The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2292-24

School and Conference on Analytical and Computational Astrophysics

14 - 25 November, 2011

Coronal Loop Seismology - State-of-the-art Models

Malgorzata Selwa
Katholic University of Leuven, Centre for Plasma Astrophysics
Belgium

KATHOLIEKE UNIVERSITEIT
LEUVEN

Coronal Loop Seismology - State-of-the-art Models

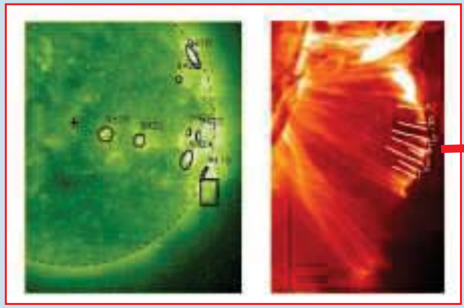
Mag Selwa

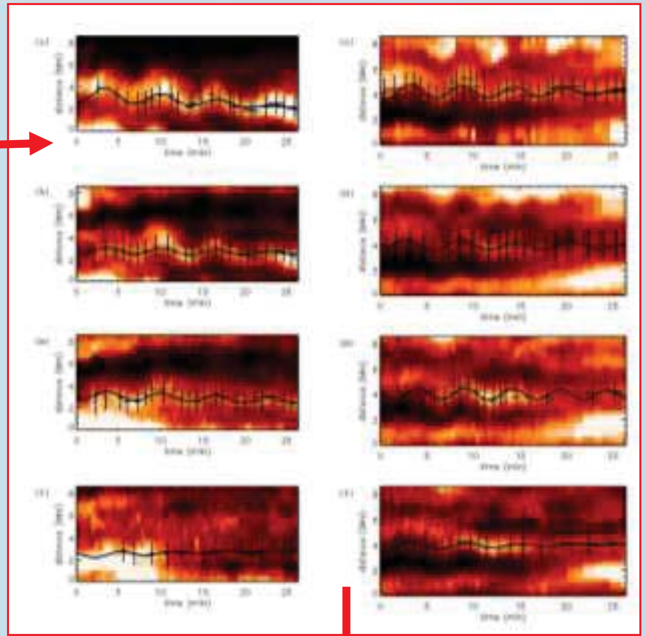
ICTP School and Conference on Analytical and Computational Astrophysics, Trieste, 23.11.2011

Outline

- ✓ Observations of coronal loops oscillations as an input for coronal seismology:
  - ➢ Scale height
  - ➢ Damping mechanisms
- ✓ Recent observations (STEREO)
- ✓ Alfvén waves
- ✓ Other structures:
  - ➢ EIT waves
  - ➢ QPP
  - ➢ streamers
  - ➢ prominences

B from kink oscillations





transverse oscillations in an off-limb arcade observed with TRACE:

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 ± 120$^{(a)}$	620 - 700	9 - 25	0.9 - 1.4 × 10^8 $^{(a)}$	1.0 - 1.7 × 10^6
	970 ± 40	690 - 790	10 - 28	0.6 - 1.0 × 10^8	1.4 - 2.9 × 10^6
D	940 ± 120$^{(a)}$	670 - 760	10 - 27	-	-
	1160 ± 90	820 - 940	12 - 33	0.3 - 0.4 × 10^8	4.4 - 7.6 × 10^6
E	1220 ± 40	860 - 980	13 - 35	0.8 - 1.5 × 10^8	1.4 - 3.0 × 10^6
F	1920 ± 810	1360 - 1550	20 - 55	-	-
G	1320 ± 110	940 - 1070	14 - 38	1.4 - 2.8 × 10^8	0.8 - 1.8 × 10^6
H	1440 ± 200	1020 - 1160	15 - 41	1.3 - 2.2 × 10^8	1.1 - 2.0 × 10^6
I	1320 ± 330	940 - 1070	14 - 38	0.6 - 0.9 × 10^8	2.6 - 4.1 × 10^6

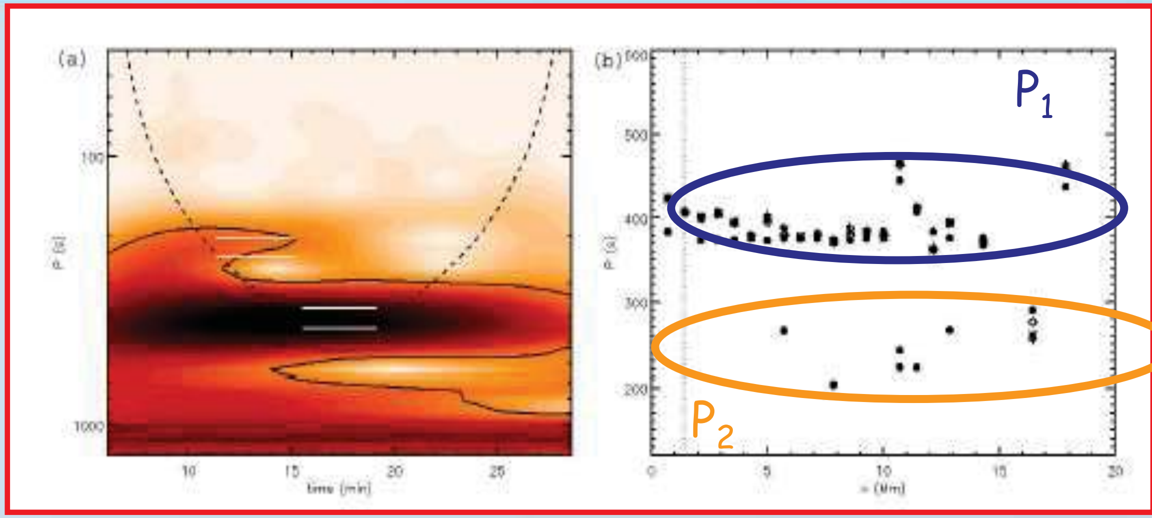
$^{(a)}$ Oscillation is assumed to be a second harmonic.

Best fit $\xi(t) = A e^{-\gamma t^n} \cos\left(\frac{2\pi}{P} t + \phi\right)$

$$B_0 \approx 7.9 \times 10^{-13} \frac{n_0^{1/2} d \sqrt{1 + n_e / n_0}}{P}$$

Verwichte et al. (2004)

B from kink oscillations



Path	Wavelet P (s)	Fit P (s)	τ_1 (s)
A	301 ± 50	326 ± 107	–
B	–	393 ± 77	–
C	247 ± 33	315 ± 144	(980)[a]
	448 ± 18	(405 ± 35)	–
D	242 ± 31	–	–
	396 ± 20	392 ± 31	1180 ± 1050
E	379 ± 54	382 ± 12	1320 ± 570
F	–	243 ± 103	–
G	346 ± 78	358 ± 30	1030 ± 680
H	317 ± 80	326 ± 45	960 ± 420
I	325 ± 107	357 ± 89	(960 ± 760)

Values between brackets are uncertain measurements.
[a] Based upon one measurement.

First identification of kink second harmonics

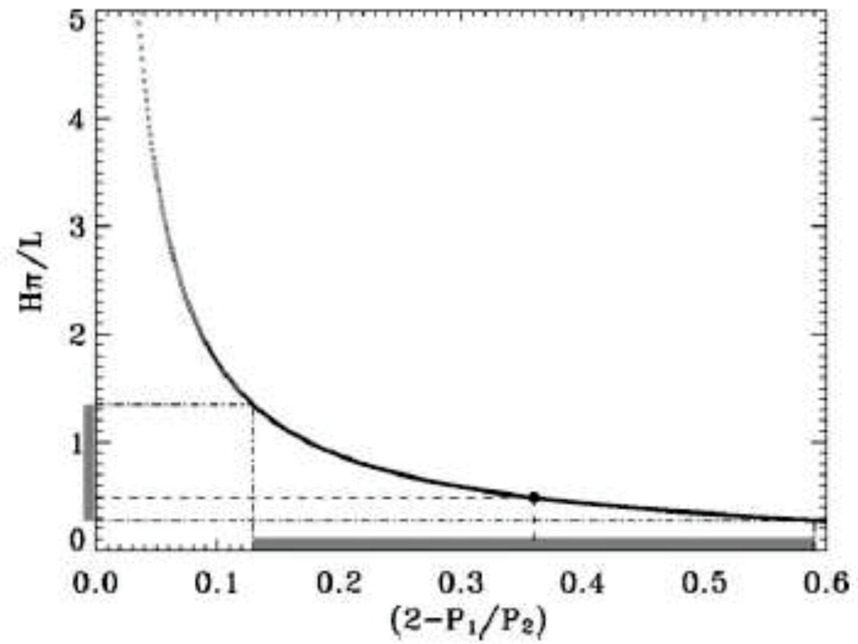
$P_2 \approx P_1/2$, the mode has a node at loop apex.

Here P_1/P_2 = 0.55 and 0.61

Verwichte et al. (2004)

Scale height from kink oscillations

Scale height (for planetary atmospheres) is the vertical distance over which the pressure of the atmosphere changes by a factor of *e* (decreasing upward). The scale height remains constant for a particular temperature.



✓exponentially stratified atmosphere

$$\rho(h) = \rho_0 \exp(-h/H)$$

✓stratification function projected on a semicircular loop of length L

$$\rho(z) = \rho_0 \exp\left[-L\sin(\pi z/L)/\pi H\right]$$

✓$P_1/P_2 \neq 2$ (no node at the loop apex)

$P_2/P_1 \sim H$ (scale height)

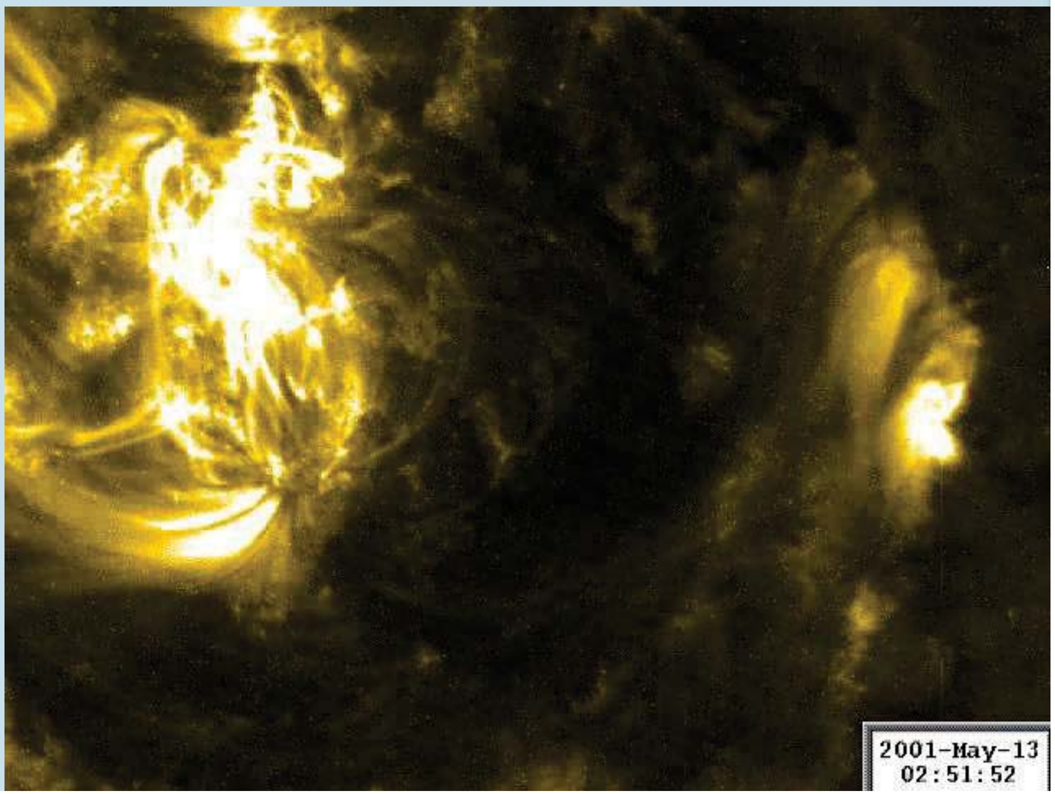
A tool for independent estimation of stratification

Andries et al. (2005)

Multiple periodicities–scale height

- ✓O'Shea et al. (2007): wave harmonics in cool loops (OV observation, TR line).
- ✓De Moortel & Brady (2007): 2nd and 4th/5th harmonic.
- ✓Van Doorsselaere et al. (2007): fundamental and 2nd harmonic in TRACE observations, calculated density scale height in the loop as 109Mm (estimated hydrostatic value is 50Mm).
- ✓Van Dooresselaere et al. (2009): reanalyzed event of De Moortel & Brady 2007 as the fundamental, 2nd and 3rd harmonic; from 3 periods estimated density scale height and loop expansion.

	P_1(s)	P_2(s)	P_1/P_2	$L/\pi H$	L(Mm)	H(Mm)
Current event	435.6 ± 4.5	242.7 ± 6.4	1.795 ± 0.051	$1.17^{+0.28}_{-0.30}$	400	109^{+37}_{-21}
path C (1)	447.7 ± 15.8	246.5 ± 6.0	1.82 ± 0.08	$1.02^{+0.46}_{-0.44}$	218	68^{+52}_{-21}
path D (1)	387.4 ± 7.5	244.8 ± 7.7	1.58 ± 0.06	$2.43^{+0.38}_{-0.36}$	228	30^{+5}_{-4}



Multiple periodicities–expansion

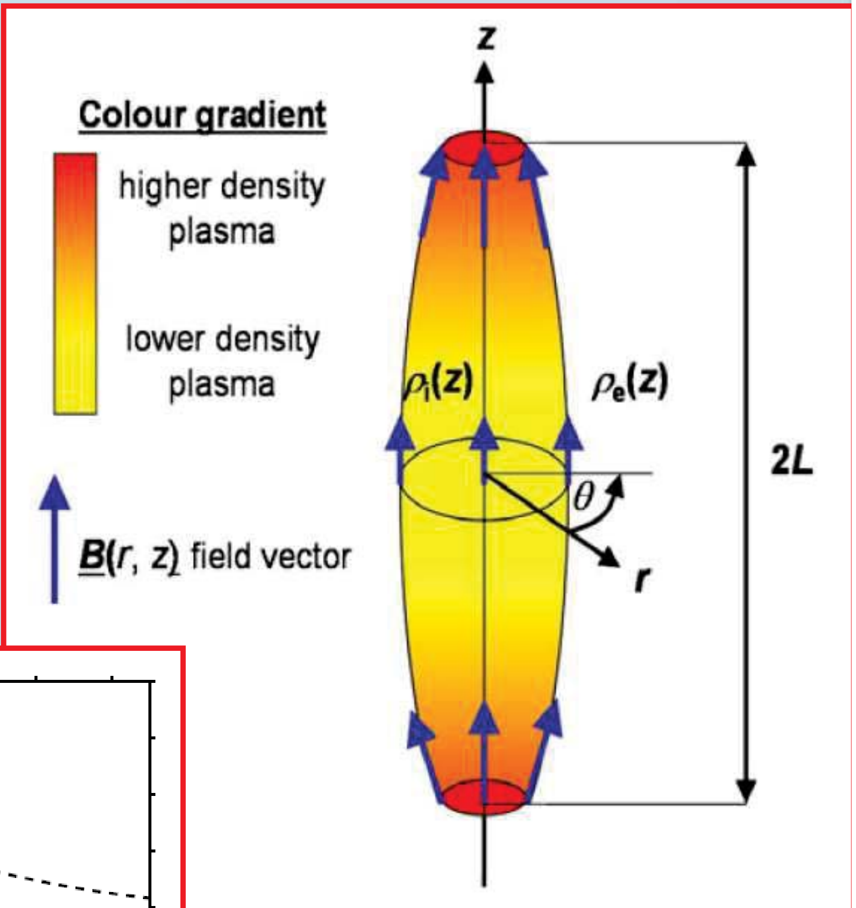
Verth (2007), Verth et al. (2008), Verth & Erdélyi (2008), Van Doorsselaere et al. (2009), Andries et al. (2009): **tube expansion and variation of magnetic field**

