Growing Transverse Oscillations of a Multistranded Loop Observed by SDO/AIA

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Outline

1. Introduction

   a) Basic theory of MHD waves in magnetic flux tube

   b) Brief overview of studies of transverse loop oscillations

2. Analysis of amplitude-growing transverse loop oscillation by SDO/AIA

3. Discussion and Conclusions

Introduction

- **Motivation**

  - MHD waves $\Rightarrow$ possible source for coronal heating and solar wind acceleration

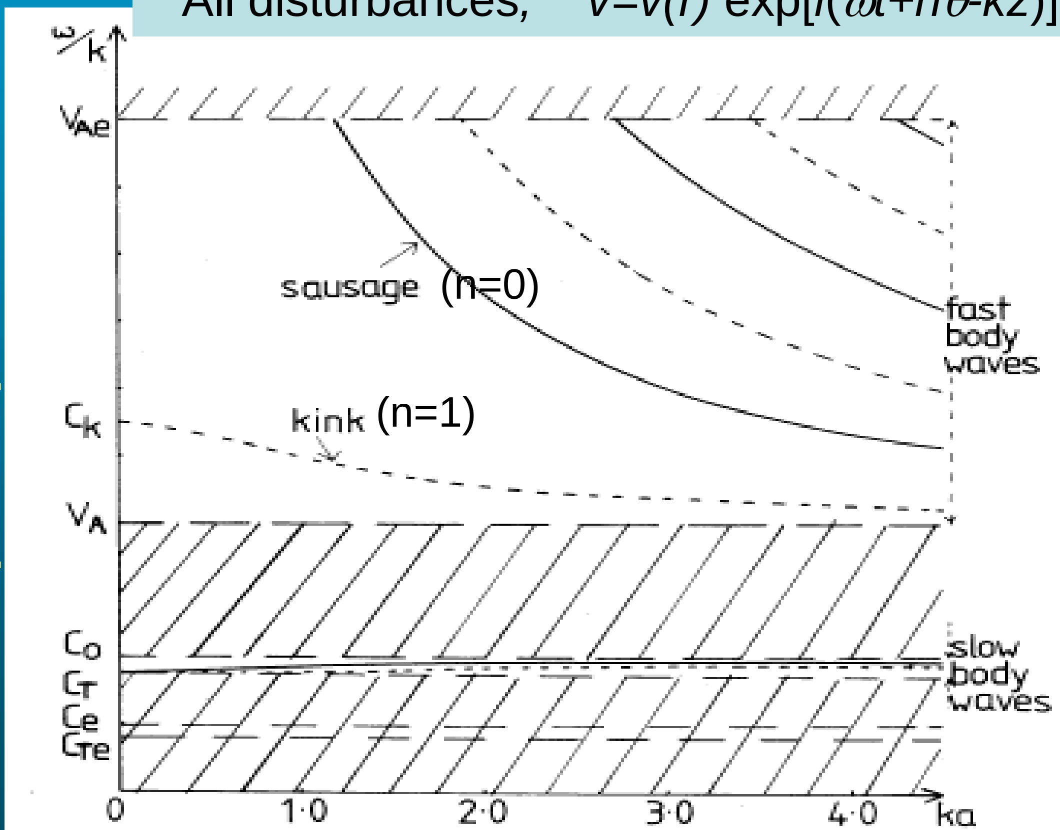
- Understand physical processes of excitation and damping mechanisms of various oscillation modes in coronal structures

- Develop coronal seismology $\Rightarrow$ diagnostic tool for determining physical parameters of coronal structure (Roberts, Edwin & Benz 1984; Roberts 2000)

MHD oscillations and waves in coronal loops

- In a straight magnetic cylinder
  (Edwin & Roberts 1983; Robert et al. 1984)

All disturbances, $v=v(r)\exp[i(\omega t+n\theta-kz)]$



phase speed

longitudinal wavenumber

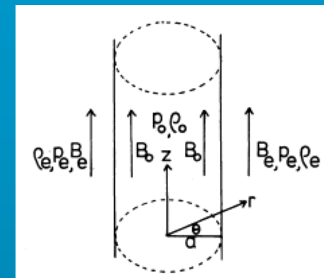


FIG. 1a

Loop length= *L*, radius = *a*

Periods for standing modes

P=2π/ω

$$P_{slow} = \frac{2L}{jc_T} \approx \frac{2L}{jc_0}$$

$$P_{kink} = \frac{2L}{jc_k} \approx \frac{2L}{jV_A}\left(\frac{1+\rho_e/\rho_0}{2}\right)^{1/2}$$

$$P_{sausage} \le \frac{2\pi}{k_c V_{Ae}} \approx \frac{2.6a}{V_A}\left(1-\frac{\rho_e}{\rho_0}\right)^{1/2}$$

- **Expected oscillation periods**

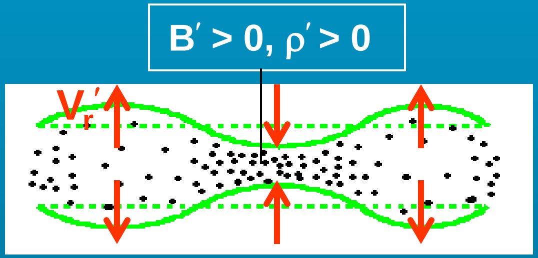
Slow modes: P = 7 –70 min
Kink modes: P = 1.4 – 14 min
Sausage modes: P = 0.1 – 5 s

(Aschwanden 2003)

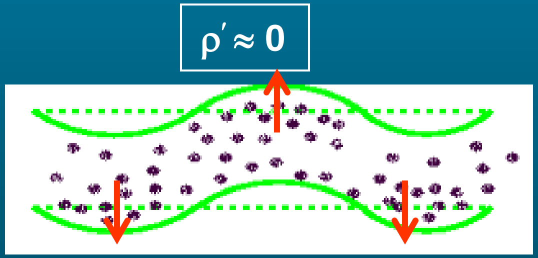
Sketches of oscillation modes

1) Fast modes:

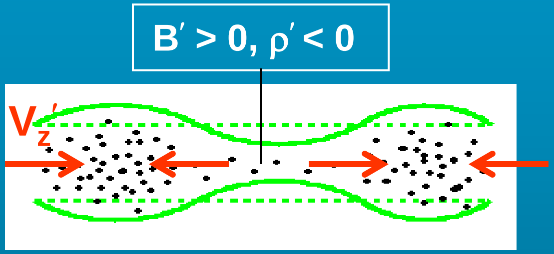
(a) sausage (symmetric)



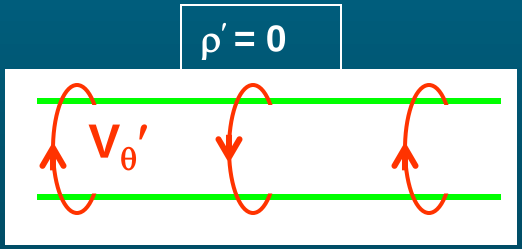
(b) kink (asymmetric)



2) Slow (sausage) modes:



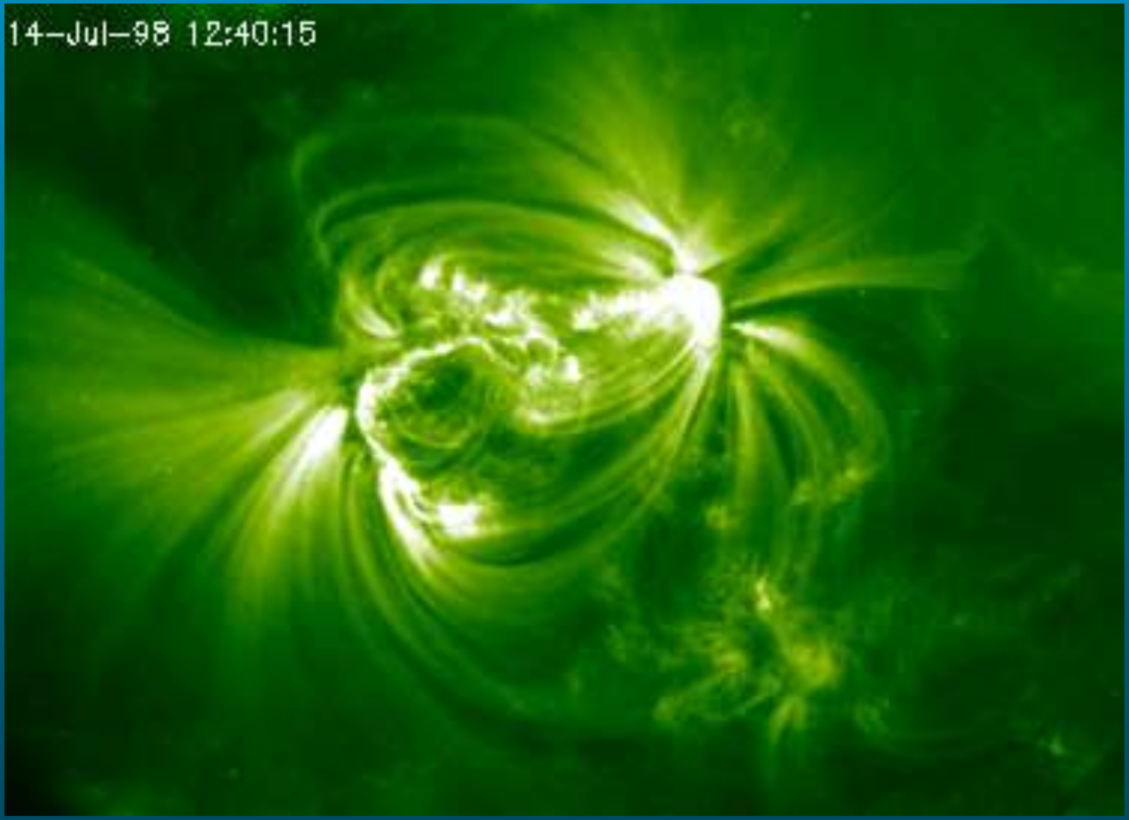
3) Torsional Alfven modes:



Transverse loop oscillations observed by TRACE

- Triggered by flares or CME eruptions

(Aschwanden et al. 1999; 2002)



Movie in 171 A

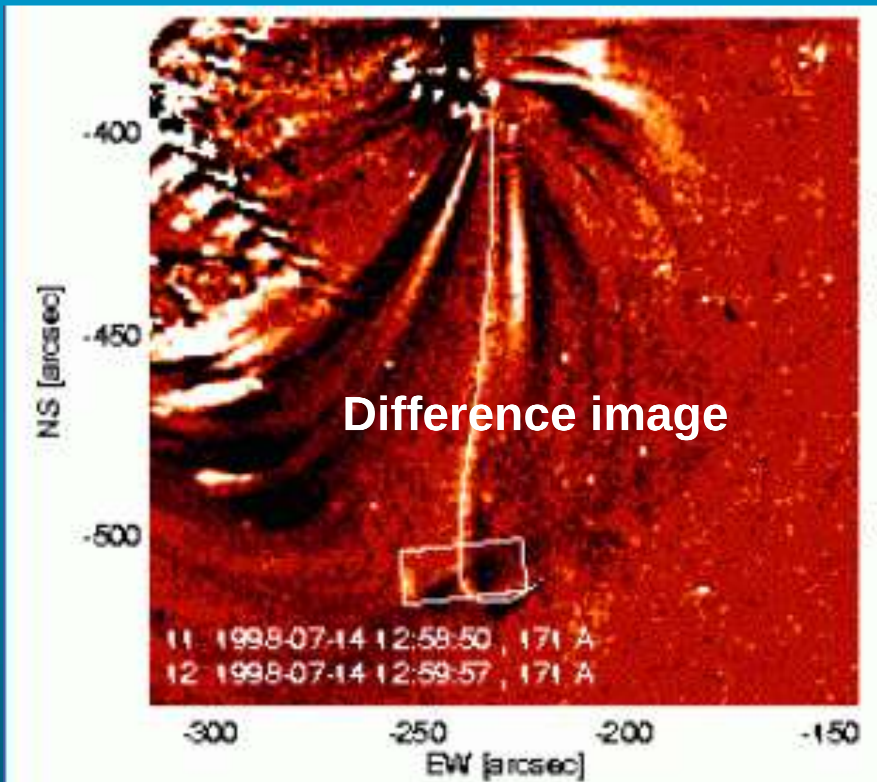
- excited by a flare disturbance
- Period: 5 - 6 min

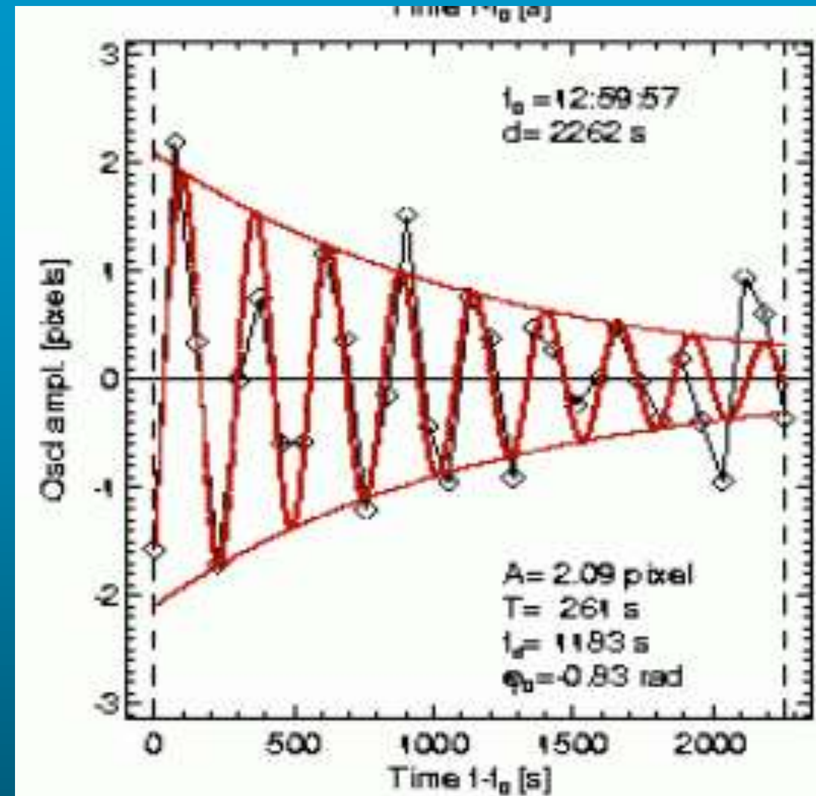
  Loop length: 160 - 200 Mm
- Phase speed:

  $V_p = 2L/P = 1300$ km/s
- Interpretation:

  Standing fast kink mode oscillations in fundamental mode

Measurement of the physical properties





(Aschwanden et al. 2002, Sol. Phys.)

