loops above plage regions: P=5.4 ± 1.2 min (5-min p-modes)

- Physical parameters: (De Moortel et al. 2002a,b)
  V_p=122 ± 43 km/s, P=282 ± 93 s, amplitude I/I_0=4.1 ± 1.5%
  detected length of propagating disturbances d=8.9 ± 4.4 Mm

Damping of propagating slow magnetoacoustic waves

- Thermal conduction, enhanced compressive viscosity, and stratification (Nakariakov et al. 2000, De Moortel & Hood 2003)

- Effects of gravitational stratification and field line divergence on the damping scale along the loop (De Moortel et al. 2004, A&A)

- Coupling of slow and fast modes and "Phase mixing" of the slow waves due to the (horizontal) density inhomogeneity in 2D Model (De Moortel & Hood 2004, A&A; Voitenko et al. 2005, A&AL)

- Complex modelling by Klimchuk, Tanner & De Moortel (2004, ApJ) shows:

1) Dissipation, pressure and temperature stratification are the most important effects in the low corona.

2) To explain the observed damping, thermal conduction described by classic transport theory is sufficient, anomalous processes are not necessary.

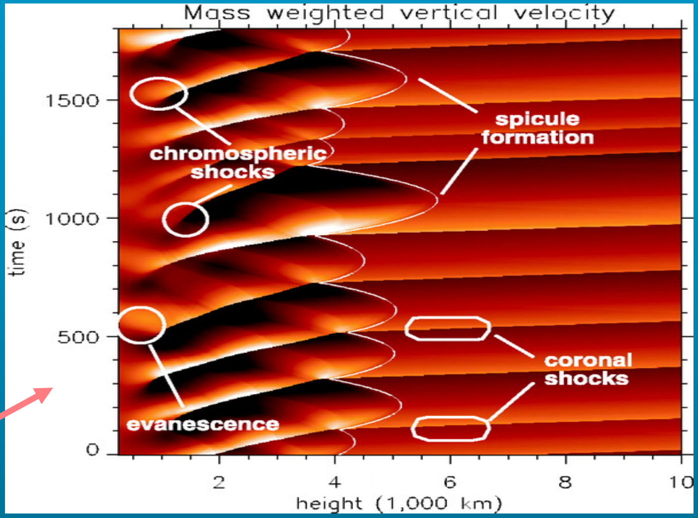
Excitation of propagating slow magnetoacoustic waves

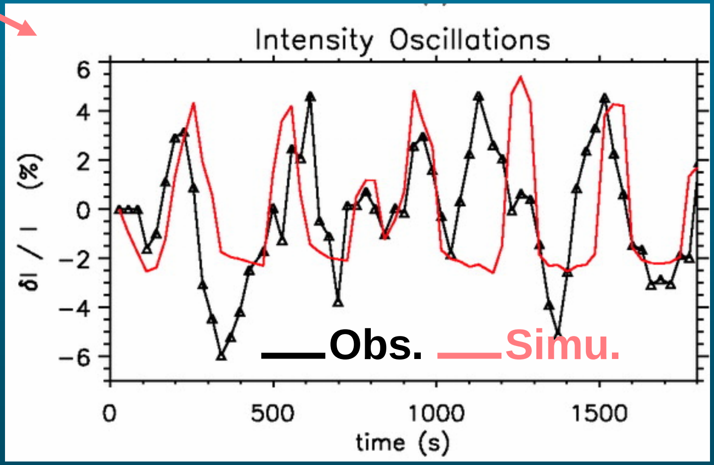
- Stable, long-term remaining**,** Not likely driven by flares (De Moortel et al. 2002a,b)

- Leakage of *p*-mode photospheric oscillations into the chromosphere and corona, due to the increase of the acoustic cut-off period in an inclined flux tube (De Pontieu et al. 2004, Nature)
(De Pontieu, Erdelyi, & De Moortel, 2005 ApJL)

The photospheric oscillations develop into shocks which drive chromospheric spicules and reach the corona, forming propagating magneto-acoustic waves observed by TRACE.

However, because the model does not include the thermal conduction, whether the damping scale of the propagating coronal shocks in consistent with the observations are not verified.





Simulated oscillations in a flux tube inclined by 35° from the vertical, driven by 5-min photospheric oscill.

Summary

1. TRACE has discovered transverse (horizontal and vertical) loop oscillations, and interpreted as a global kink mode. The exciter could be the flare shock.

2. SUMER has discovered slow-mode standing waves in hot (T>6MK) coronal loops. The trigger could be small flare-like events at a single footpoint.

3. EIT and TRACE have found propagating intensity oscillations in fan-like coronal loops, and interpreted as the propagating slow magneto-acoustic waves. The trigger may be the leakage of p-mode photospheric oscillations.

4. The observed kink and slow mode standing oscillations can be used as a new diagnostic tool for determining the mean magnetic field strength in coronal loops.

5. These oscillations are all strongly damped. The kink modes are most likely damped by phase mixing and resonant absorption, and the slow mode oscillations and waves are mainly damped by thermal conduction.

Outlook

Solar-B and **Solar Orbit:**

Detections of high-frequency fast mode (kink and sausage) and torsional Alfven waves and oscillations in coronal loops, which are believed to be important for coronal heating.