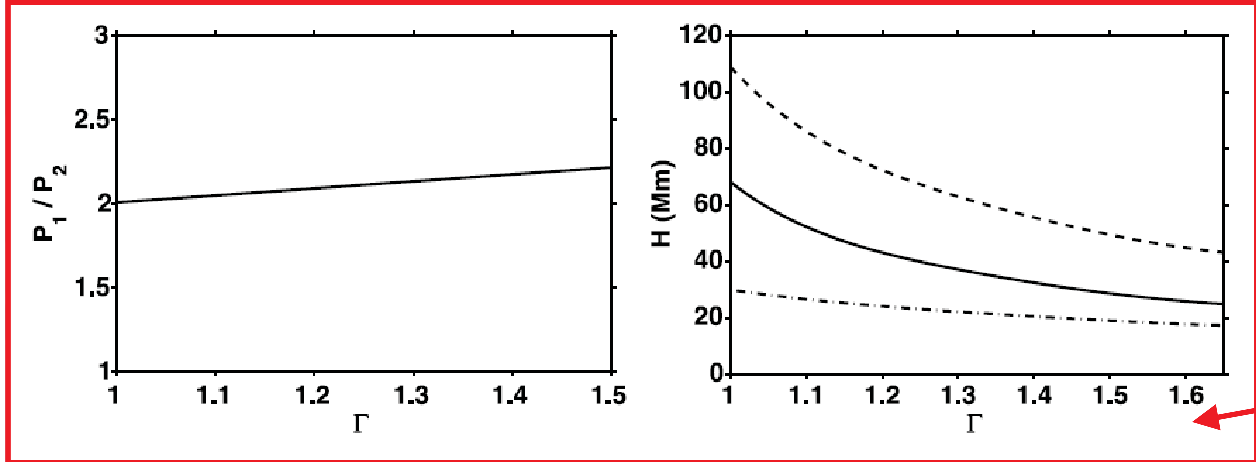
$$B_z(z) \propto \left[1 + \frac{1-\Gamma^2}{\Gamma^2}\frac{\cos(z/L)-\cos(1)}{1-\cos(1)}\right]$$

magnetic flux conservation $\Gamma = \frac{B_f}{B_a}$

-> the period ratio of the fundamental mode to the first overtone can be approximated for a constant density loop to the first order by

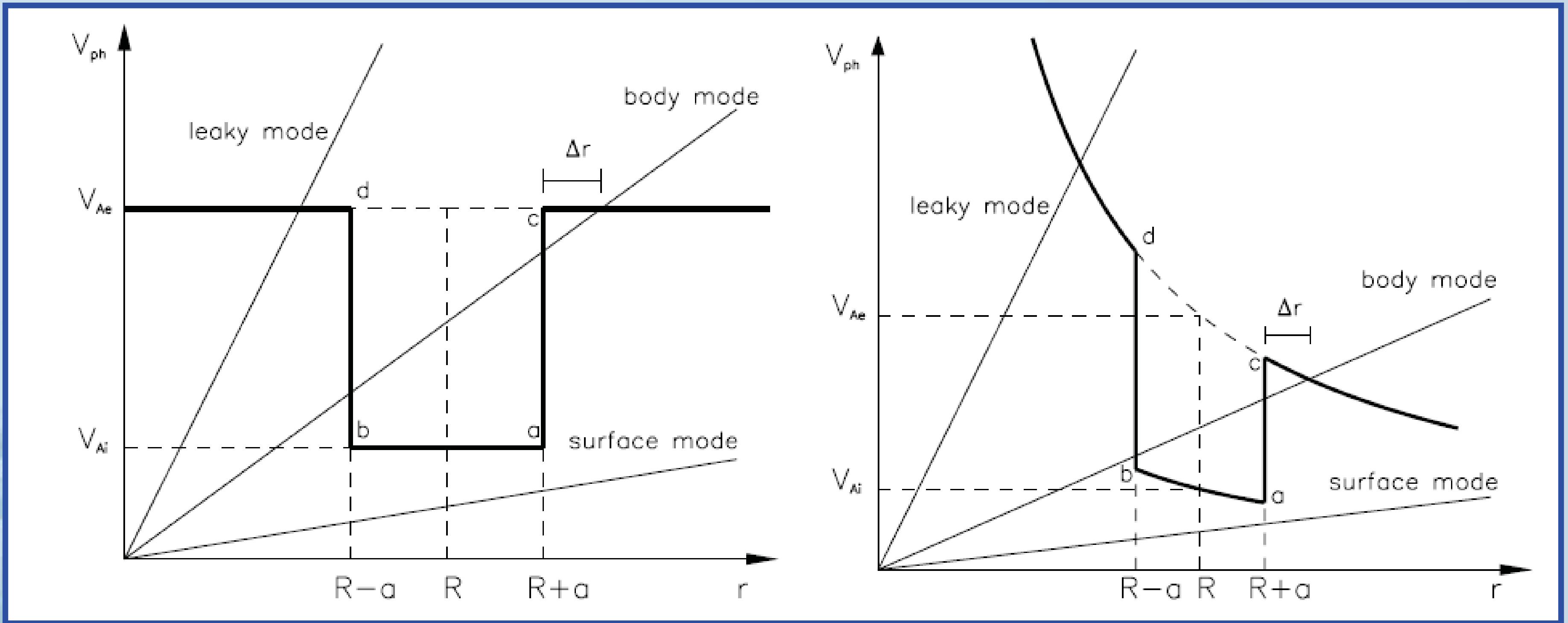
$$\frac{P_1}{P_2} = 2\left[1 + \frac{(3\Gamma^2 - 1)}{2\pi^2}\right]$$





opposite effect

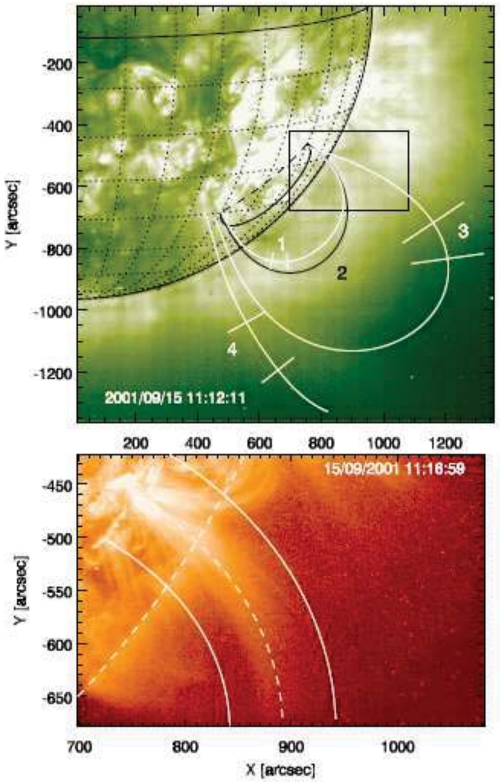
Damping mechanisms-Alfvén speed



Brady et al. (2006)

Verwichte et al. (2006)

Damping mechanisms-Alfvén speed

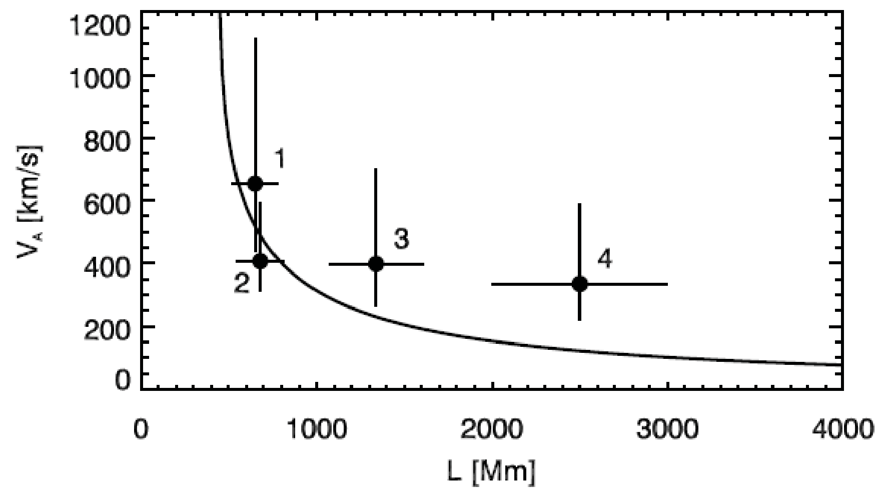


✓The oscillations of a **whole coronal arcade** above an active region provide information of the Alfvén speed profile at different loops as a function of height in the global corona, which may be compared with magnetic field extrapolation models.

✓With each oscillating loop, we can associate an average value of the average Alfvén speed (in that loop) and a loop length and height, or range of heights, in the corona.

Loop No.	L (Mm)	P (s)	V_{ph} (km s^{-1})
1	$\gtrsim$610	1440 ± 230	$\gtrsim$850
2	680	2418 ± 5	562
3	$\gtrsim$1280	4900 ± 900	$\gtrsim$520
4	(2000–3000)	(10800)	(460)

Note. Values within brackets have large uncertainties.



Verwichte et al. (2010)

Damping mechanisms: resonant absorption

$$\frac{P}{\tau_d} = \frac{\pi}{2}\left(\frac{l}{R}\right)\left(\frac{\gamma - 1}{\gamma + 1}\right)$$

✓ Ruderman & Roberts (2002): damping due to resonant absorption

density contrast $\gamma = \frac{\rho_i}{\rho_e}$

✓ Goossens et al. (2002)

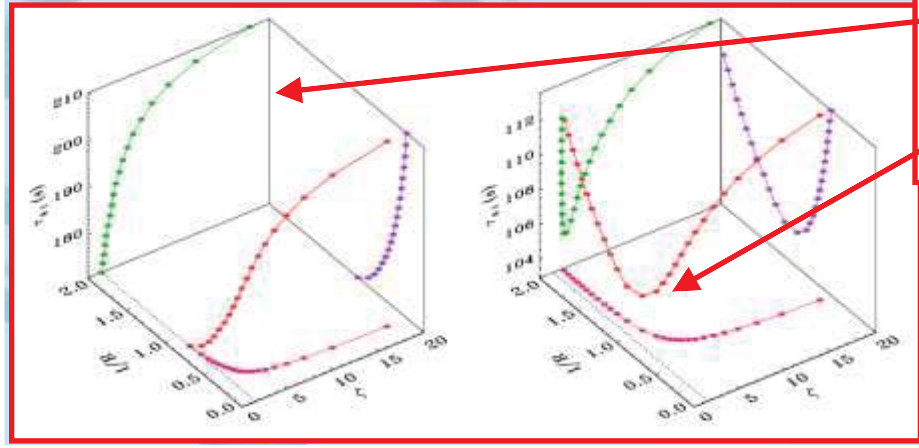
for γ=10 -> l/R

No.	L [m]	R [m]	R/L	P [s]	$\tau_{\rm decay}$ [s]	l/R
1	1.68e8	3.60e6	2.1e-2	261	840	0.16
2	7.20e7	3.35e6	4.7e-2	265	300	0.44
3	1.74e8	4.15e6	2.4e-2	316	500	0.31
4	2.04e8	3.95e6	1.9e-2	277	400	0.34
5	1.62e8	3.65e6	2.3e-2	272	849	0.16
6	3.90e8	8.40e6	2.2e-2	522	1200	0.22
7	2.58e8	3.50e6	1.4e-2	435	600	0.36
8	1.66e8	3.15e6	1.9e-2	143	200	0.35
9	4.06e8	4.60e6	1.1e-2	423	800	0.26
10	1.92e8	3.45e6	1.8e-2	185	200	0.46
11	1.46e8	7.90e6	5.4e-2	396	400	0.49

✓ Arregui et al. (2007)

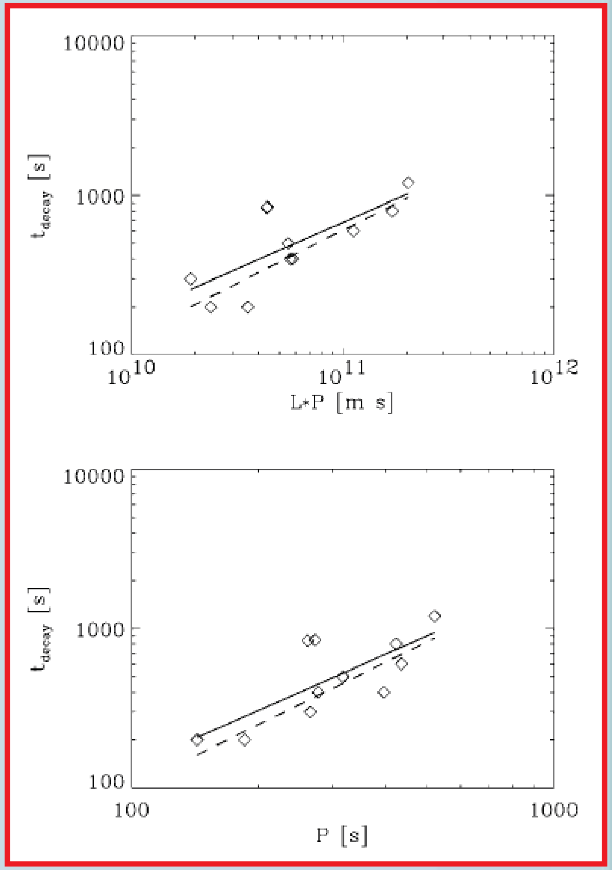
1D solution curves

Loop	R (10^6 m)	L (10^8 m)	$\varepsilon = \pi R/L$	P (s)	τ_d (s)	P/τ_d	l/R	$\tau_{\rm Ai}$ (s)	$V_{\rm Ai} = L/\tau_{\rm Ai}$ (km s^{-1})
1	3.60	1.68	0.067	261	870	0.30	0.20–0.83 ★	155–190	880–1080 ★
2	3.35	0.72	0.146	265	300	0.88	0.58–2.0	378–423	170–190
3	4.15	1.74	0.075	316	500	0.63	0.41–2.0	225–259	670–770
4	3.95	2.04	0.061	277	400	0.69	0.45–2.0	163–183	1110–1250
5	3.65	1.62	0.071	272	849	0.32	0.22–0.90 ★	170–210	770–950★
6	8.40	3.90	0.068	522	1200	0.44	0.30–2.0	327–386	1010–1190
7	3.50	2.58	0.043	435	600	0.73	0.47–2.0	181–203	1270–1420
8	3.15	1.66	0.059	143	200	0.72	0.46–2.0	85–93	1780–1950
9	4.60	4.06	0.036	423	800	0.53	0.35–2.0	140–165	2460–2900
10	3.45	1.92	0.056	185	200	0.93	0.57–2.0	105–113	1690–1830
11	7.90	1.46	0.169	396	400	0.98	0.62–2.0	663–730	200–220



Damping mechanisms

Ofman & Aschawanden (2002), Nakariakov (2004), Verwichte et al. (2004)Ruderman & Roberts (2002):



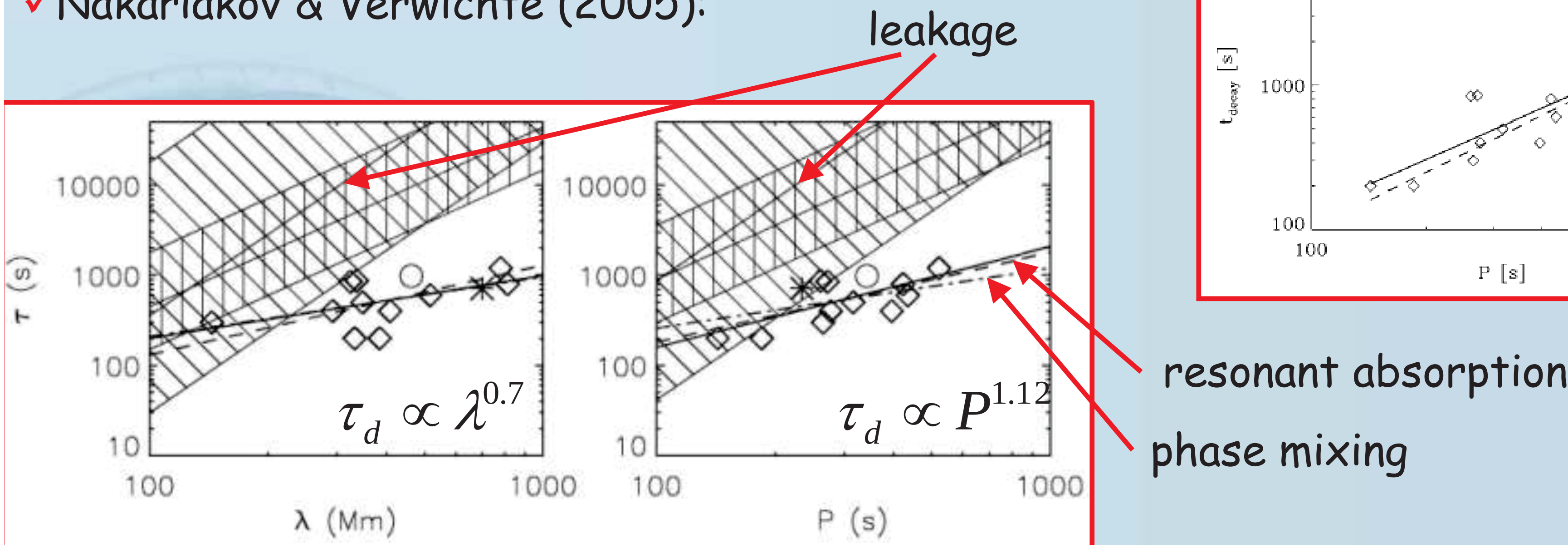
✓Phase mixing $\tau_d \propto (lP)^{2/3} \propto P^{4/3}$ if layer ~ loop length