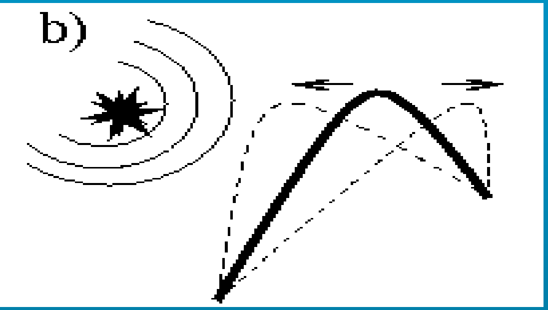
- Typically with a rapid decay within several periods
- Some oscillations are undamped (Ashwanden & Schrijver 2011)

Excitation of kink modes

- **Observation**

  - Flare-generated disturbance -- a blast wave, or a EIT wave (fast-mode wave) propagate in the corona and produce kink oscillations of nearby loops

  - Triggered by filament eruptions or CMEs



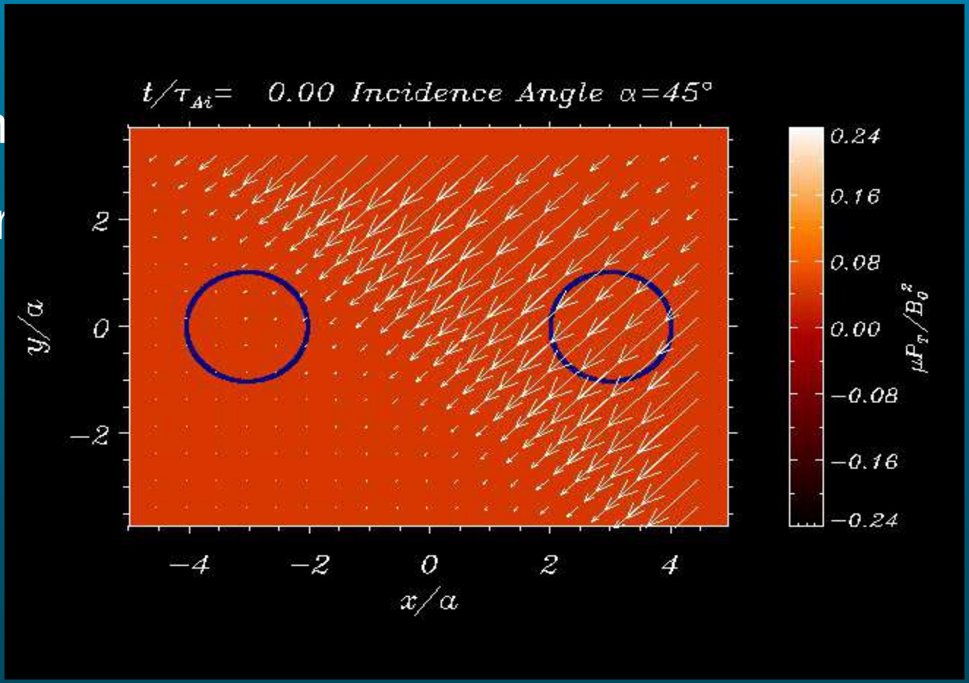
- **Theory and modeling**

  - Slab or cylinder configuration

  - Normal modes or Time-depen

  - Energy deposit by initial distur

  - Single or multi-stranded loop



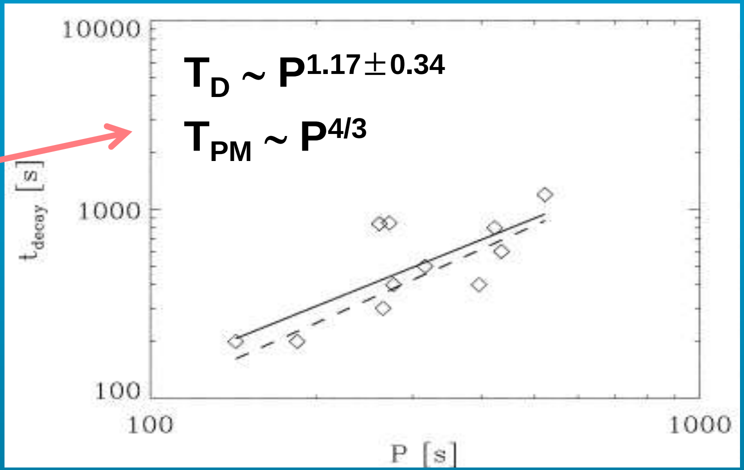
Luna et al (2008)

blast wave

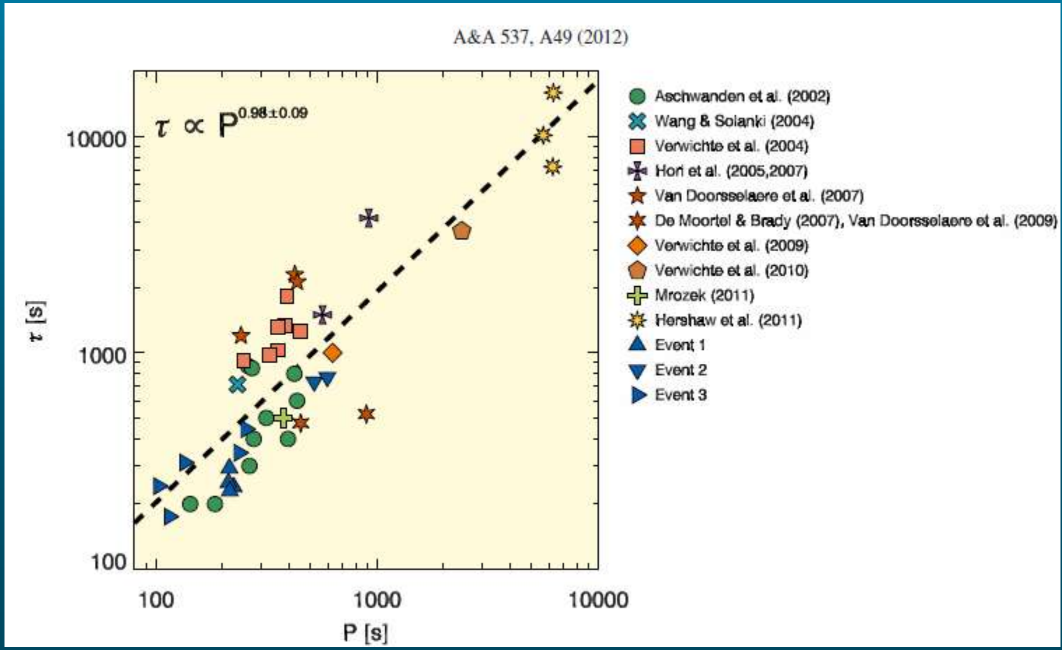
Damping mechanism of kink waves

- Phase mixing

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



(assuming the inhomogeneity scale, *l ~ w or l ~ L)*



Td ~ P $^{0.98\pm0.09}$

For more than 40 cases (White and Verwichte (2012)

