Coronal Seismology

ASTR 598

Laurel Farris

Spring 2016

Magnetohydrodynamics (MHD) Theory

[Relationship between size and decay time]. Characteristic speeds are determined by the environment (e.g. sounds waves traveling at $c_s = \sqrt{\frac{\gamma P}{\rho}}$) Types of waves/oscillations:

- Alfvén: $V_A = \frac{B}{\mu_0 \rho}$
- Magnetoacoustic: $C_s = \sqrt{\frac{\gamma P}{\rho}}$
  - Fast $C_{A_0} < C_{fast} < C_{A_e}$
  - Slow $C_{T_0} < C_{slow} < C_{s_0}$

Coronal seismology

Technique and motivation

Problem: properties of the corona, such as magnetic field strength, densities, and Alfvén velocities, are difficult to measure.

Solution: coronal seismology.

- Observe disturbances in the corona:
  - Period
  - Velocity
  - Timescales
- Compare observed quantities to MHD theory to identify the type of wave or mode.
- Insert observed properties into appropriate equations to derive coronal parameters.

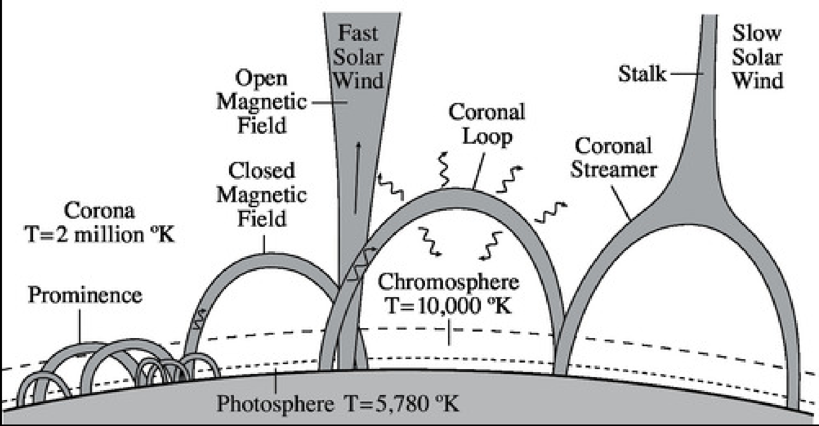
Current questions:

- How are these disturbances initiated?
- How are they damped, and what determines the timescales?

Motivation:

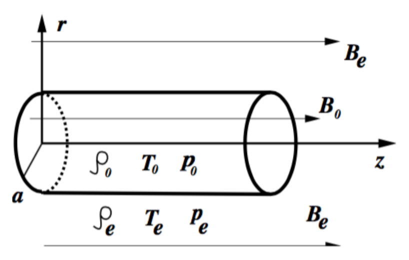
- Coronal heating problem
- Constraining flare/CME environment

Coronal seismology



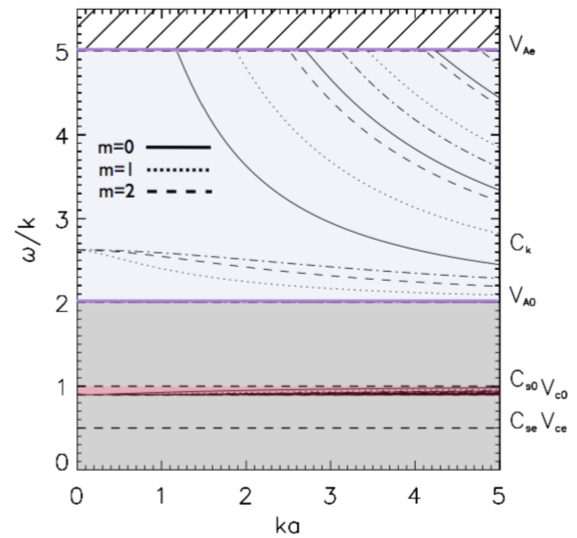
Magnetohydrodynamics (MHD)

Theory



- Straight flux tube in uniform magnetic field.
- $\xi(x) = \xi(r)e^{i(kz+m\phi)}$

Dispersion diagram



Background

Nak, Asc, Roberts, all those common authors.

MHD modes

Oscillations vs. waves

Or magnetoacoustic vs. Alfvén. Or fast vs. slow.