(does not involve torsional mode, but is connected with kink perturbations of neighbouring loops)

✓Wave leakage $\tau_d \propto LP \propto P^2$ if layer ~ loop length

✓Resonant absorption $\tau_d \propto P$

✓Nakariakov & Verwichte (2005):



3D STEREO observations

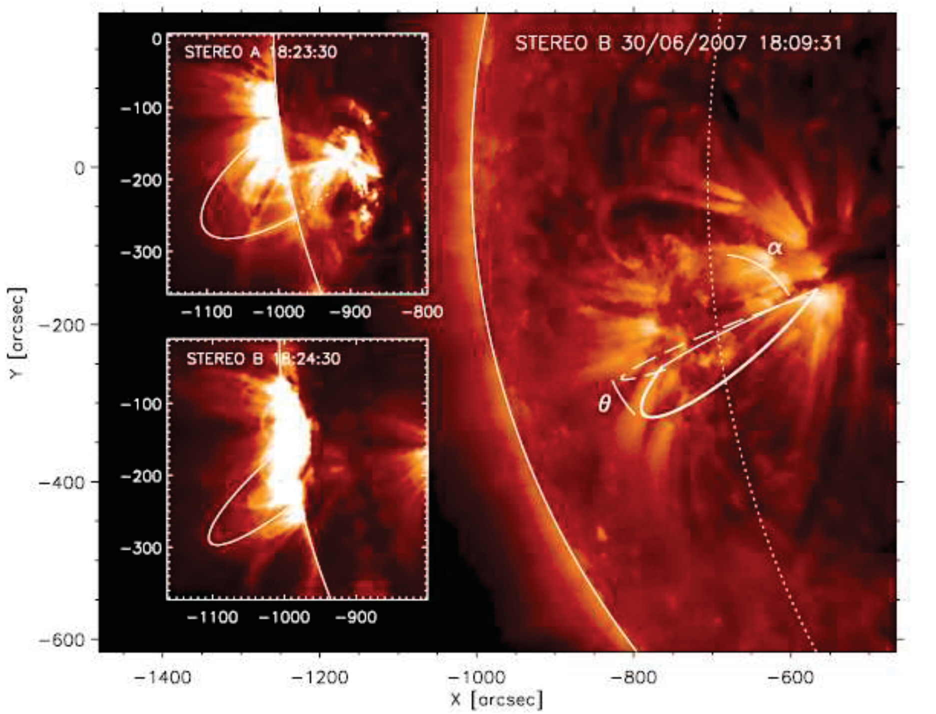
✓ Aschwanden (2008):

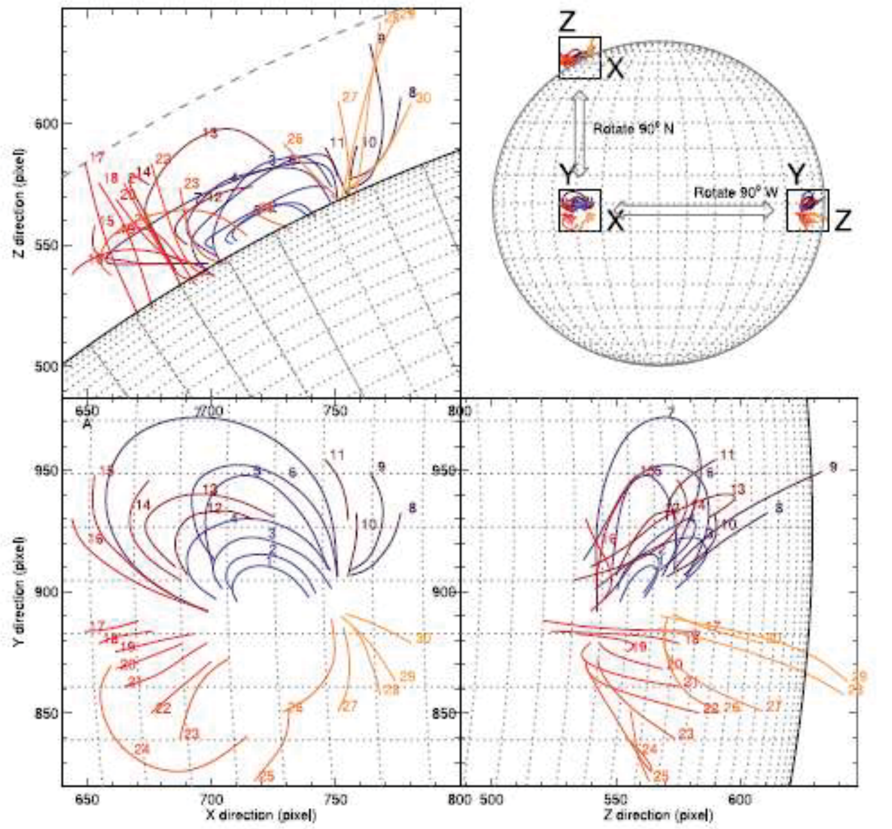
paper I: 3D geometry and motion of the loops

paper II: electron density and temperature

✓ Verwichte et al. (2009):

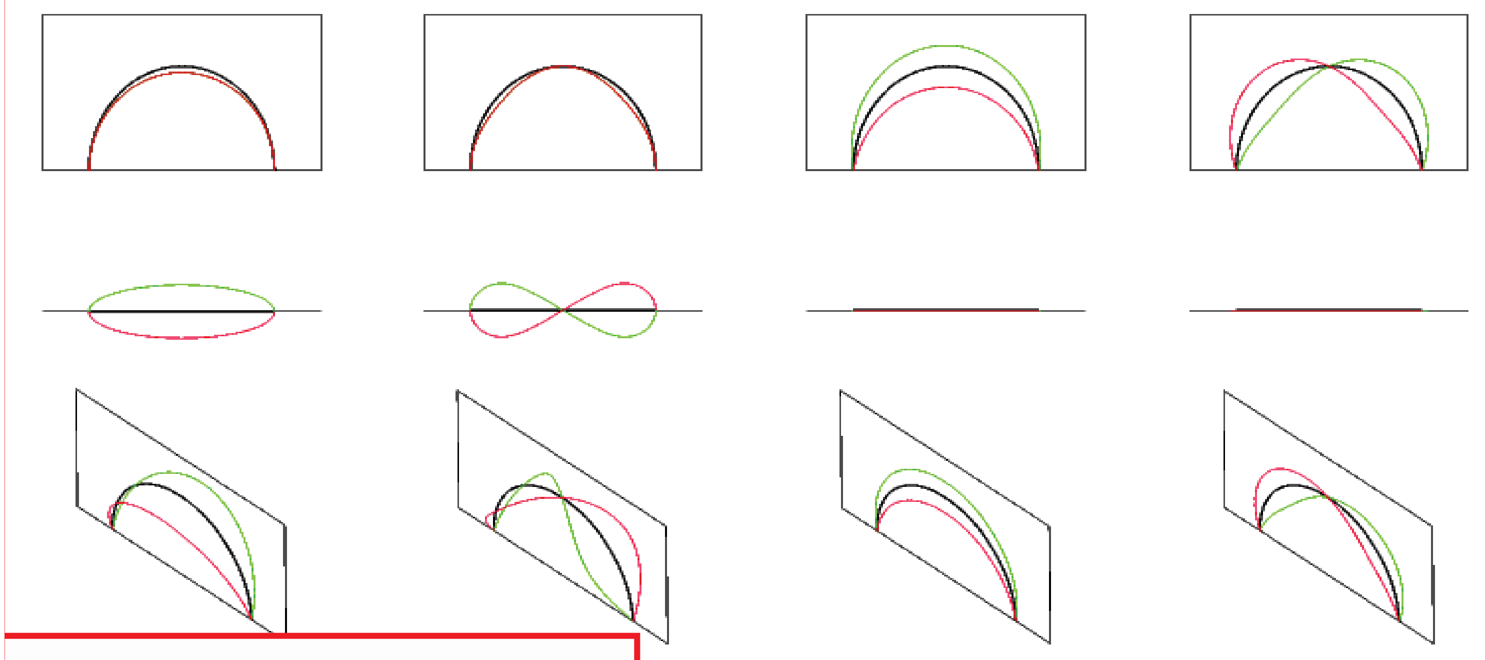
seismology of large coronal loop -> B=11±2G

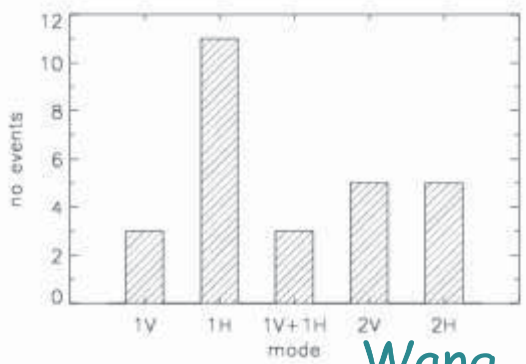


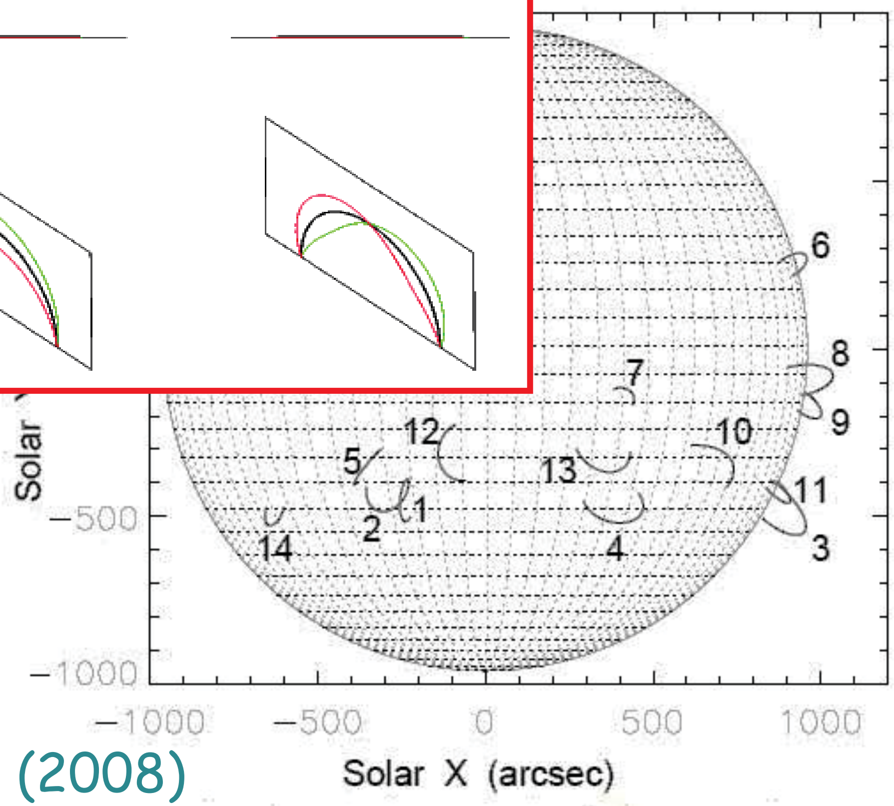


3D STEREO observations

Fundamental horizontal mode	Second harmonic horizontal mode	Fundamental vertical mode	Second harmonics vertical mode





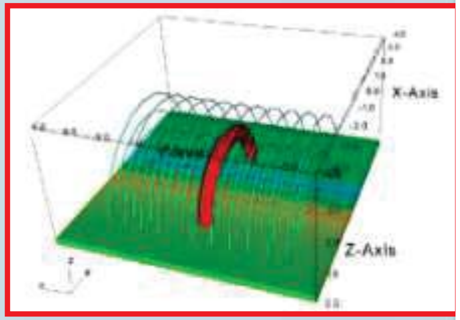


Wang, Solanki, Selwa (2008)

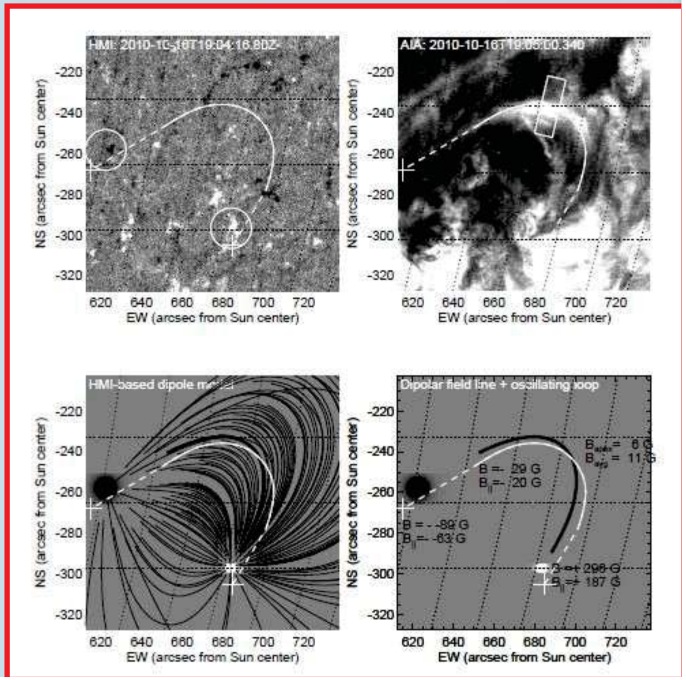
Problems with magnetic field

✓McLaughlin & Ofman (2008): reduction of vertical kink oscillation period compared to the horizontal one.

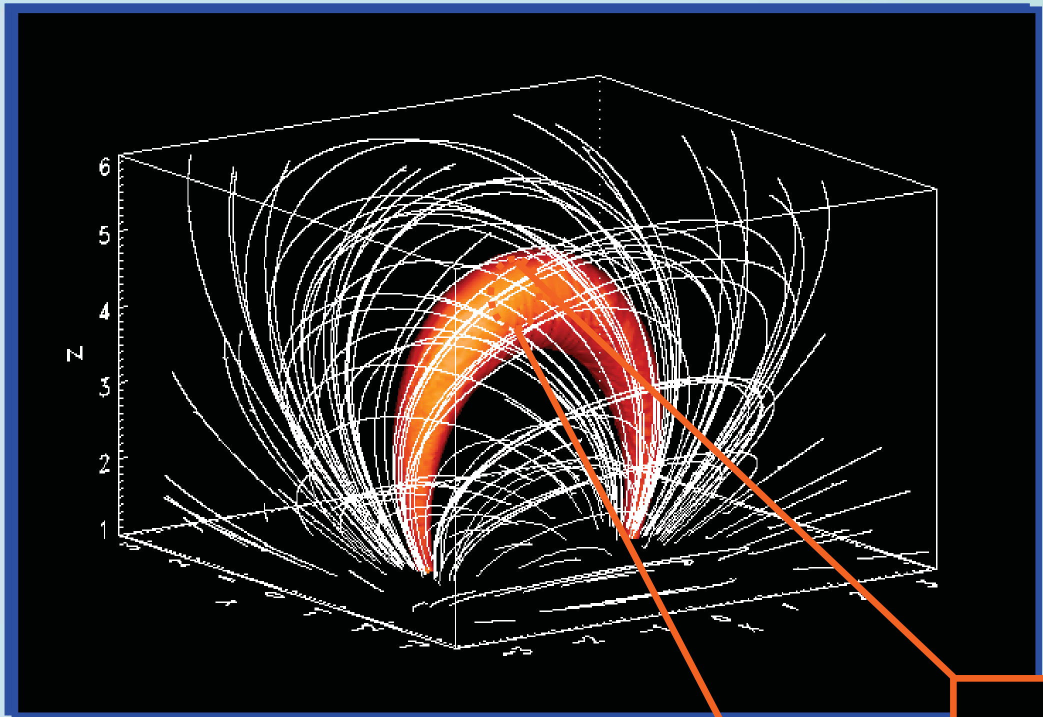
✓De Moortel & Pascoe (2009): magnetic field derived from simulation differs by 50% from the input value (overestimated).