Damping mechanism of kink waves

- Wave leakage

-**Footpoint leakage very small**

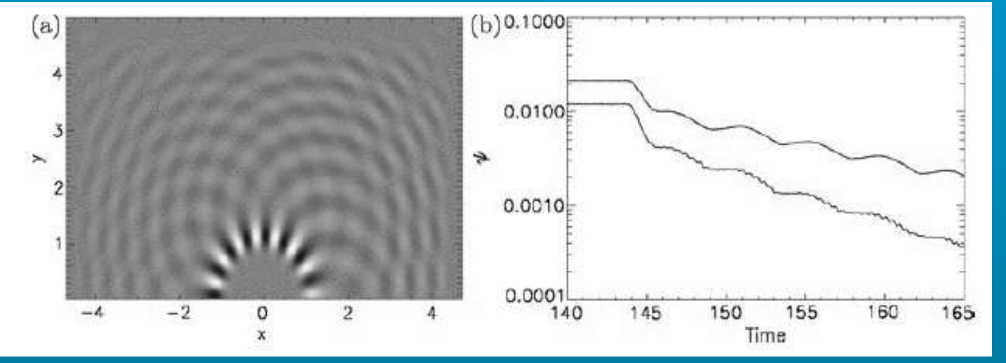
(Ofman 2002)

- **Lateral leakage by tunneling effect**

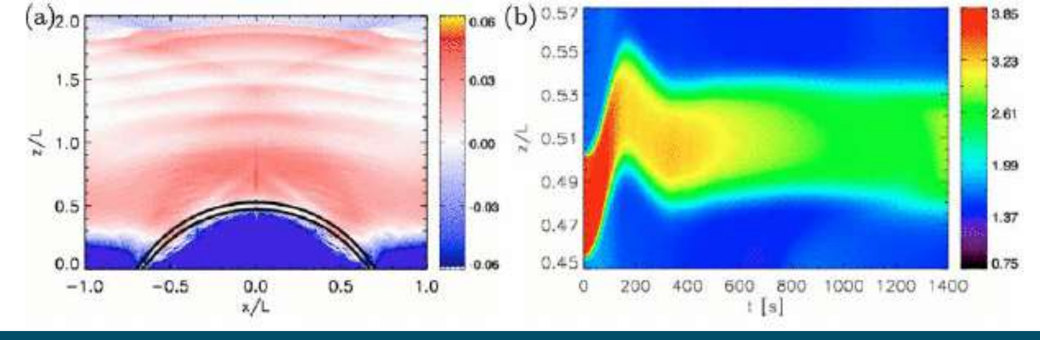
(Brady & Arber 2005, A&A) 2D MHD

(Verwichte et al. 2006)

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

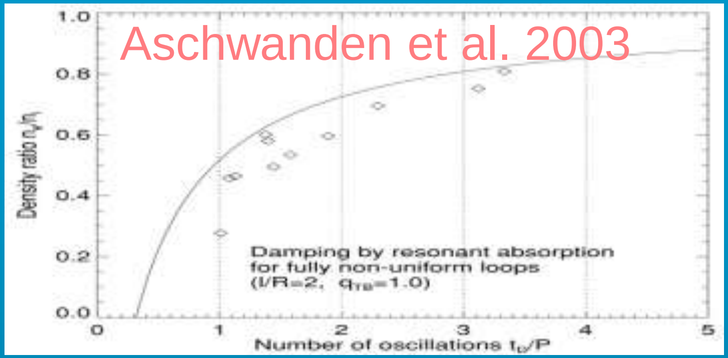


Brady & Arber 2005



Selwa et al 2007

Damping mechanism of kink waves



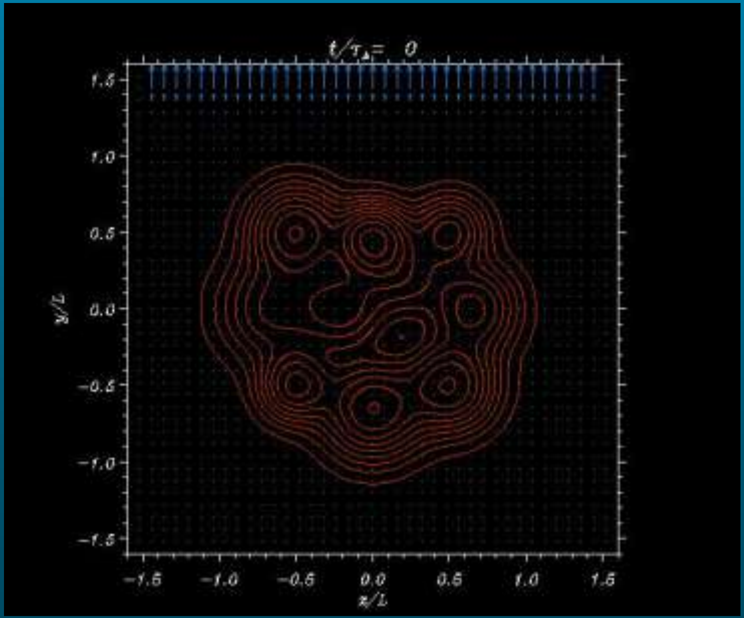
- Resonant Absorption

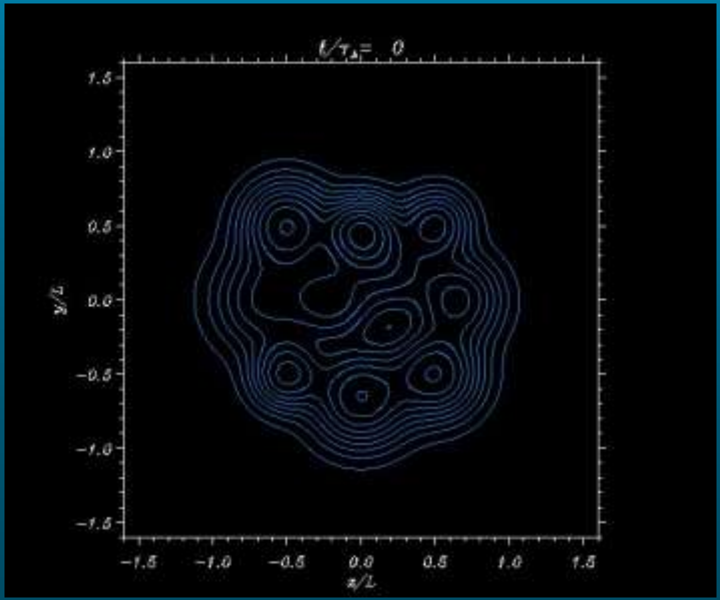
Conversion of global modes into torsional Alfven mode in thin layer of a loop

(Ruderman & Roberts, 2002, ApJ) Theory
(Goossens et al. 2002, A&AL) 1D MHD

(Van Doorsselaere et al. 2004, ApJ) 1D MHD

$$\left(\frac{\tau_D}{P}_{thin}\right) = q_{TB} \frac{2}{\pi} \left(\frac{r_{loop}}{l_{skin}}\right) \frac{(1+q_n)}{(1-q_n)} ,$$