- Fast standing oscillations
  - Kink
  - Sausage
- Slow standing oscillations
  - Acoustic
- Propagating slow waves
  - Acoustic
- Propagating fast waves
  - Moreton
  - EIT waves
- Torsional modes (aka. Alfvén waves)

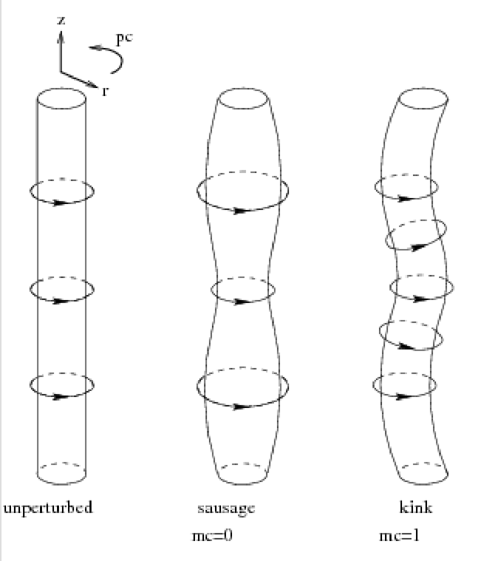
Observational Methods

How do you know what kind of mode you're looking at, or how to find potential MHD modes in the first place?

McIntosh et al. algorithm

Fast standing oscillations

Kinks vs. Sausages



Kink

- loop spatial displacement
- Asymmetric
- No intensity change
- $k\sigma \ll 1$, or $\sigma \ll \lambda$

Sausage

- No loop spatial displacement
- Symmetric
- Intensity change $\rightarrow$ density change
- $\lambda \sim \sigma$

Fast standing oscillations

Kinks vs. Sausages

The long-wavelength limit

Kink

- $k\sigma \ll 1$, or $\sigma \ll \lambda$

Sausage

- $\lambda \sim \sigma$

Kink modes

general characteristics

- $c_k = \sqrt{\frac{\rho_o V_{Ao}^2 + \rho_c V_{Ac}^2}{\rho_o + \rho_c}} \approx V_A \sqrt{\frac{2}{1 + \frac{\rho_e}{\rho_o}}}$ in the low-β plasma.
- $v_{ph} = \frac{\omega}{k} \approx C_k \gtrsim V_A$
- Period $P = \frac{2l}{V_A} \sqrt{\frac{1 + \rho_e/\rho_o}{2}}$ where $\lambda = 2l$ (l is the loop length). Typically, $l \approx 60 - 600$ Mm in the corona.
- "current pinch" instability
- Important observation from which magnetic field strength can be derived.

Research Goals

- Learn what the field is doing (review articles).
- Global contribution to topic — variety of authors, work done within the last five years or so.
- Fit research into the “big picture”

Kink modes

Coronal loop oscillations observed with the *Transition Region And Coronal Explorer (TRACE)*

- Not just a single, global mode.
- Gaussian vs. exponential
- Plasma motions around footpoints of coronal loops

Kink modes

"Excitation and damping of broadband kink waves in the solar corona"

Footpoint-driven, *propagating* kink waves (which are temporally and spatially ubiquitous in the corona). Both standing and propagating kink waves are rapidly damped.

Sausage modes

The basics

Trapped fast modes supported by thick, dense loops because of the cutoff wavenumber (pfw_2). Observe spatially resolved radio (see sources in pfw_2).

Sausage modes

Observations of sausage modes in magnetic pores

Sausage modes

Sausage waves in transversely nonuniform monolithic coronal tubes

Standing acoustic oscillations

[Insert movie here?] Characteristics:

- Pressure forces in opposition
- Period = 7–31 minutes (20 minutes from another source)
- Decay times = 5.7–36.8 minutes
- Peak velocity = 200 km/sec

Standing oscillations vs. propagating waves

- In loops, propagating waves damp before reaching opposite footpoint.
- Velocity and intensity are 90° out of phase for standing oscillations, and are in phase for propagating acoustic waves.
- Frequencies less than the cutoff are standing oscillations, waves with frequency greater than the cutoff propagate into the chromosphere.
- no loop shape change or displacement
- near footpoints.

Propagating acoustic waves

Slow

- $v_{ph} < 150$ km s^{-1} $\rightarrow$ slow
- longitudinal, compressive, anisotropic
- Parallel to $\vec{B}$, perturbation of $\vec{B}$ is negligible.
- Generated impulsively at one end of a footpoint.
- Only penetrate $\sim 10\%$ into loop before damped by thermal conduction
- weak dispersion in coronal conditions ($V_A \gg c_s$)
- 3 phases: periodic, QP, decay
- period = 3, 5, 10 minutes? Or 2–22 seconds? (see kink_1),
- velocity: 50–200 km s^{-1}
- $c_T = \sqrt{\frac{c_s^2 v_A^2}{c_s^2 + v_A^2}}$ propagate sub-sonically at c_T, which is less than c_s
- "large" amplitude, max in top of chromosphere
- Observed using spectroscopy (intensity variations in EUV emission and Doppler shifts)