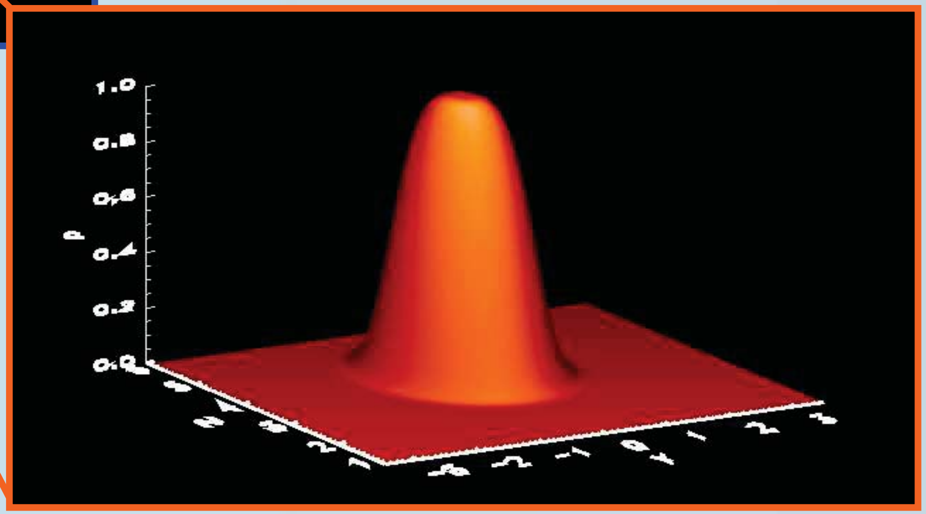


✓Aschwanden & Schrijver (2011): magnetic field from coronal seismology 4G, from potential field extrapolation 6G (apex), after correction of variable Alfvén speed along the loop 11G (2.8 times higher than the value from coronal seismology).



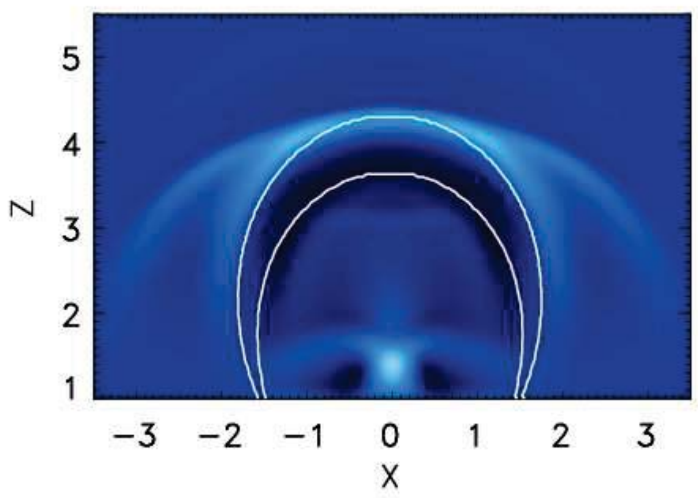
Problems with magnetic field

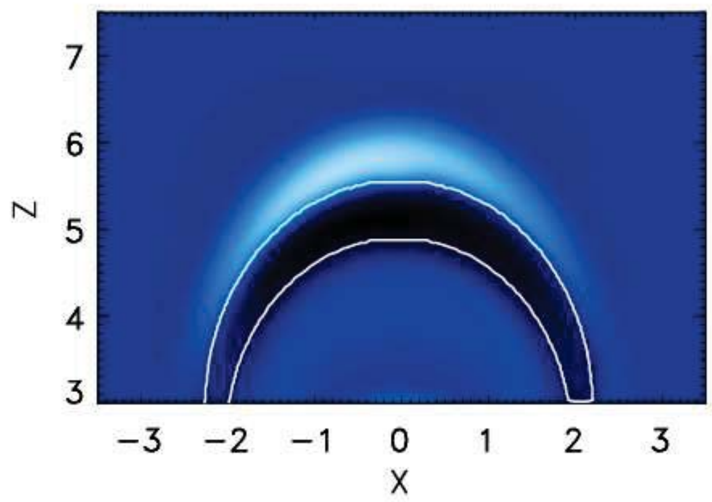




Selwa, Ofman, Solanki, Paper I (2011)

Problems with magnetic field



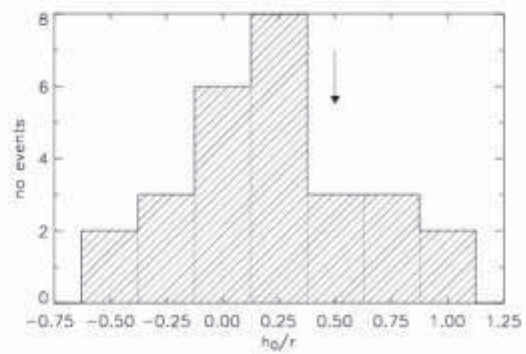


P(simulations): 12 τ
P(analytical):24 τ

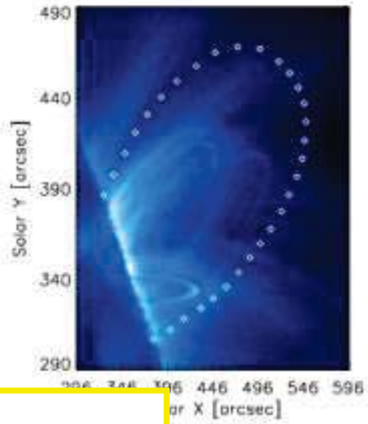
P(simulations): 44 τ
P(analytical):45 τ

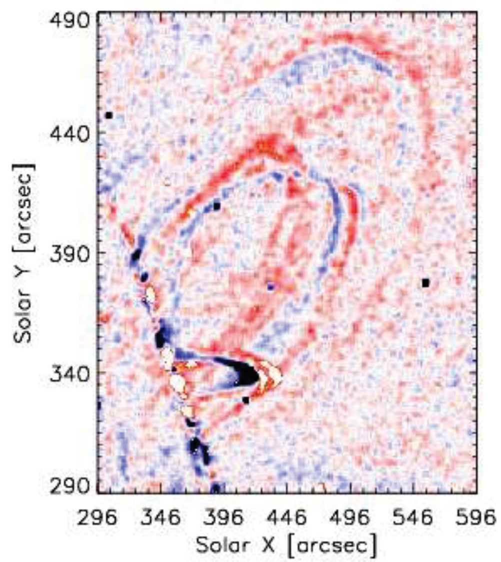
- ✓ Difference in periods (but not the 2nd mode)
- ✓ Does not depend on excitation type
- ✓50% error in B estimation!

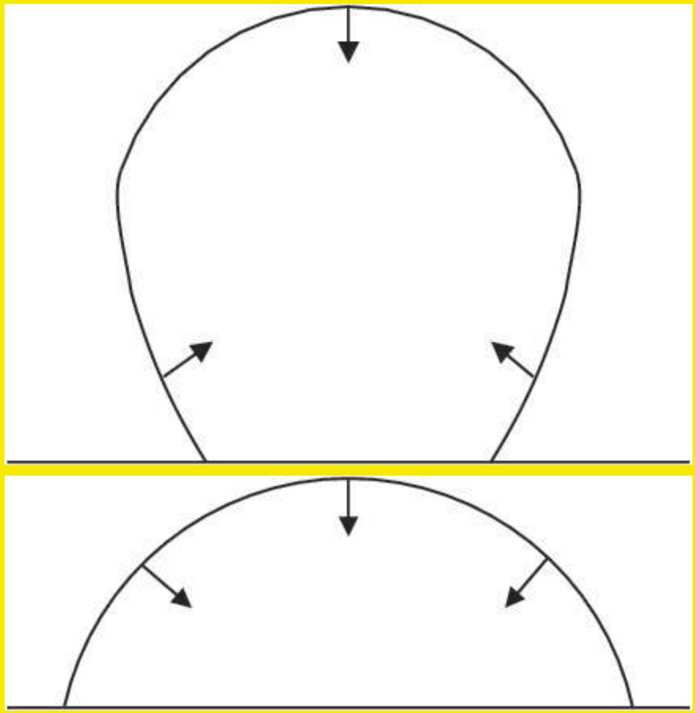
Selwa, Ofman, Solanki, Paper I (2011)

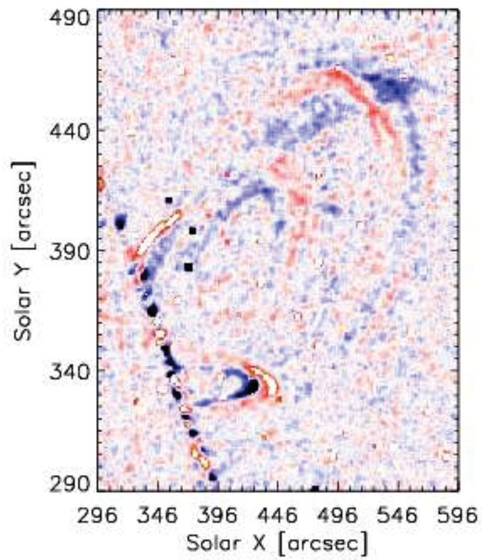


Problems with magnetic field



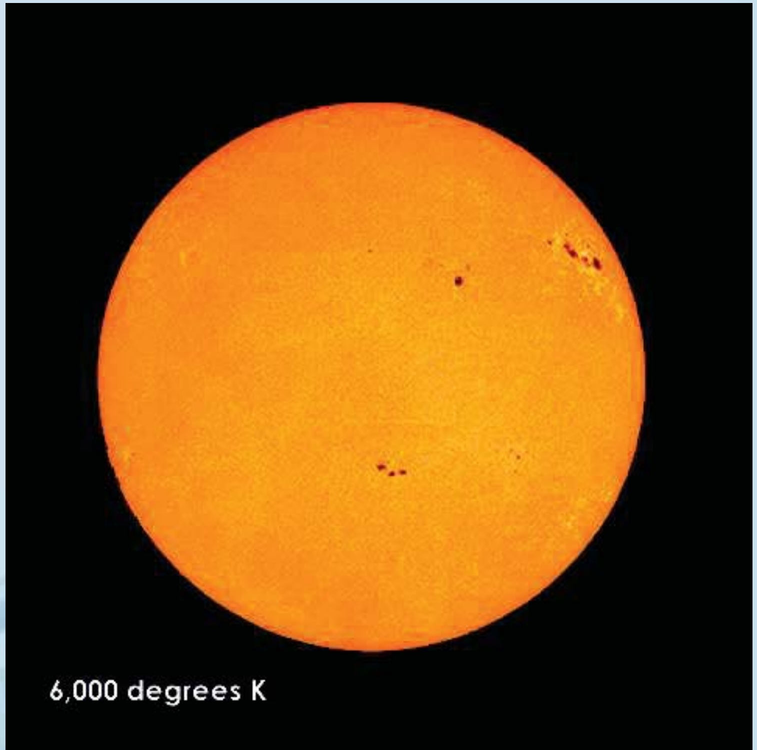


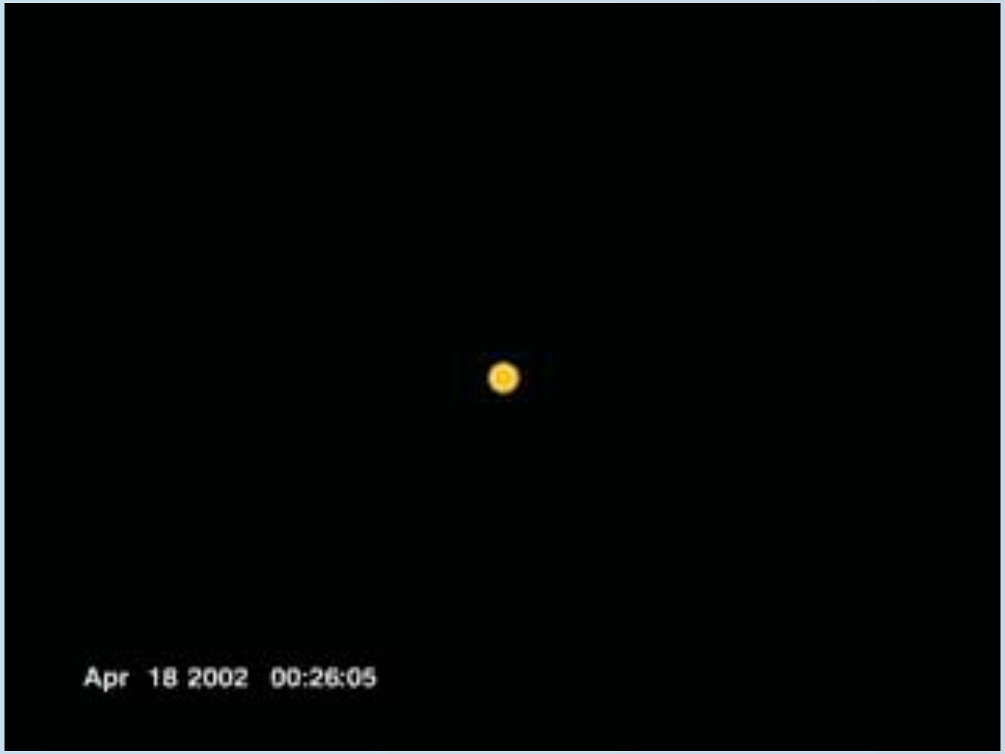




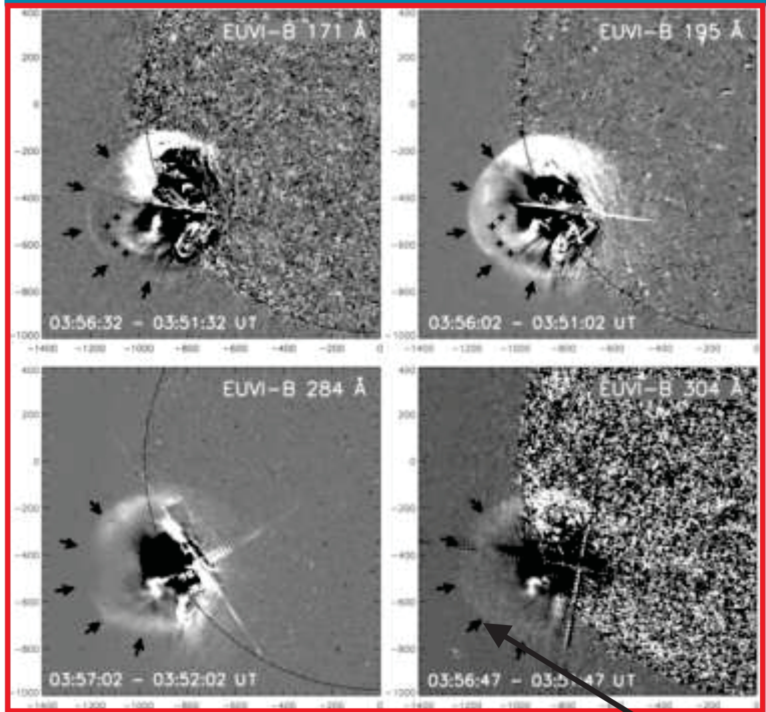
Selwa, Ofman, Solanki, Paper I (2011)