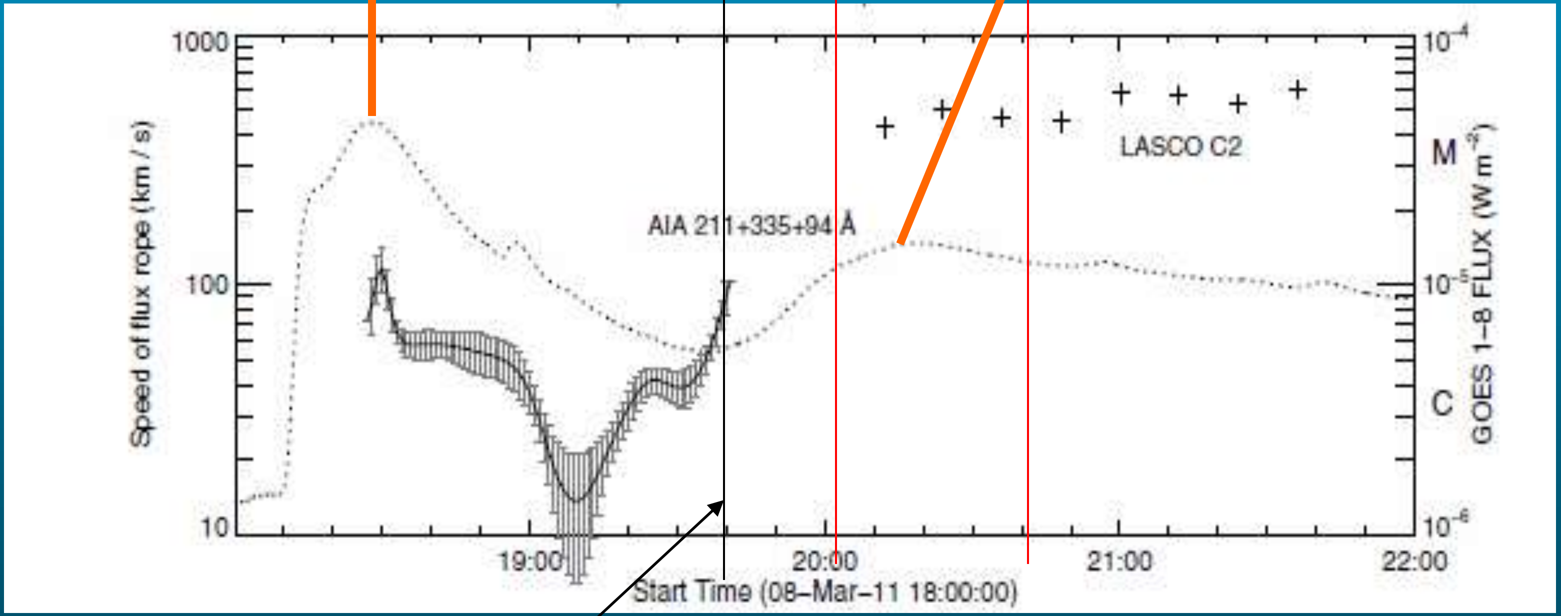
Velocity (Terradas et al. 2008) Energy density

2. Observations

- A two-stage flare-CME event on 2011 March 8

using SDO/AIA, STEREO/EUVI-A, and RHESSI by Su et al. (2012)

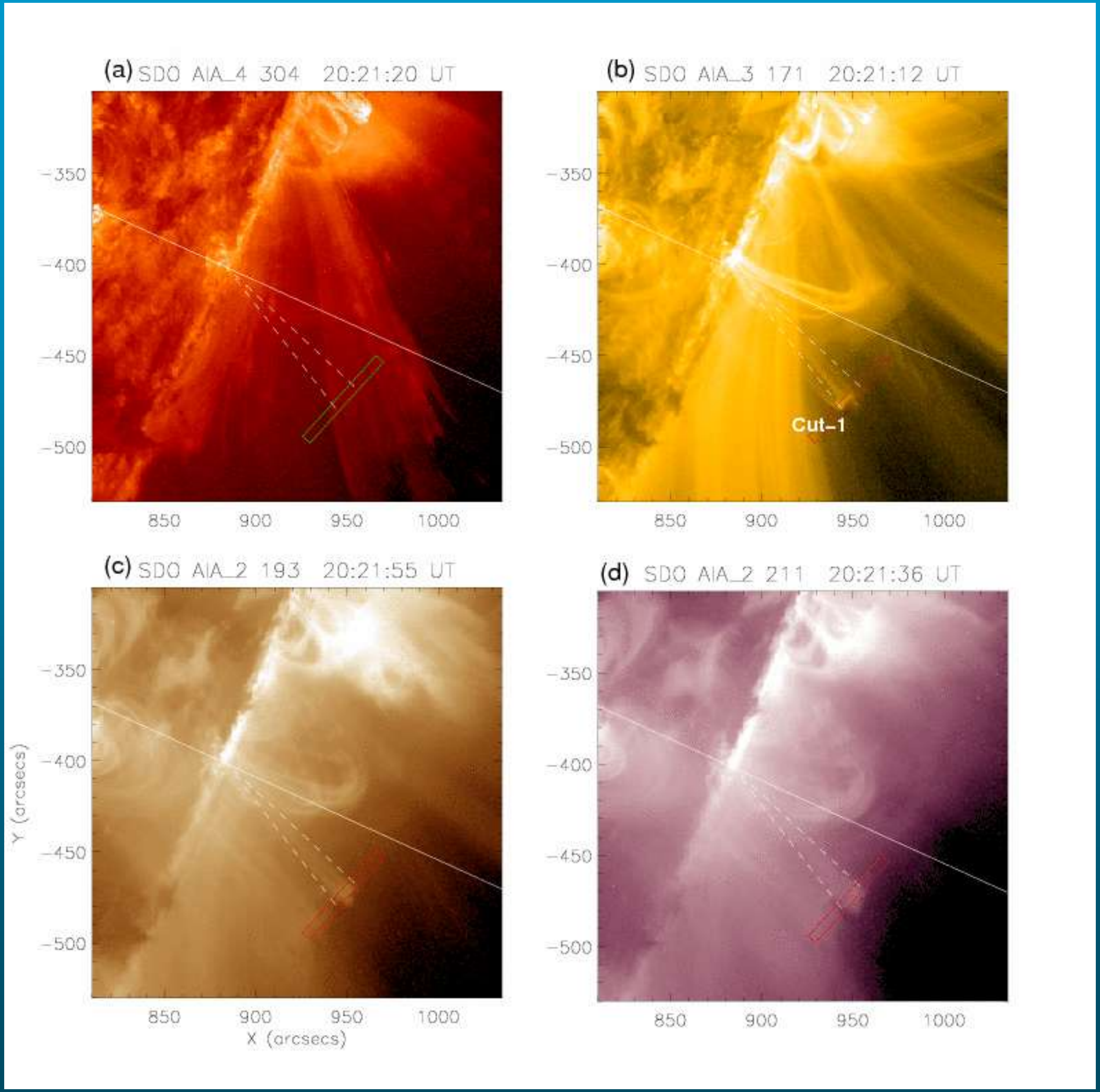
I: Forming a flux rope   II: Flux rope eruption (CME)