Propagating acoustic waves

Fast

- $v_{ph} > 150$ km s^{-1} $\rightarrow$ fast (*or* transverse standing waves).
- Quasi-isotropic
- Driven by magnetic forces + plasma pressure forces
- Compressive (magnetic sound wave)
- Speed: $c_F = \sqrt{c_s^2 + v_A^2}$
- Moreton waves in the chromosphere
- Fast EUV waves in the corona

“FIRST SIMULTANEOUS OBSERVATION OF AN Hα MORETON WAVE, EUV WAVE, AND FILAMENT/PROMINANCE OSCILLATIONS”

Asai, et al. (pfw_2)

pfw_2

Torsional modes

aka. Alfvén wave

Properties:

- m=0 (Axisymmetric, or azimuthally symmetric)
- transverse (shear) perturbations
- Parallel to $\vec{B}$
- Driving force: magnetic tensioin
- incompressible
- velocity: $v_A = \frac{B}{\mu_o \rho}$; ~ 1000 km s^{-1} in the corona

How to observe:

- Only get Doppler shifts from *long*-period waves ($>$ a few minutes).
- Measure additional (i.e. non-thermal) broadening of coronal emission lines; indirect way to observe short-period waves.
- Spatial variation in Doppler shift for long periods. Gyrosynchrotron emission in radio regime.

Effects of twisting:

- Coupling of various MHD modes

tor_1

tor_2

Important Properties

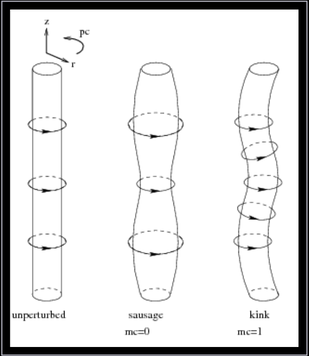
	period	wavelength	velocity
kink osc	value	value	value
sausage osc	value	value	value
acoustic osc	value	value	value
acoustic waves	value	value	value
fast waves	value	value	value
torsional modes	10 m	value	1000 km s^{-1}

Example Table

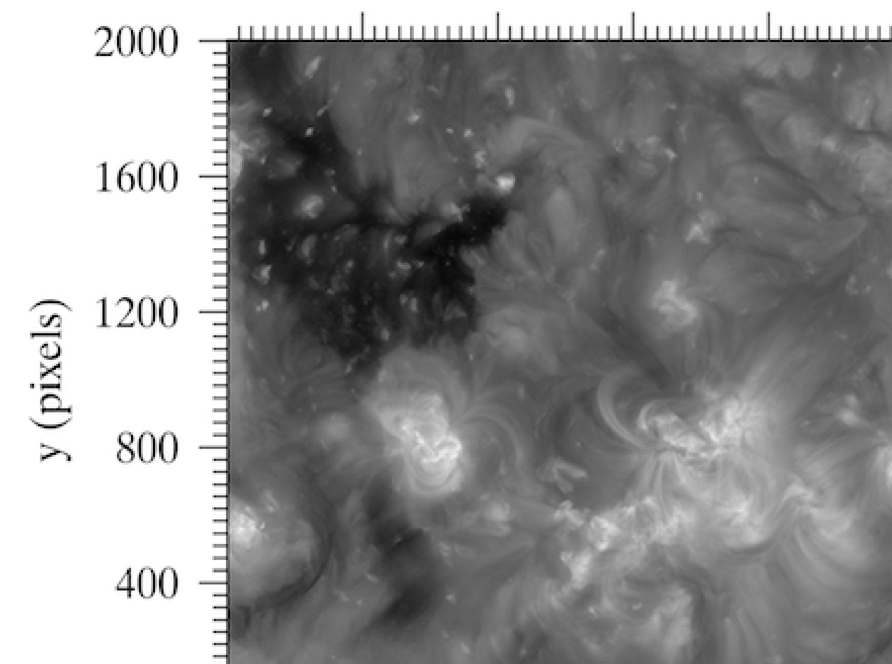
		Condition (Gold standard)	
		True	False
Test outcome	Positive	True Positive	False Positive
	Negative	False Negative	True Negative