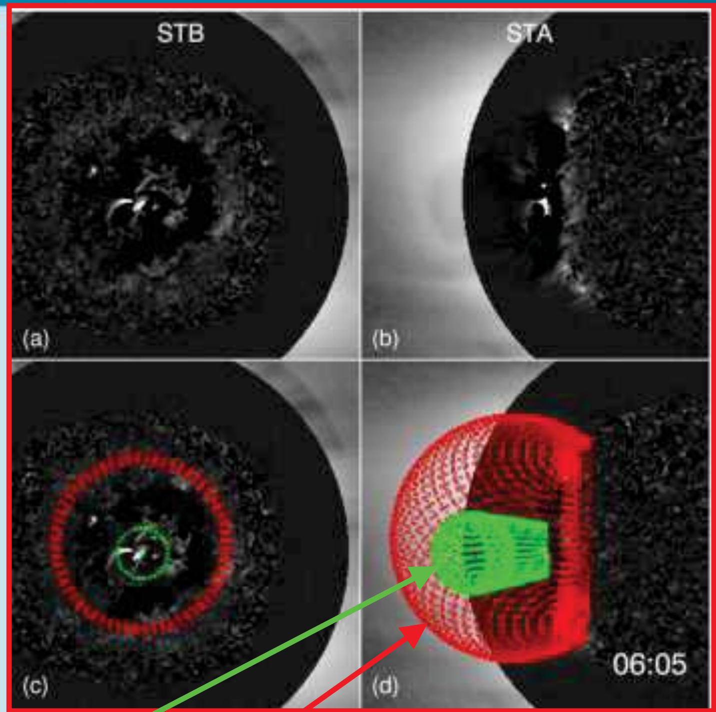
Structures on the Sun





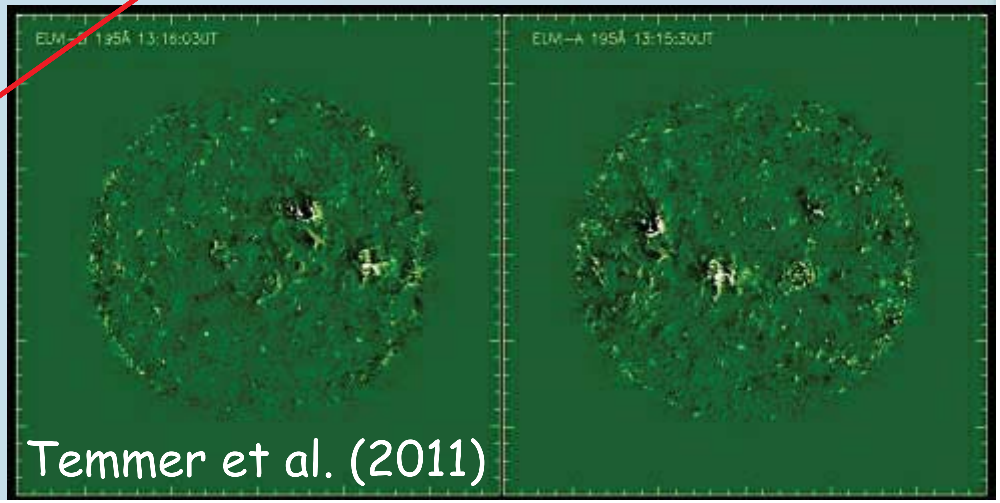
EIT/EUV waves



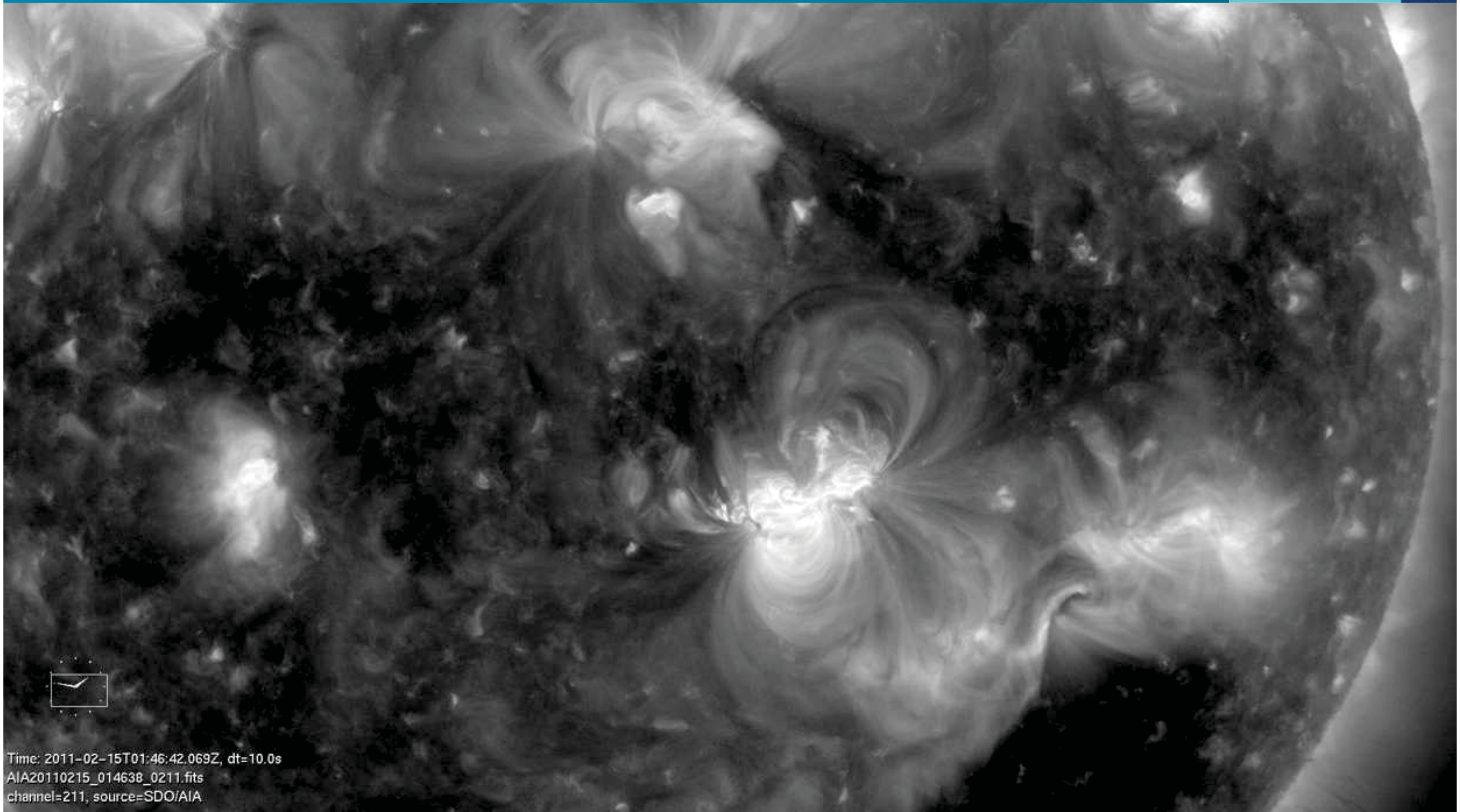


✓Veronig et al. (2010): wave **dome** in EUVI-B channels

✓Patsourakos et al. (2009): best-fit CME and wave model determined for STA



EIT/EUV waves



NOAA 11158 (Schrijver C.J., Aulanier G., Title A.M., Pariat E. & Delannée C., ApJ, 2011): an X-class flare follows EIT wave in time on 15.02.2011

EIT/EUV waves

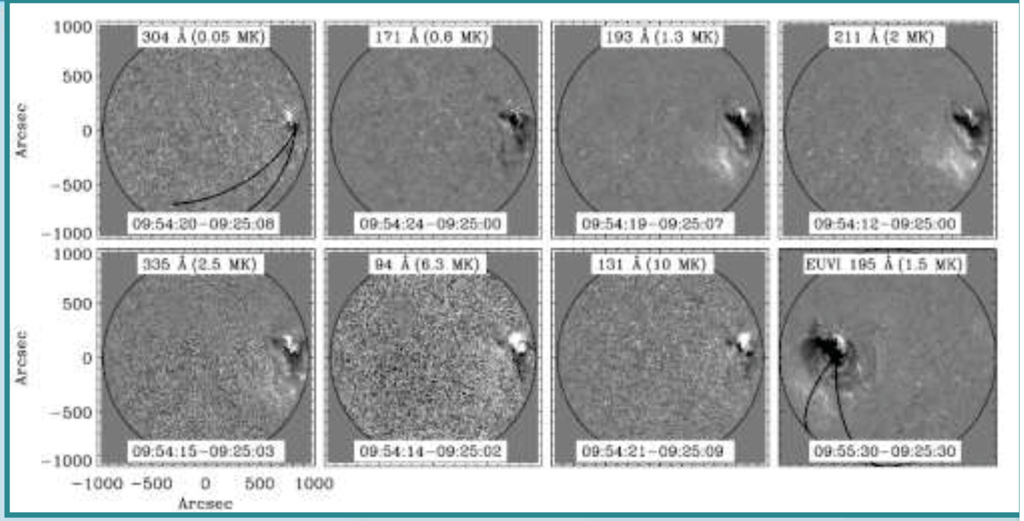
✓Event of 14.08.2010, SDO & STEREO observations

✓Using fast speed $V_f = \sqrt{V_A^2 + c_s^2}$

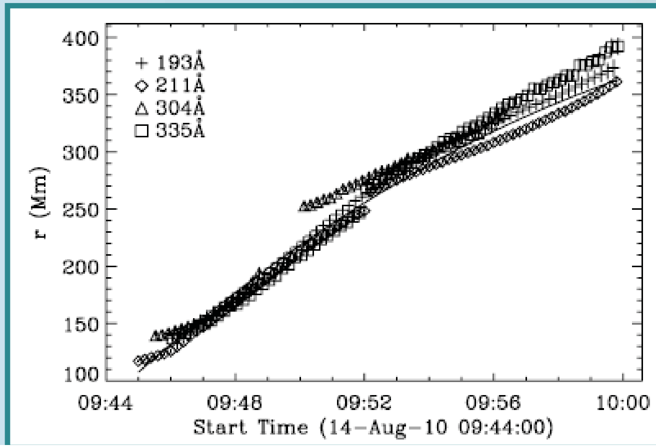
$$c_s^2 = \frac{\gamma p}{\rho} = \sqrt{\gamma k_B T / m} \qquad V_A^2 = \frac{B^2}{4\pi n m}$$

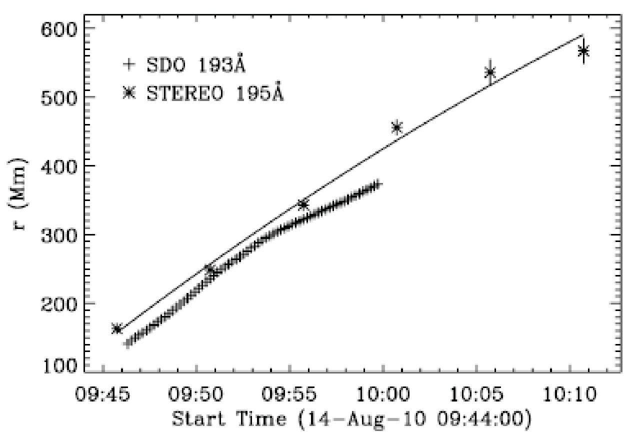
formula for magnetic field can be derived

$$B = \sqrt{4\pi n\left(m V_f^2 - \gamma k T_{peak}\right)}$$



✓Assuming quiet corona density (Wills-Davey et al. 2007) $n=2\text{-}6\times10^{8}\,cm^{-3}$ -> B=1-2G





Long et al. (2011)

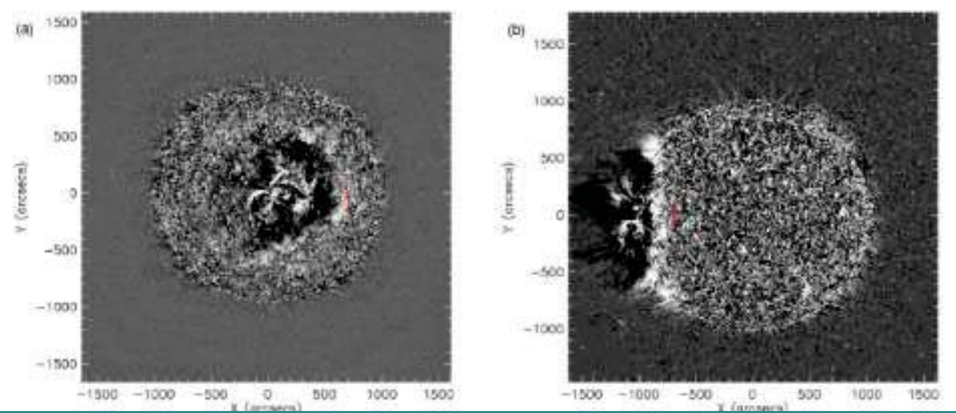
EIT/EUV waves

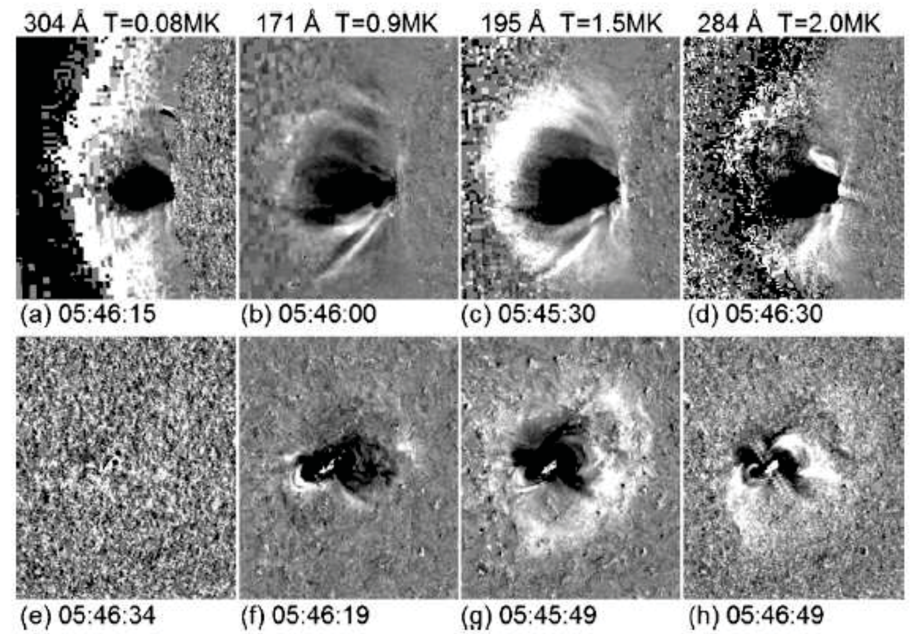
- ✓ Event of 13.02.2009, STEREO & Hinode observations
- ✓ Using fast speed $$V_f^2 = \frac{1}{2}\left[V_A^2 + c_s^2 + \sqrt{\left(V_A^2 + c_s^2\right)^2 - 4V_A^2 c_s^2 \cos^2 \vartheta}\right] \approx V_A^2 + c_s^2$$

magnetic field can be estimated $B = \sqrt{4\pi\left(\rho V_f^2 - \gamma P\right)}$ $P = 2nk_B T$

together with plasma β $\beta = \frac{8\pi P}{B^2}$

- ✓ Wave seems to be formed at T=1.5±0.5MK

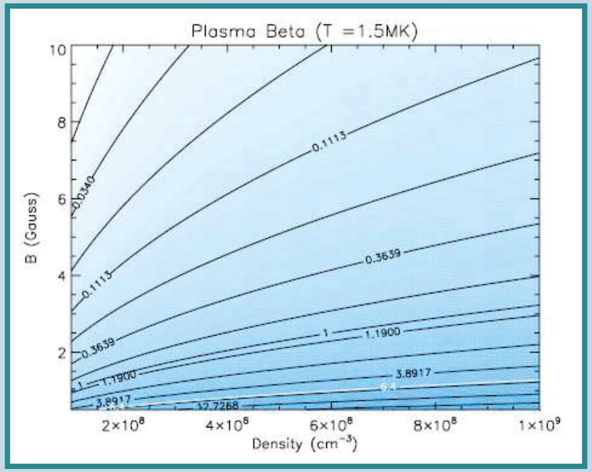


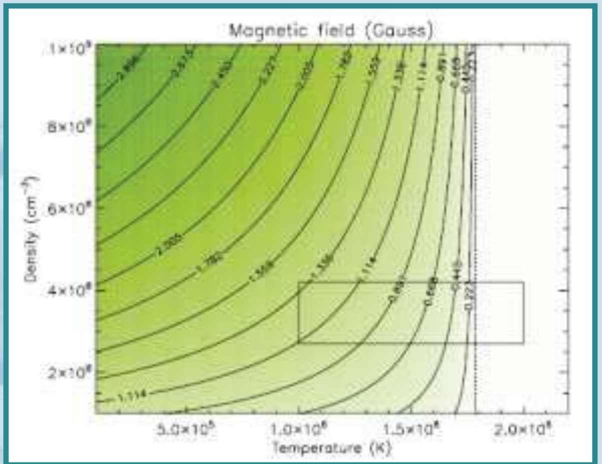


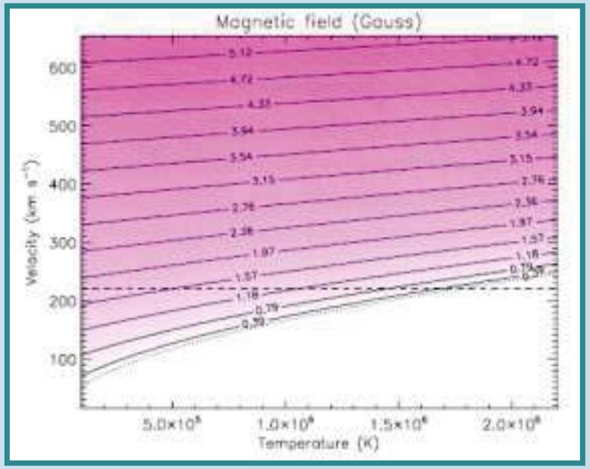
West et al. (2011)