Start time of oscillation

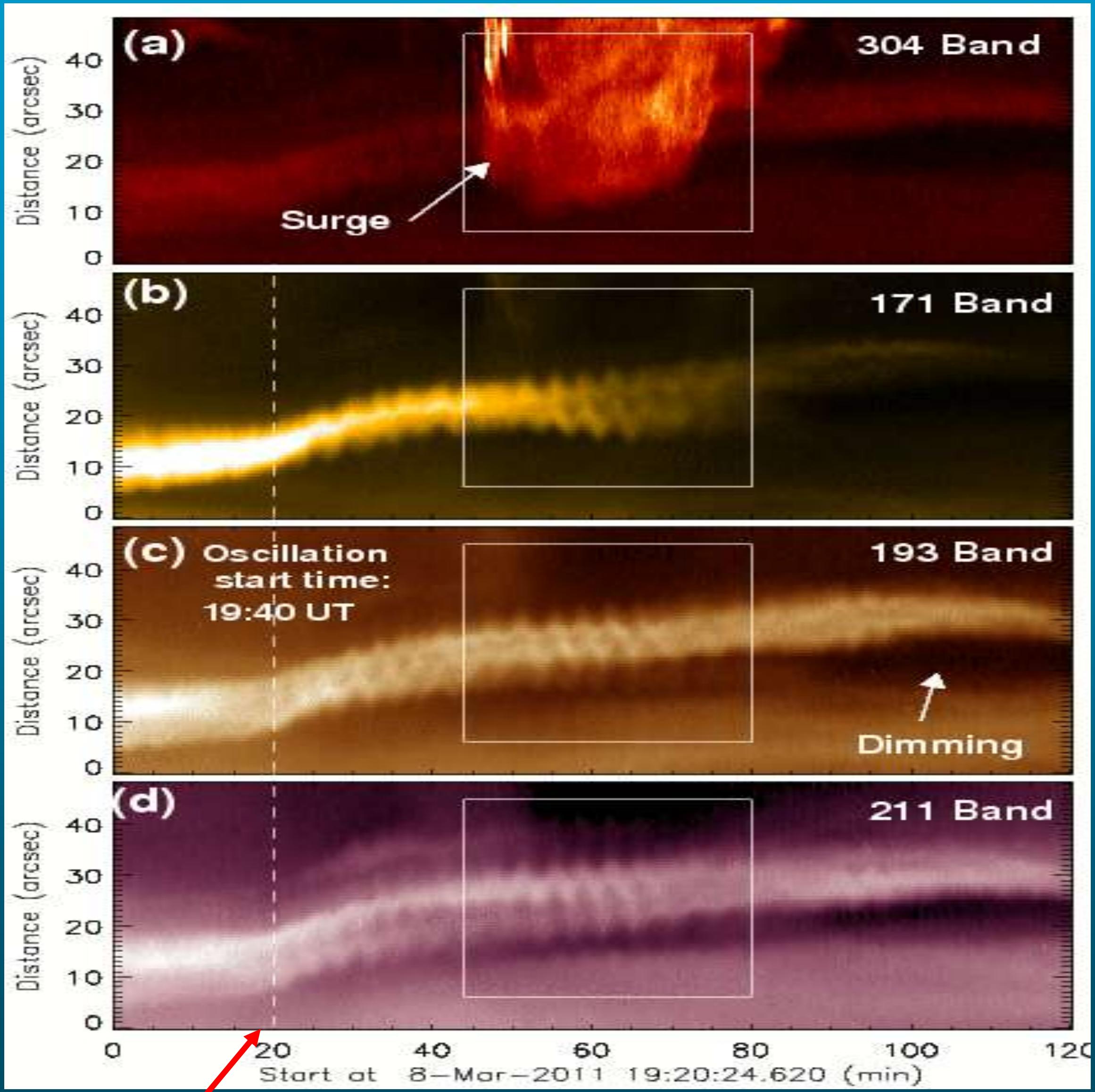
Oscillation event of interest from 20:00 – 20:40

3. Analysis of transverse loop oscillations



- Dashed lines outline the oscillating loop seen in 211 A band
- A cut at loop apex used for time stacking plot to measure transverse oscillations
- Oscillation apparently associated with a surge/jet event, but actually not as shown by STEREO-A

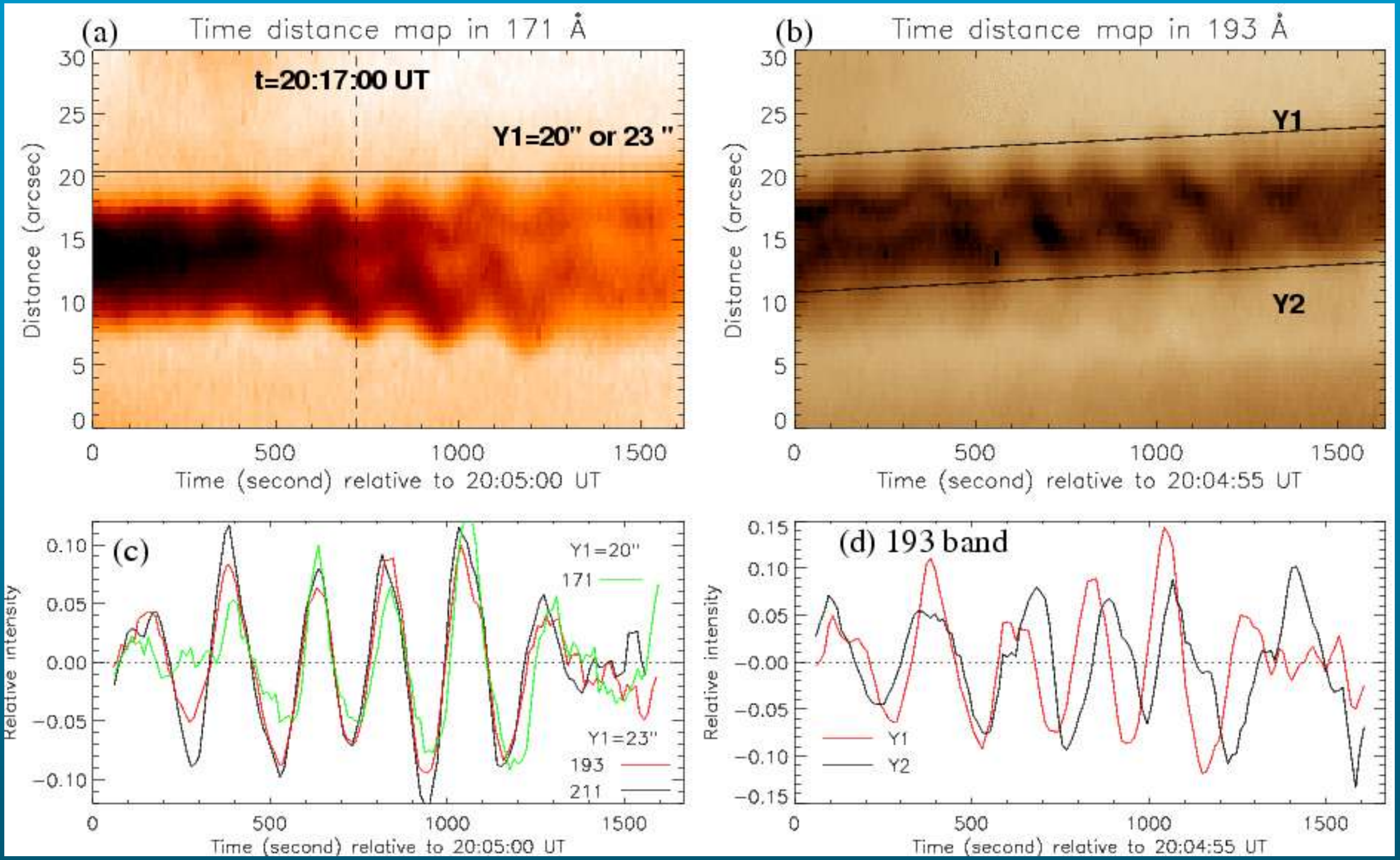
3. Analysis of transverse loop oscillations



Erupting time of a flux rope

- Loop consists of temperature-dependent multiple strands showing different dynamic behaviors
- Lower part of loop disappeared associated with dimming in all bands – erupted
- Upper part dimmed in 171 and remain in 193 and 211 - heating