Example of Two Column Output

Practical TEX 2005
Practical TEX 2005
Practical TEX 2005

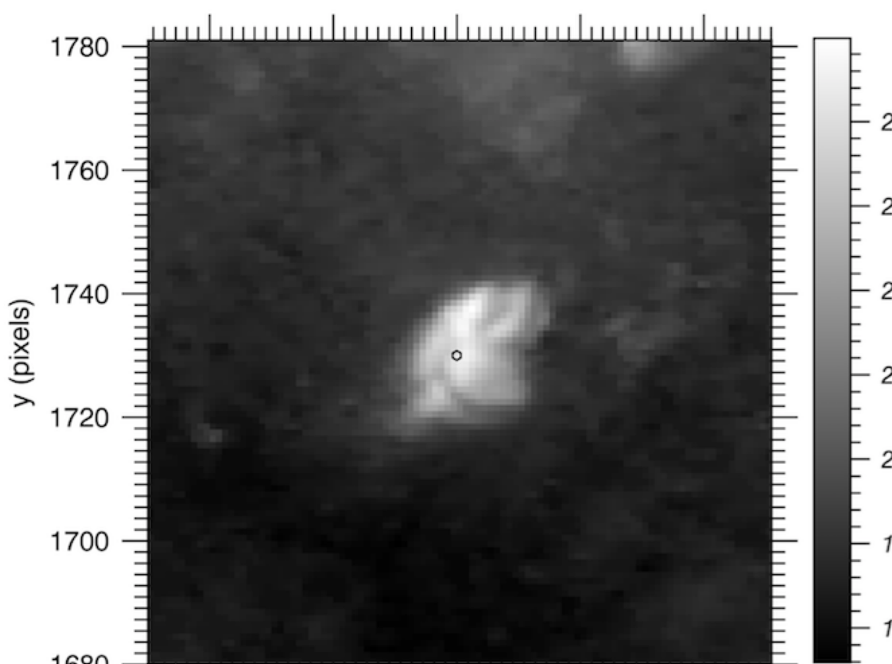


Research

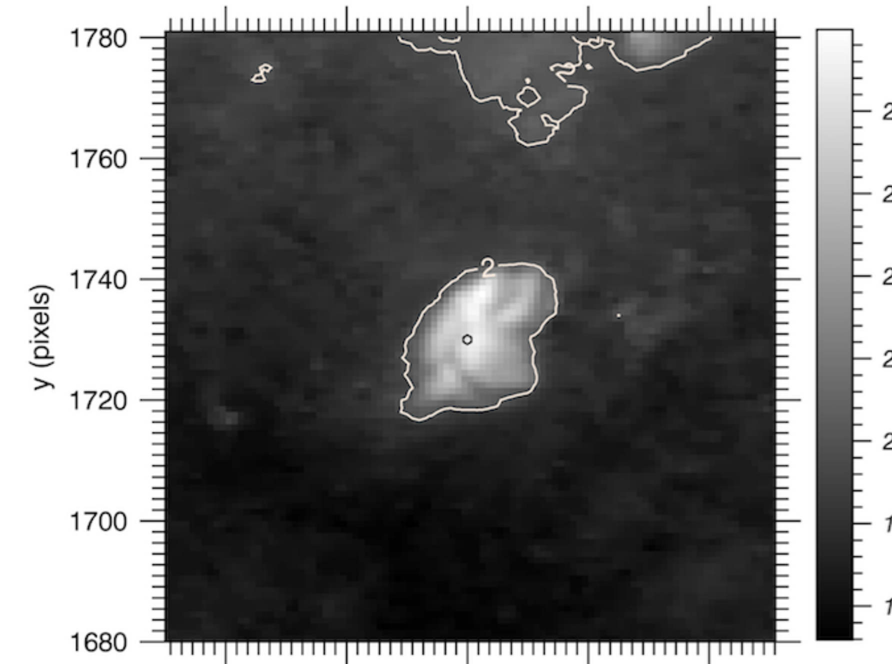


Research

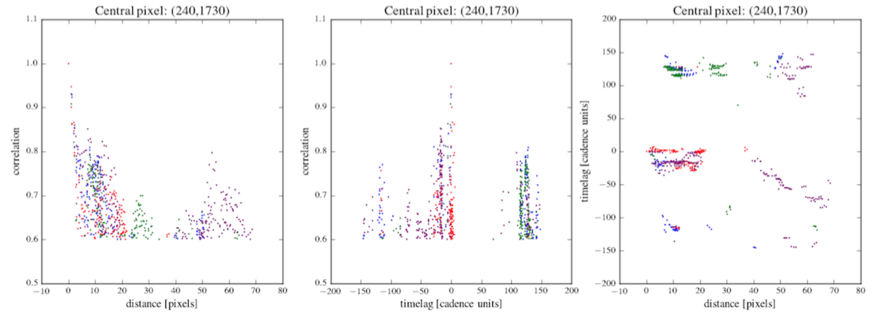
Research



Research



Research


Central pixel: (240,1730)
correlation
distance [pixels]
Central pixel: (240,1730)
correlation
timelag [cadence units]
Central pixel: (240,1730)
timelag [cadence units]
distance [pixels]