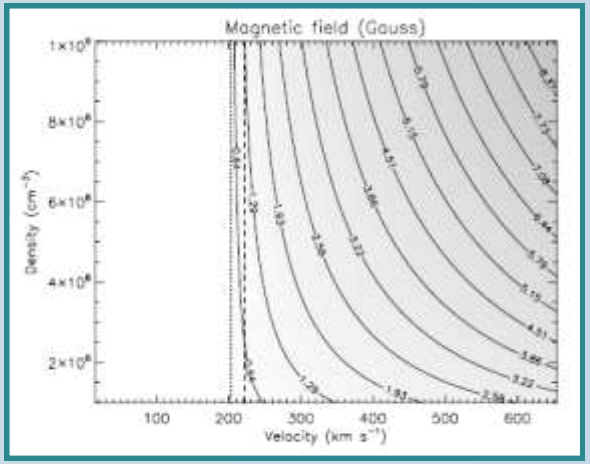
EIT/EUV waves

- ✓ Superimposed EIS(Hinode) slit on ST EUVI 195Å at similar times
- ✓ SiX 258/261 lines are used (similar temperature to the strongest line of FeXII 195 in EUVI) -> density of $3.4 \pm 0.8 \times 10^{8} cm^{-3}$
- ✓ MDI photospheric value: 7±21 G at the EIS slit
- ✓ Using detected fast speed $V_f = 220 \pm 30$ km/s , n and T -> $B = 0.7 \pm 0.7$G and $\beta = 6.4 \pm 3.1$
- ✓ Using Thompson & Myers (2009) speeds of 15-654 km/s -> more possibilities





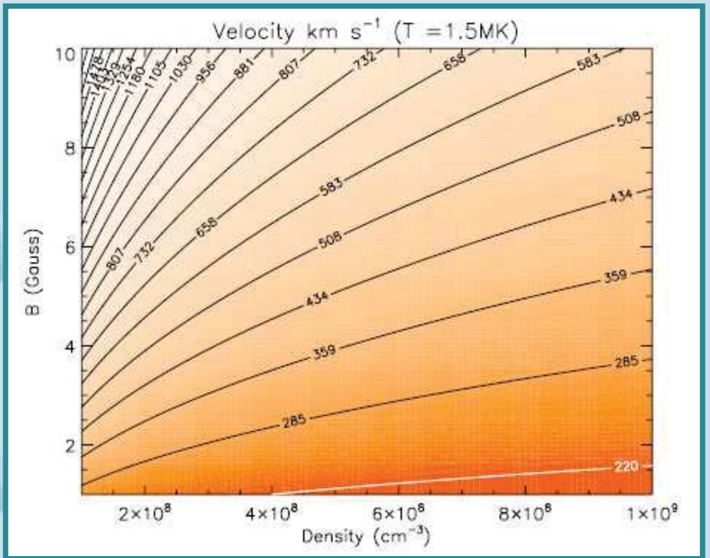


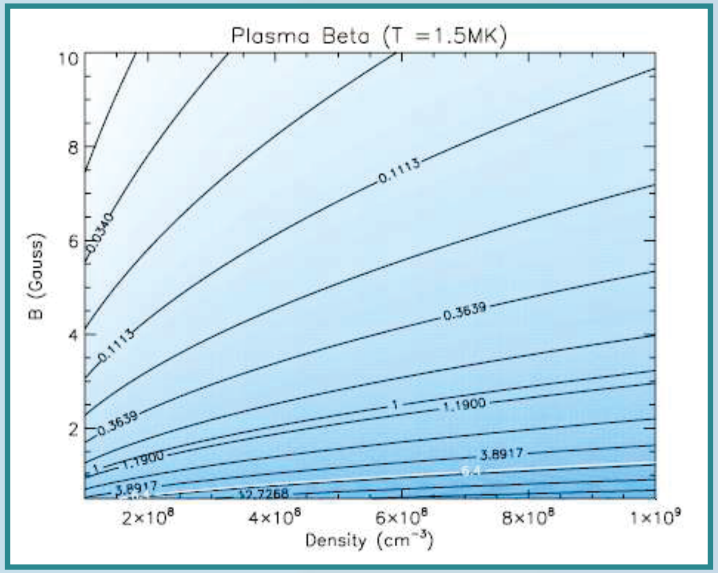


West et al. (2011)

EIT/EUV waves

- ✓ Superimposed EIS(Hinode) slit on ST EUVI 195Å at similar times
- ✓ SiX 258/261 lines are used (similar temperature to the strongest line of FeXII 195 in EUVI) -> density of $3.4 \pm 0.8 \times 10^8 cm^{-3}$
- ✓ MDI photospheric value: 7±21 G at the EIS slit
- ✓ Using detected fast speed V_f=220±30km/s , n and T -> B=0.7±0.7G and β=6.4±3.1
- ✓ Using Thompson & Myers (2009) speeds of 15-654 km/s -> more possibilities





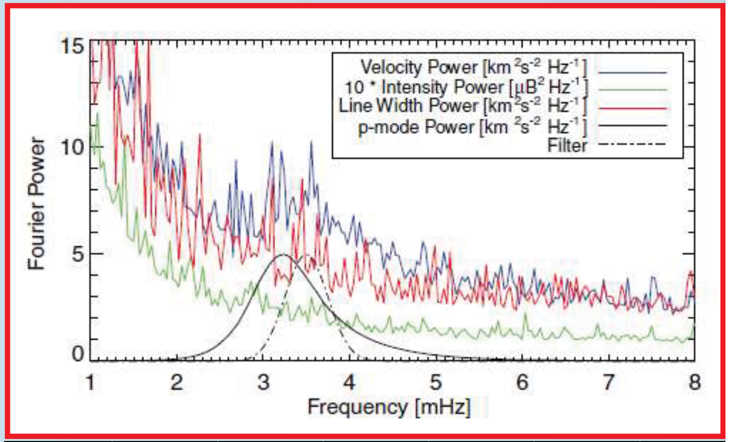
West et al. (2011)

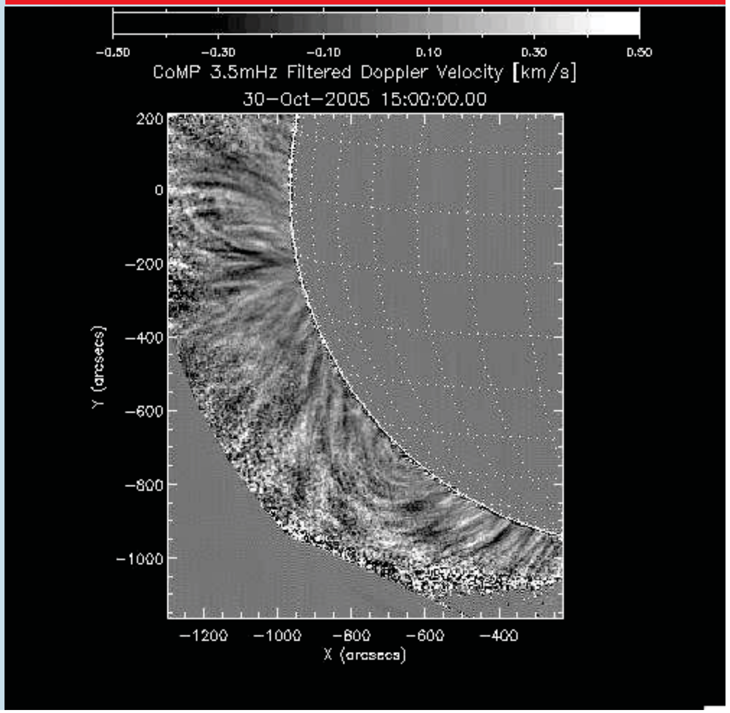
Alfvén waves

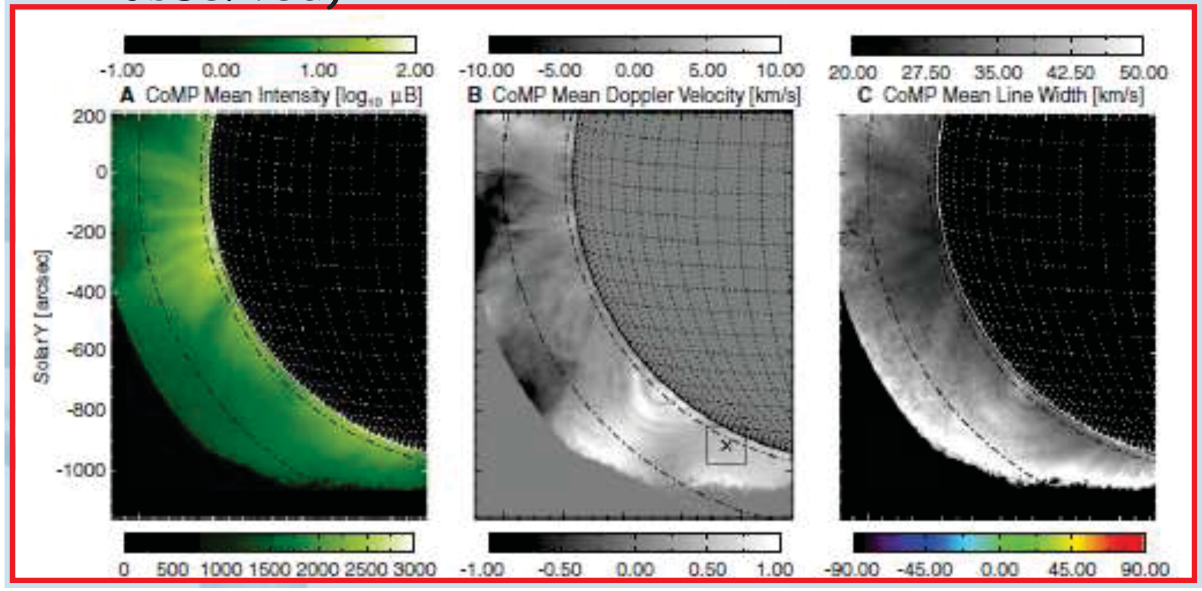
Tomczyk et al. (2007): Coronal Multi-Channel Polarimeter, **CoMP** (ground based observations):

- ✓ The waves travel at supersonic speeds,
- ✓ The waves have a transverse (perp. to B) V component and travel along magnetic field,
- ✓ The waves are incompressible (no density perturbations observed)

} **Alfvén waves**







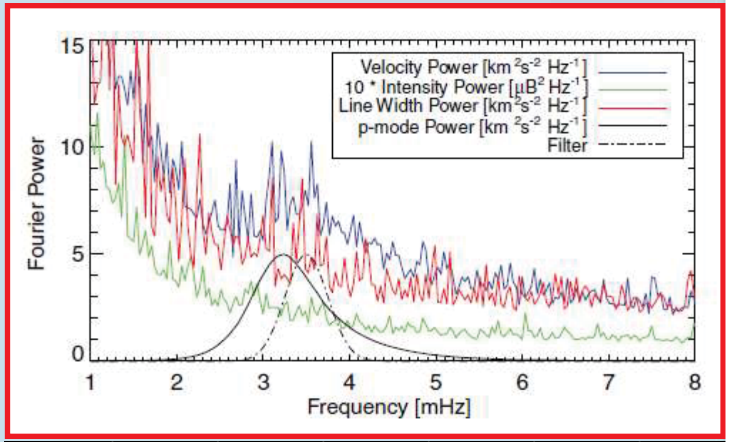
Alfvén waves

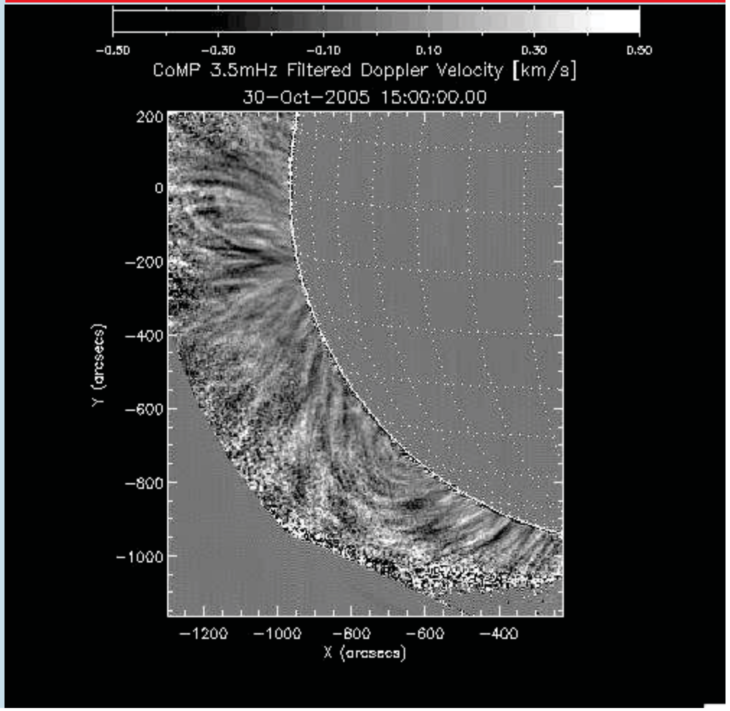
Seismology:

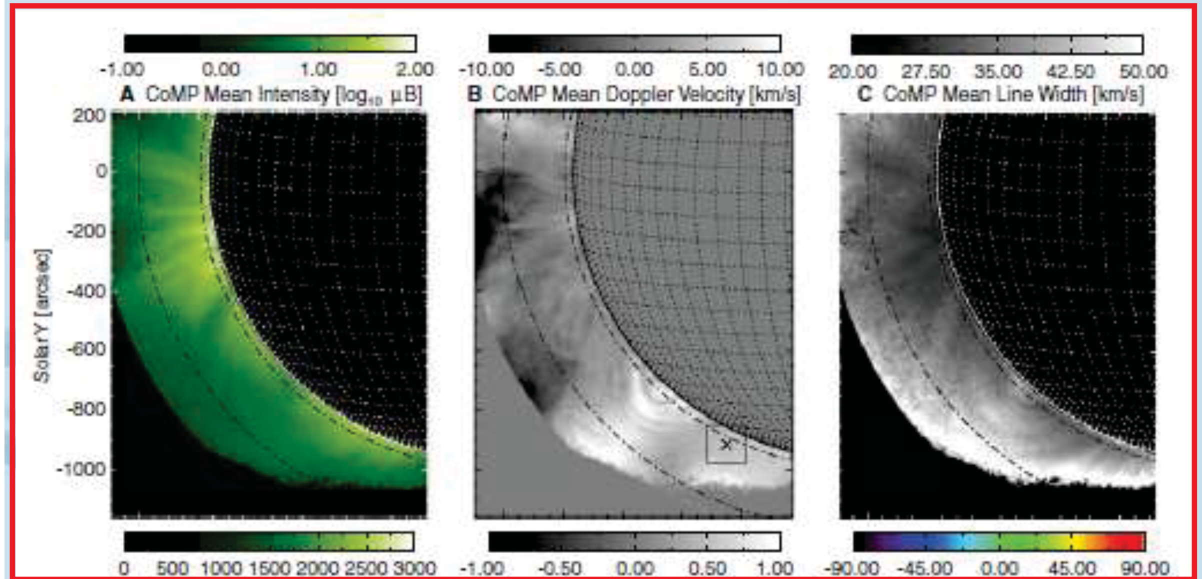
- ✓ Phase speeds obtained in this study are a projection onto the POS (the speed multiplied by sin(ϕ), where ϕ is the angle between LOS and the direction of wave propagation)
- ✓ Assuming typical electron density of 10^8 cm^{-3} and measured phase speeds 1.5-4 Mm/s -> B=8 and 26 G.