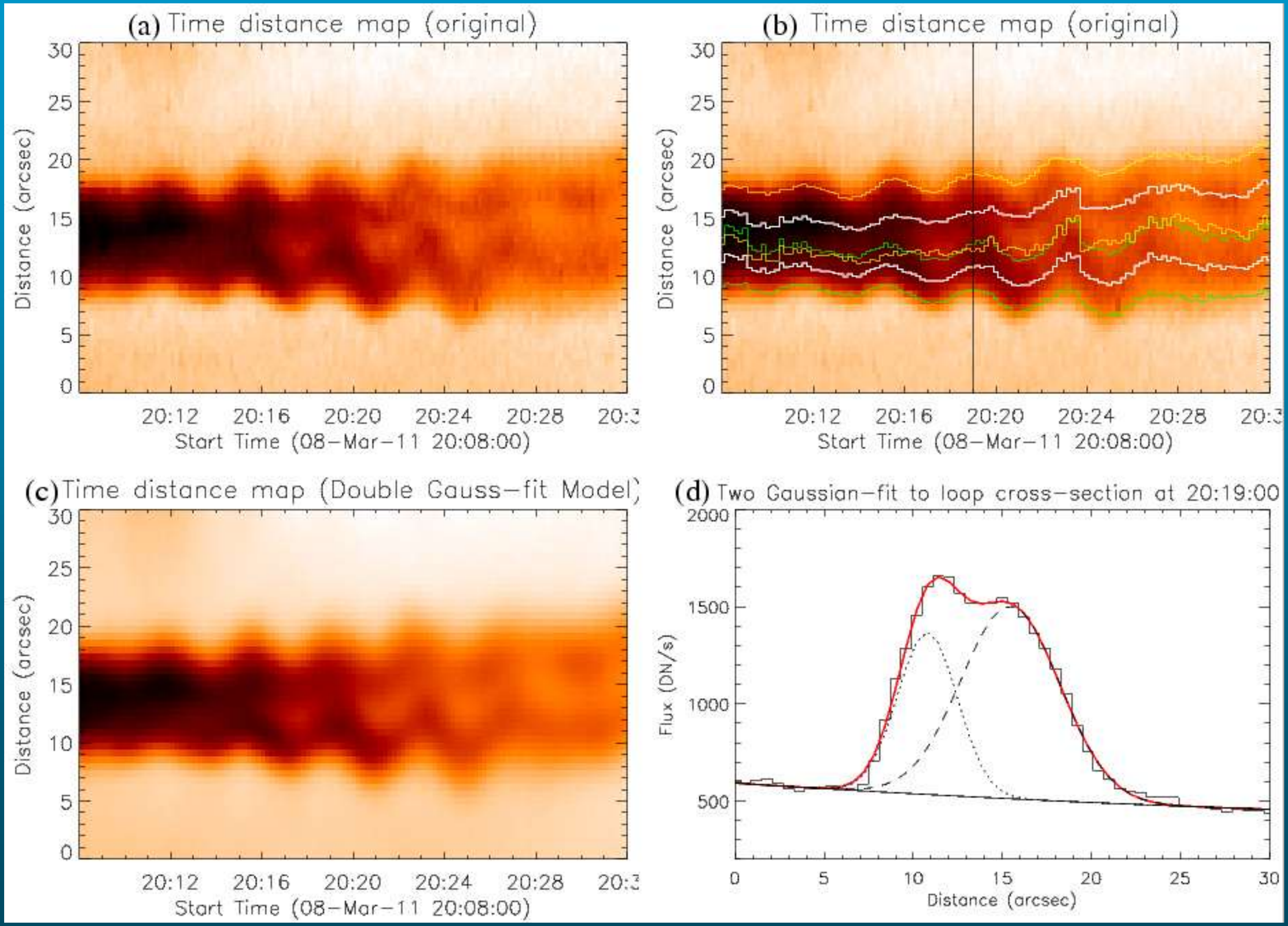
3. Analysis of transverse loop oscillations
phase relationship of different strands



- Two strands in 171 show inphase oscillations with growing amplitudes
- Upper strands in 171 and 193 not co-spatial, they are inphase
- Two strands in 193 oscillate in phase for ~2 periods, then a P/4 phase delay set up with periods decreased by ~ 20%

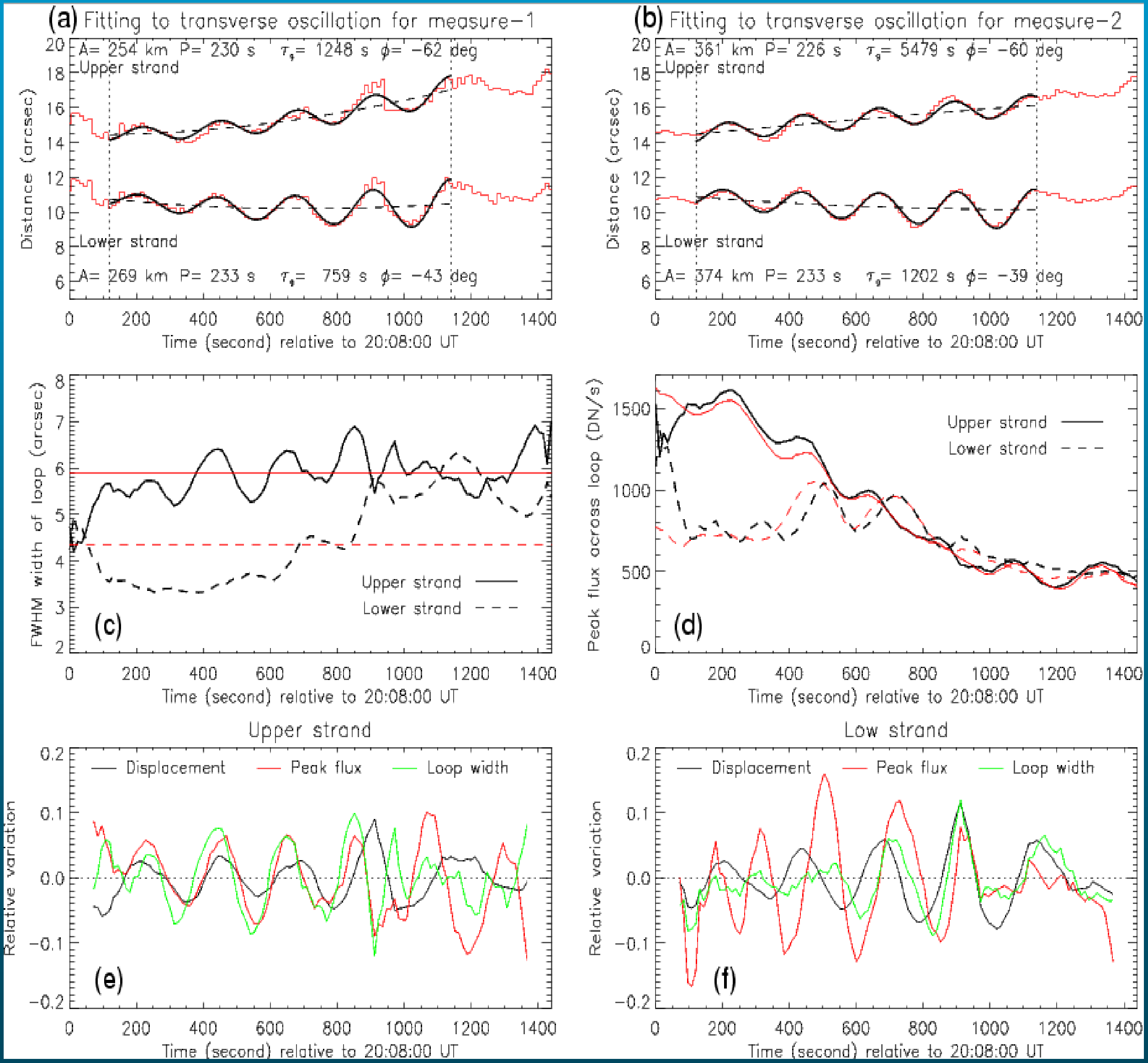
3. Analysis of transverse loop oscillations