$$V_A = B / \sqrt{4\pi\rho}$$

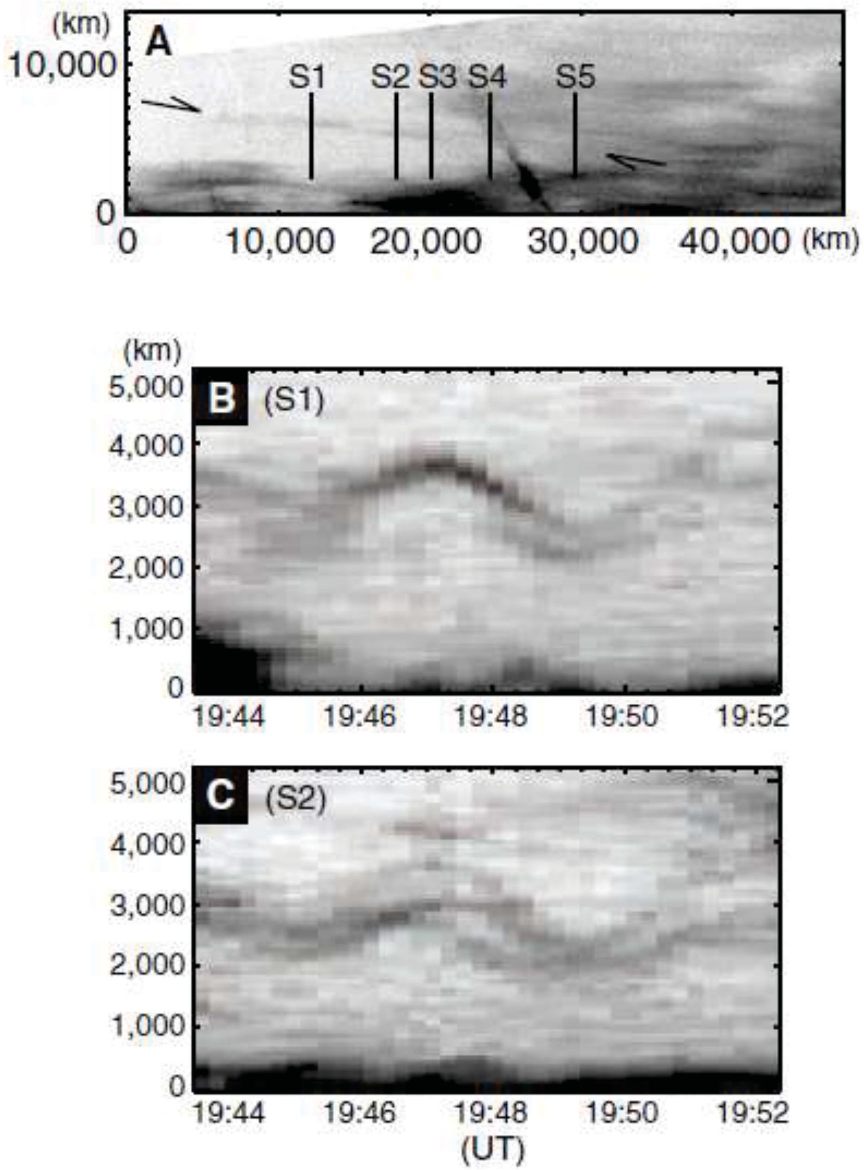
Tomczyk et al. (2007)





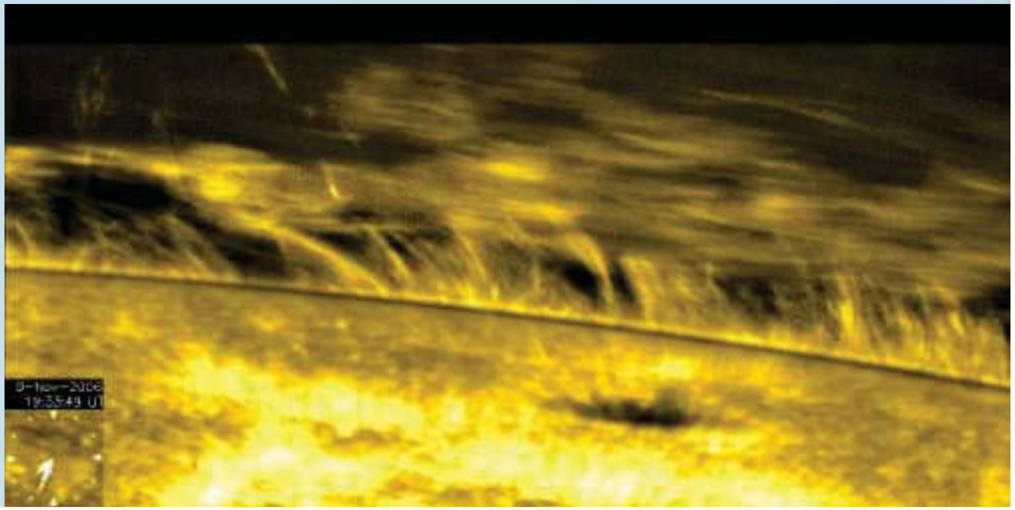


Prominences

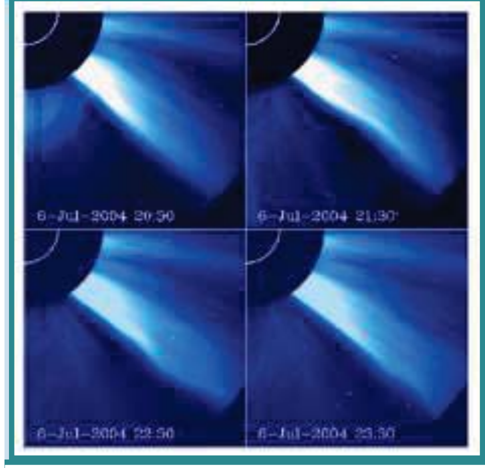


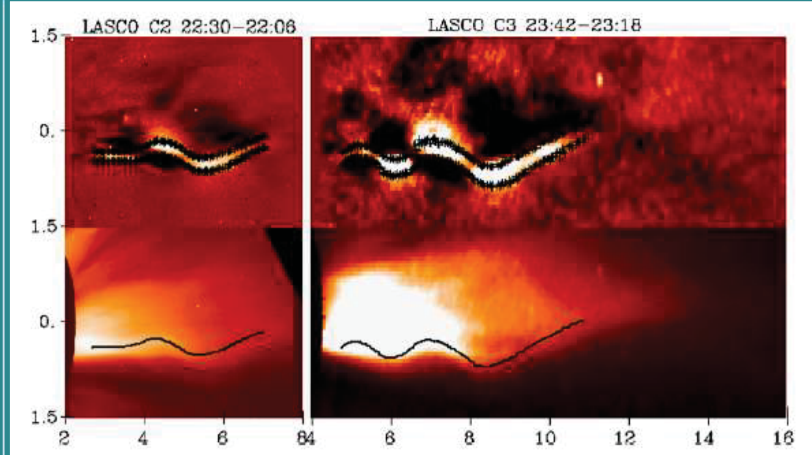
- ✓NOAA 10921 Hinode CaII SOT observations
- ✓Threads of prominence show oscillatory motion with periods 130-250s
- ✓Wave speed estimated to be >1050 km/s
- ✓Assuming plasma density 10^{10} cm^{-3} -> magnetic field strength for propagating Alfvén waves ~50G

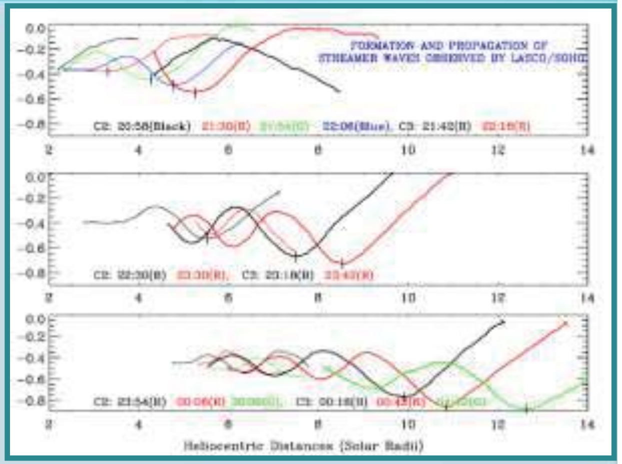
Okamoto et al. (2007)

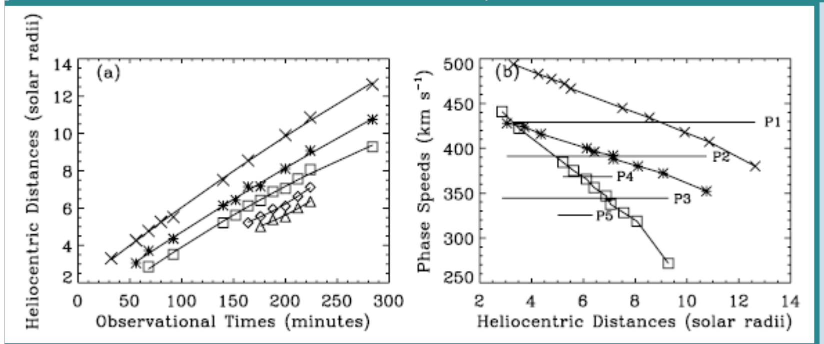


Streamers









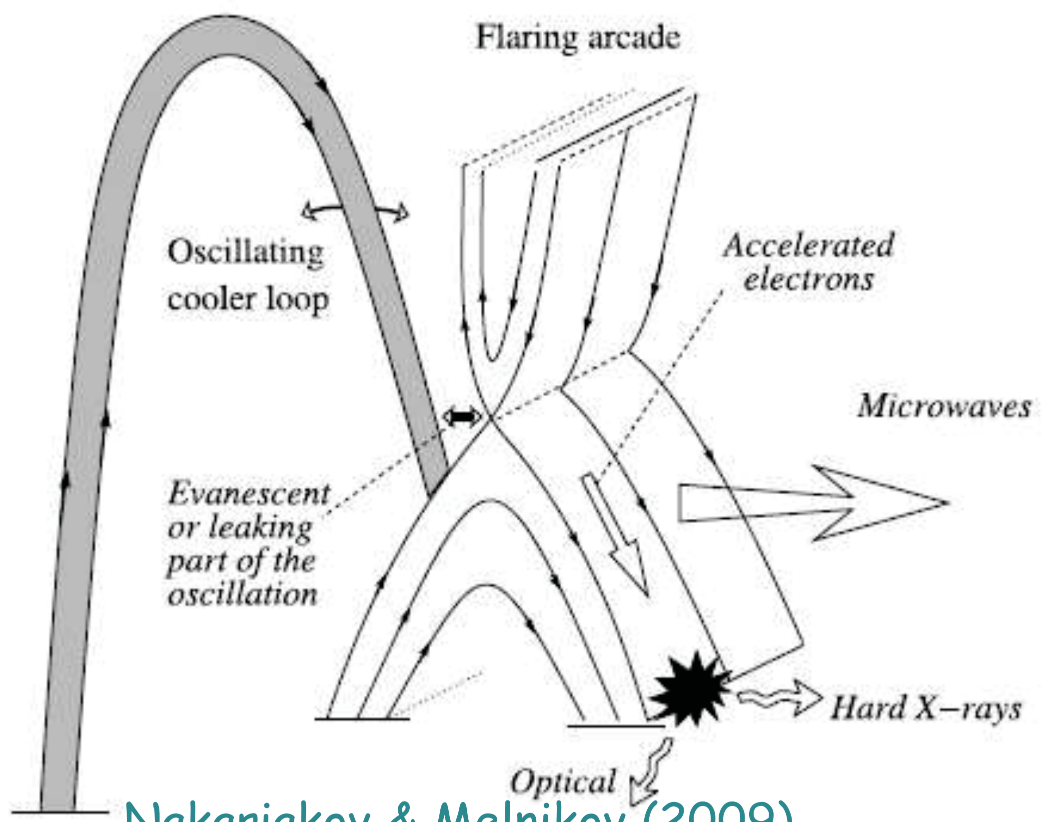
- ✓ With the white light coronagraph data streamer wave observations
- ✓ Periods of about 1 hr, wavelength 2-4 solar radii, an amplitude of about a few tens of solar radii, and a propagating phase speed in the range 300–500 km/s

- ✓ The motions were apparently driven by the restoring magnetic forces resulting from the CME impingement, suggestive of magnetohydrodynamic kink mode propagating outward along the plasma sheet of the streamer
- ✓ Using Alfvén speed formula B is calculated in 2 places (parameters from Chen & Hu (2001)):
- ✓ $5R_s$: V_{sw}=100 km/s, n=1×10^5cm^{-3} -> B=0.045G
- ✓ $10R_s$: V_{sw}=200 km/s, n=2×10^5cm^{-3} -> B=0.01G

Chen et al. (2010)

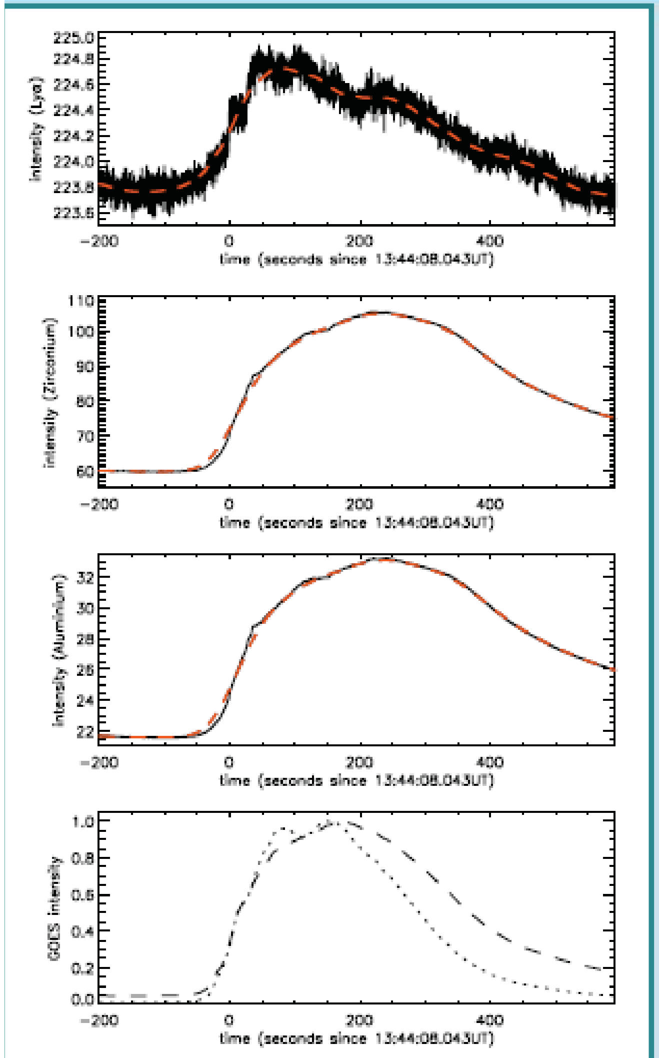
QPP

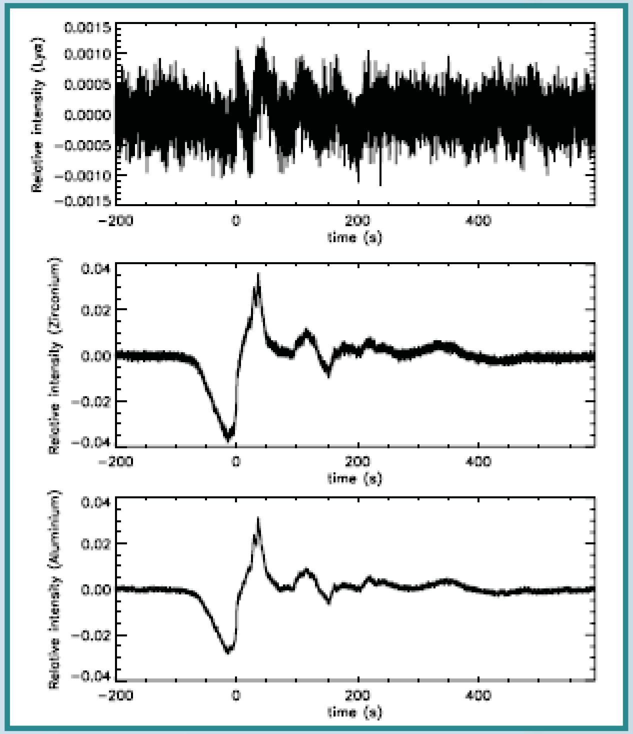
- ✓ QPP: oscillations in solar flares
- ✓ Often showing multi-periodicity: Inglis & Nakariakov (2009): 12s, 18s, 28s; Nakariakov et al. (2010) 13s & 40s (radio band)
- ✓ Recent observations by Van Doorsselaere et al. (2011) from LYRA (PROBA2) (irradiance measurement) show multi-periodicity

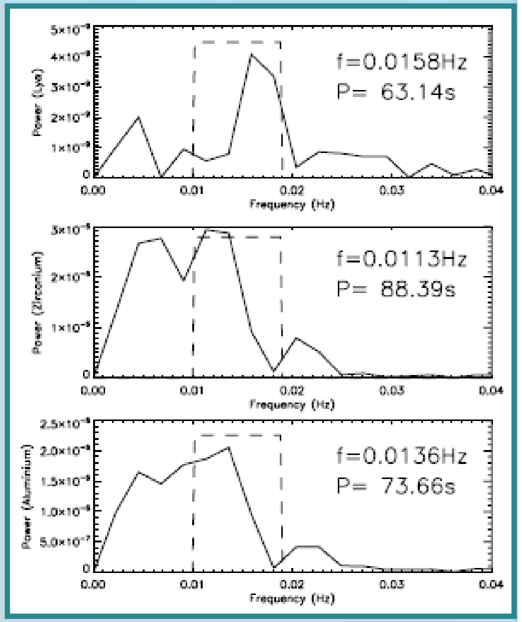


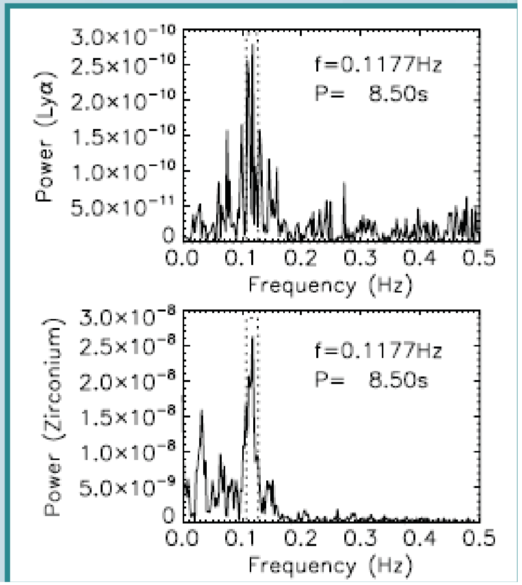
Nakariakov & Melnikov (2009)

QPP









Van Doorresselaere et al. (2011)

QPP

✓ Recent observations by Van Doorsselaere et al. (2011) from LYRA (PROBA2) (irradiance measurement) show multi-periodicity: 63-88s and 8.5s, ratio r=8.8.

✓ Interpretation: modulation of intensity of flare emission -> slow and sausage waves

✓ Classical waveguide model

(pressure balance between internal and external medium)

$$p_i + \frac{B_i^2}{2\mu} = p_e + \frac{B_e^2}{2\mu}$$

$$\frac{\rho_e}{\rho_i} = \frac{2c_{si}^2 + \gamma V_{Ai}^2}{2c_{se}^2 + \gamma V_{Ae}^2}$$

$$\frac{V_{Ae}^2}{V_{Ai}^2} = \zeta \frac{\beta_i + 1}{\beta_e + 1}$$

$$\zeta = \frac{\rho_i}{\rho_e}$$

✓ Short wavelength limit

fundamental mode, equal loop length,

fast sausage mode V_{Ai}, slow mode c_{si}

$$V_{Ai} = r c_{si}$$

$$\beta_i = \frac{2}{\gamma r} = 0.14$$

✓ Long wavelength limit

fundamental mode, equal loop length,

fast sausage mode V_{Ae} , slow mode c_{Ti}

$$V_{Ae} = r c_{Ti}$$

$$\frac{1}{c_{Ti}^2} = \frac{1}{c_{si}^2} + \frac{1}{V_{Ai}^2}$$

$$r = \frac{V_{Ae}}{V_{Ai}} \sqrt{1 + \frac{V_{Ai}^2}{c_{si}^2}} \rightarrow r^2(\beta_e + 1) = \zeta(\beta_i + 1)\left(\frac{2}{\gamma \beta_i} + 1\right)$$

Van Dooresselaere et al. (2011)

QPP

- ✓ Long wavelength limit

  fundamental mode, equal loop length,

  fast sausage mode V_{Ae} , slow mode c_{Ti}

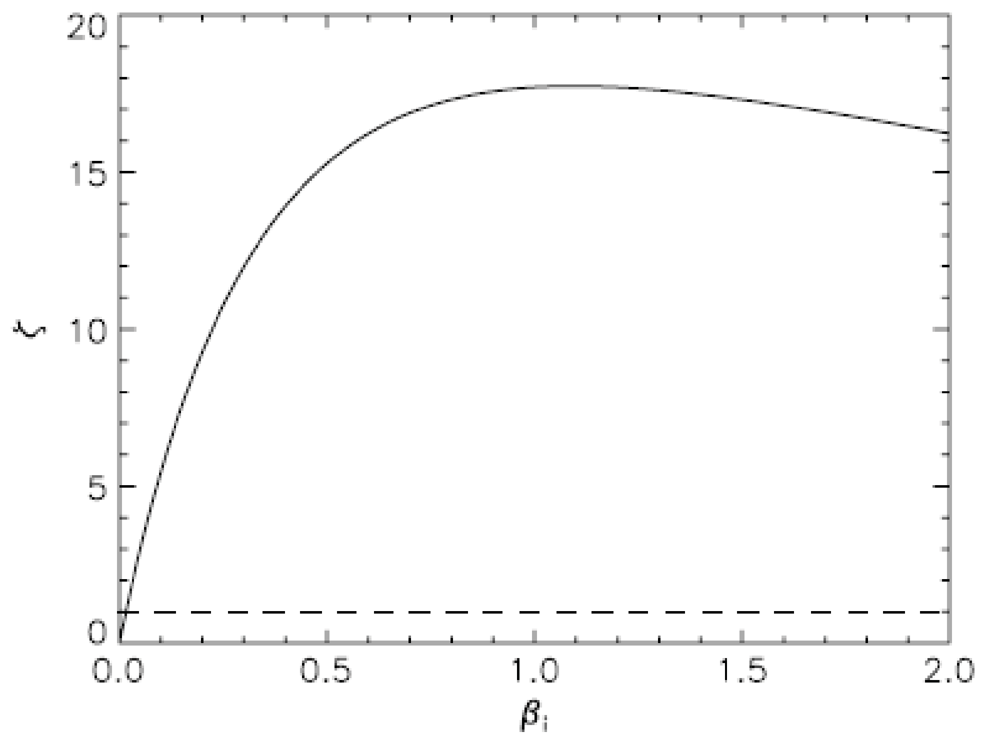
$$V_{Ae} = r c_{Ti}$$

$$\frac{1}{c_{Ti}^2} = \frac{1}{c_{si}^2} + \frac{1}{V_{Ai}^2}$$

$$r = \frac{V_{Ae}}{V_{Ai}} \sqrt{1 + \frac{V_{Ai}^2}{c_{si}^2}} \rightarrow r^2 (\beta_e + 1) = \zeta(\beta_i + 1)\left(\frac{2}{\gamma \beta_i} + 1\right)$$

$$\zeta(\beta) \rightarrow \xi_{\max} \approx 18$$

$$\zeta > 1 \rightarrow \begin{cases} \beta_{i,\min} \approx 0.016 \\ \beta_{i,\max} \approx 75 \end{cases}$$

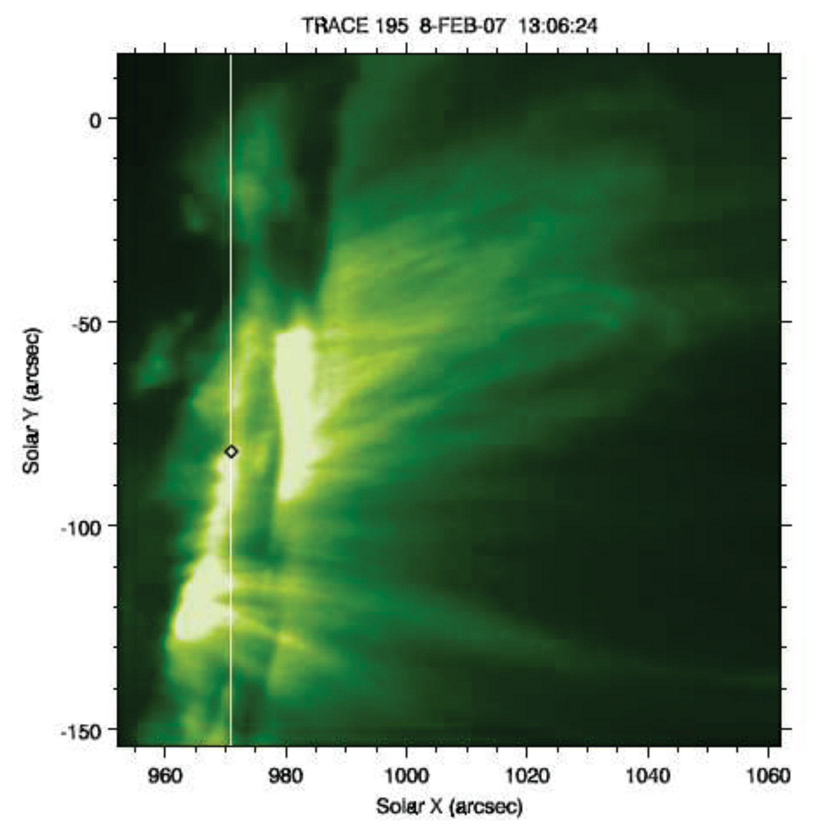


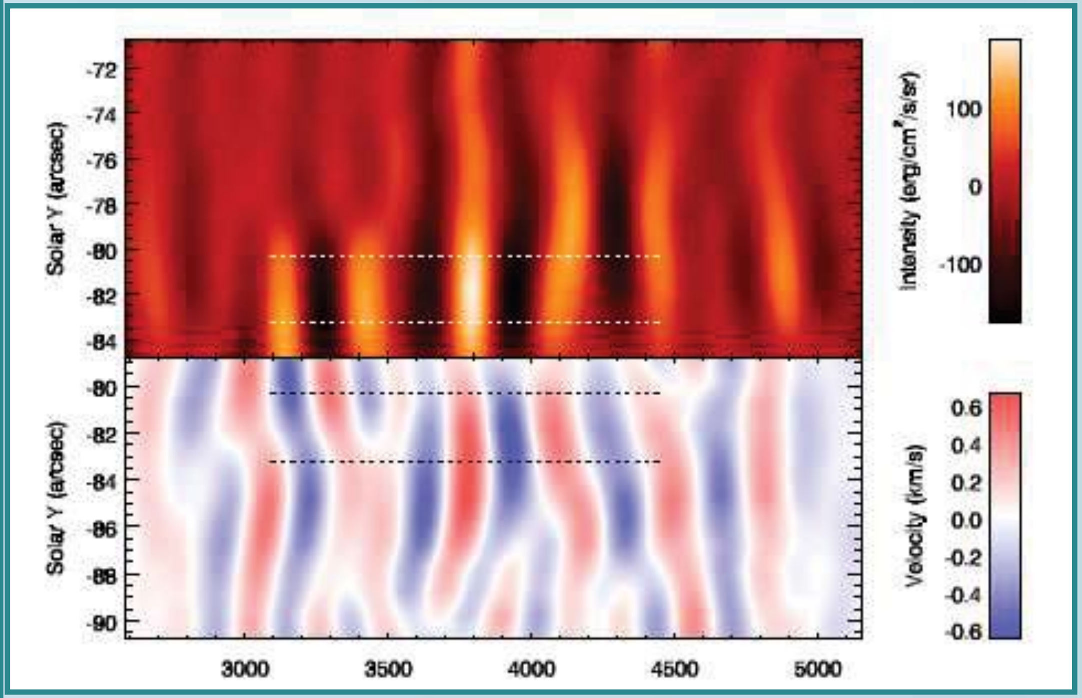
Van Dooresselaere et al. (2011)

Adiabatic index γ

✓Van Doorsselaere et al. (2011) : EIS (Hinode) obseration of 08.02.2007

✓P_V=314±83s, P_I=344±61s -> slow wave





Adiabatic index γ

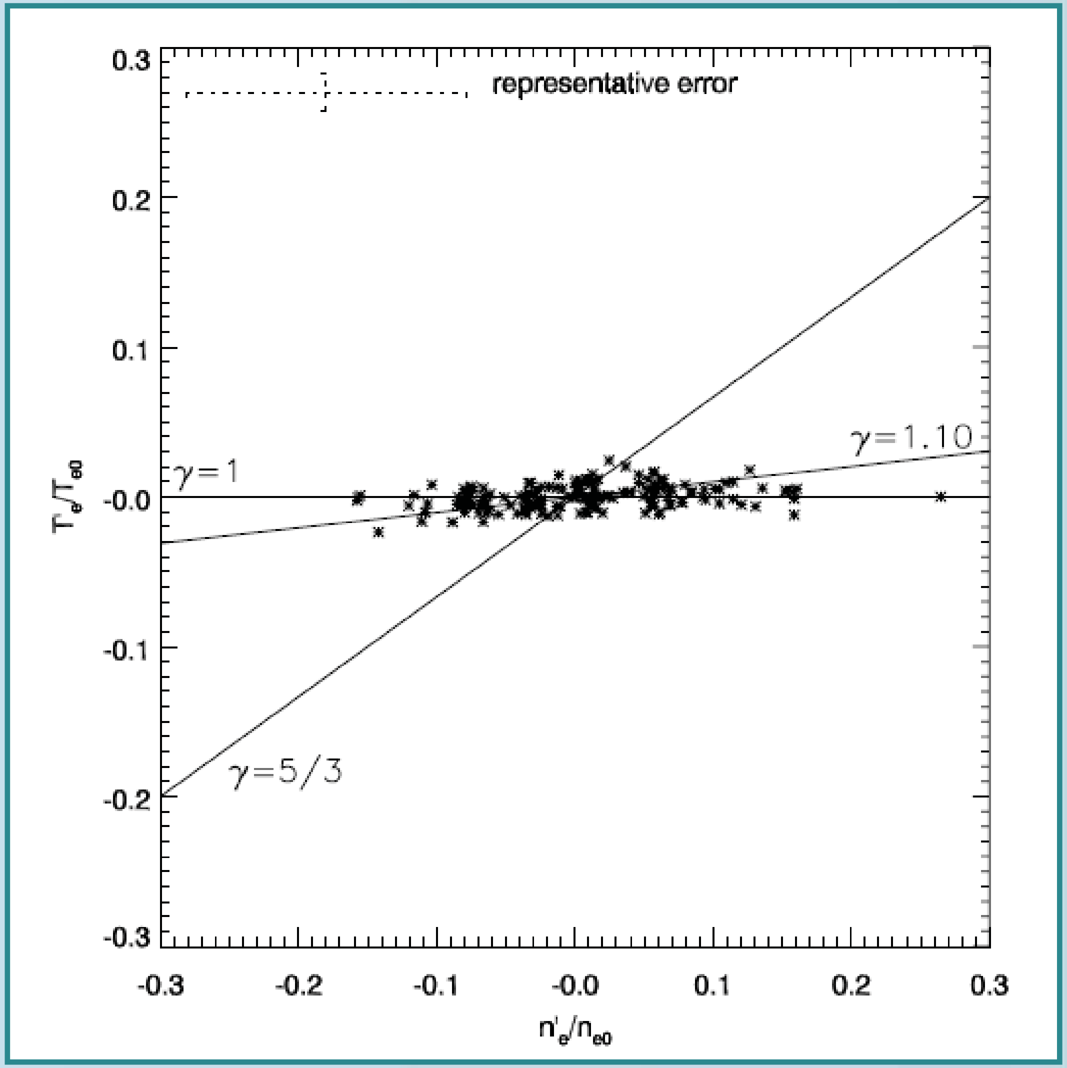
✓Linearized MHD theory (e.g. Goossens 2003) + polytropic relation

$$p = K\rho^{\gamma_{eff}}$$

$$\frac{\rho_1}{\rho_0} = \frac{1}{\gamma_{eff}} \frac{p_1}{p_0} = \frac{1}{\gamma_{eff} - 1} \frac{T_1}{T_0}$$

✓Scatter plot+ least square

$\gamma_{eff}=1.10\pm0.02 \neq 5/3$



Van Doorsselaere et al. (2011)

Conclusions

Coronal seismology;

- ✓ Observe and model coronal waves
- ✓ Compare
- ✓ Measure physical parameters
- ✓ Adjust/improve model (e.g. clue about damping mechanisms of oscillations)

- ✓ Geometry effect on magnetic field determination

- ✓ Quiet Sun parameters from EUV waves

- ✓ Magnetic field determination using Alfvén waves

- ✓ Multi-periodicity: determination of scale height, β, loop expansion