Measurement of displacement oscillations in 171



3. Analysis of transverse loop oscillations

Measurement of physical parameters of amplitude-growing oscillations in 171



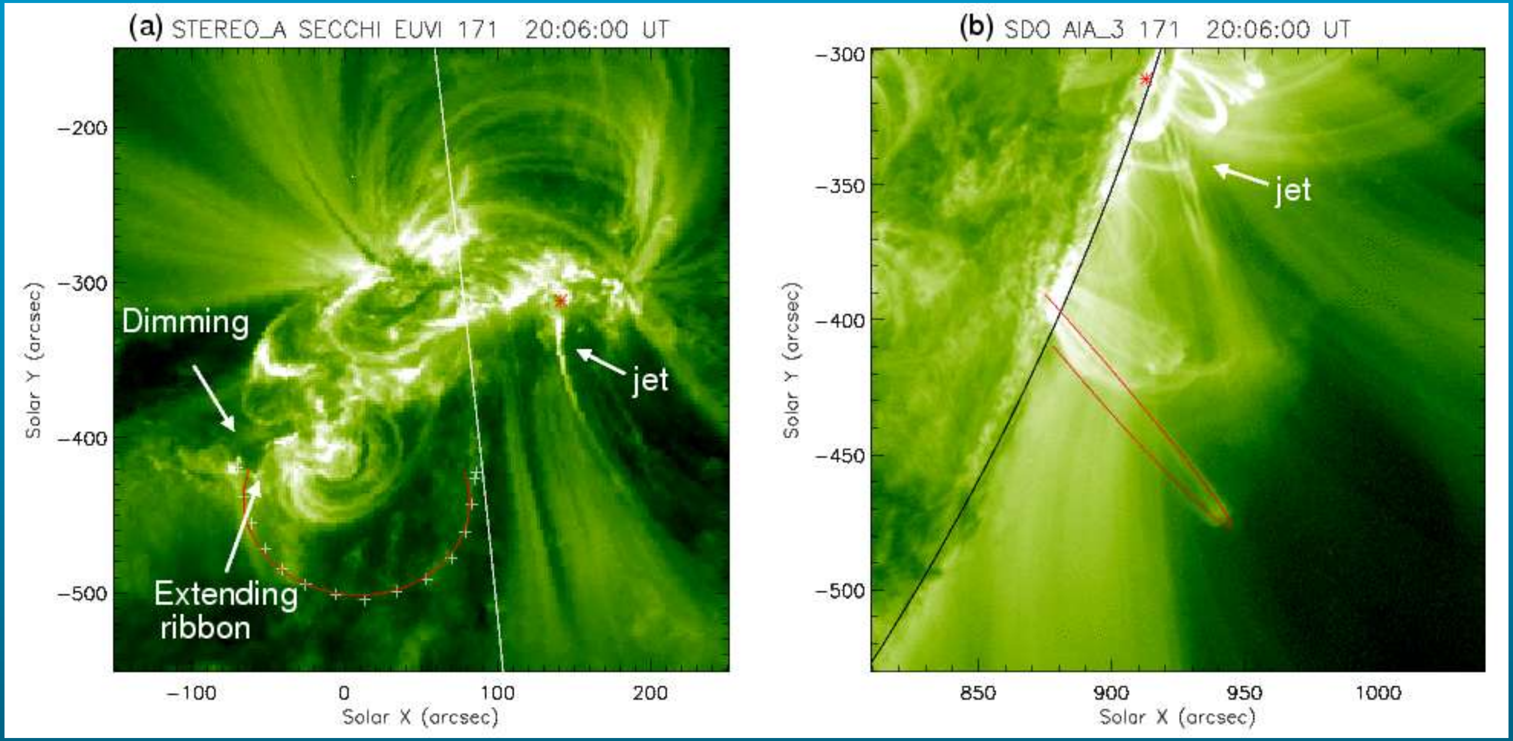
- Fits of displacement oscillations with amplitude-growing sine-function (with positive damping rate)
- Association with intensity and loop width oscillations

– intensity oscillation is real confirmed with width-fixed double Gfits

- Positive correlation suggests that loop width variations are artifacts

3. Analysis of transverse loop oscillations

Determination of trigger and loop geometry using STEREO-A



- The oscillating loop identified by fitting with a simple 3D arc-loop model
- Excluding the jet/surge as a trigger
- Association of a footpoint with extending ribbon followed by dimming region suggests that interaction of erupting flux rope (CME) continuously drive the loop oscillating, and lead it heated and partially erupted

4. Discussion

- Coronal seismology

Period P=230 s, loop length L=212 Mm, obtain V_p=2L/P=1840 km/s

$$V_p \approx C_k = V_A \sqrt{\frac{2}{1+n_e/n_i}}$$

(Roberts etal. 1984)

Obtain Alfven speed V_A=1360 km/s if n_e/n_i=0.1

magnetic field B=6 – 20 G for n=10^8 – 10^9 cm^{-3}

- Evidence for coupling of kink oscillations of multiple strands
  - similar frequencies
  - in-phase or ¼-period phase shift

Questions:
- no beating behavior as predicted
- temperature-dependent dynamics of multi-strands not modeled before

4. Discussion

- Amplification of kink oscillation by cooling effect (Rudernan 2011a,b,c)

(Ashwanden & Schrijver 2011)

Expected damping balanced by amplification due to cooling, while t_{cool} ~P is required

For the model of stratified loop with constant Te of external plasma from the measurements h/H_0 ~1.5 and n_e/n_i=0.1,
obtain $t_{amp} \sim 4\, t_{cool} < t_{grow}$
Observations t_{grow}= 1248 s and 759 s for upper or lower strands
P=230 s

obtain t_{cool}/P <1.4 or 0.8 inconsistent with observations that show the life time of >4P and no change in P,
Thus the observed growing oscillations or no damping oscillations are not due to the cooling effect.

4. Discussion

- This suggests that the wave energy in the loop is supplied continuously during the oscillations in our case, ie.

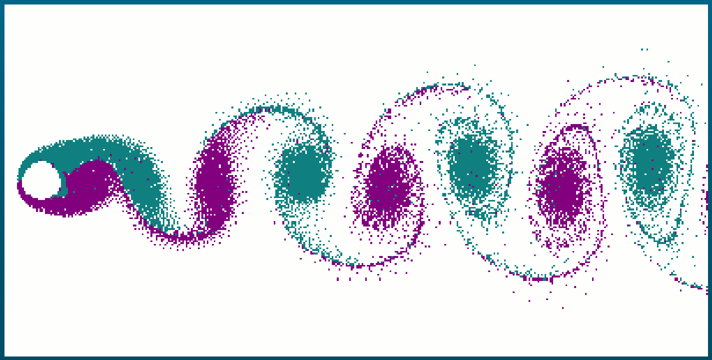
oscillations are forced by continuous, non-periodic driver (e.g. magnetic interaction caused by a CME) with energy input rate faster than damping rate
contrast with
the initial impulsive excitation suggested by the typical damping scenario of resonant absorption

- Alfvenic vortex shedding

(Gruszecki, Nakariakov,

van Doorsselaere, Arber

2010, Phys. Rev. Lett.)



Vortex shedding behind a circular cylinder

5. Conclusions

- For the first time observed clear amplitude-growing kink oscillations suggesting not impulsively generated but by continuous non-periodic driven

- Find the oscillating loop of multithermal strands showing different dynamic behaviors, which have not been studied before in theory and models

- Find the evidence for coupling and collective kink modes of multiple strands in a coronal loop