Waves in the coronal Holes

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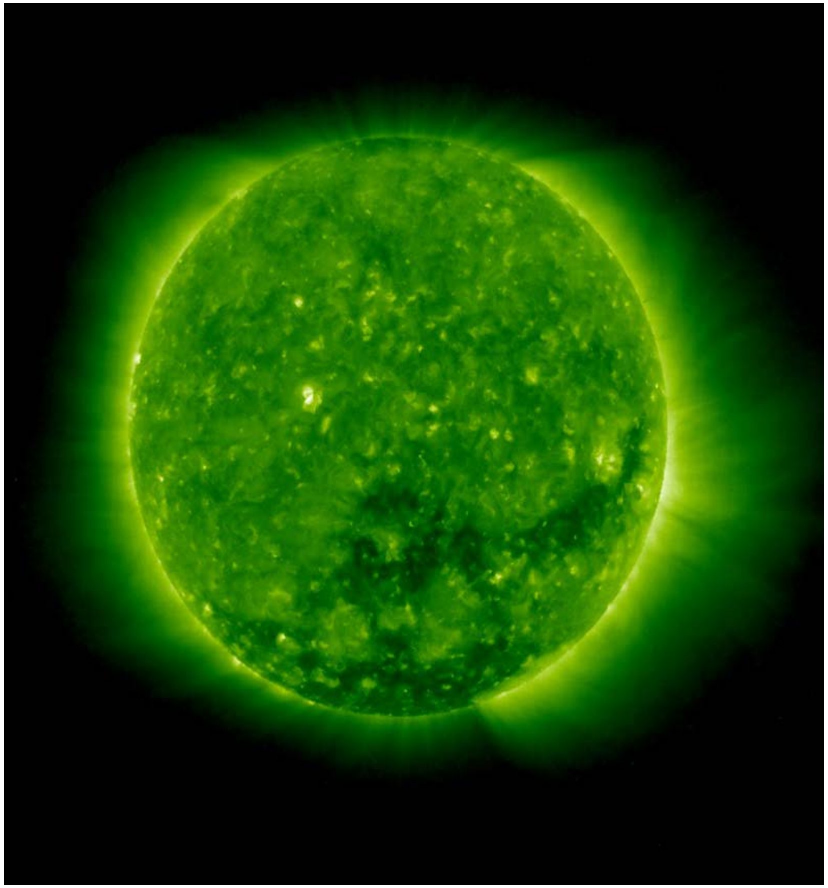
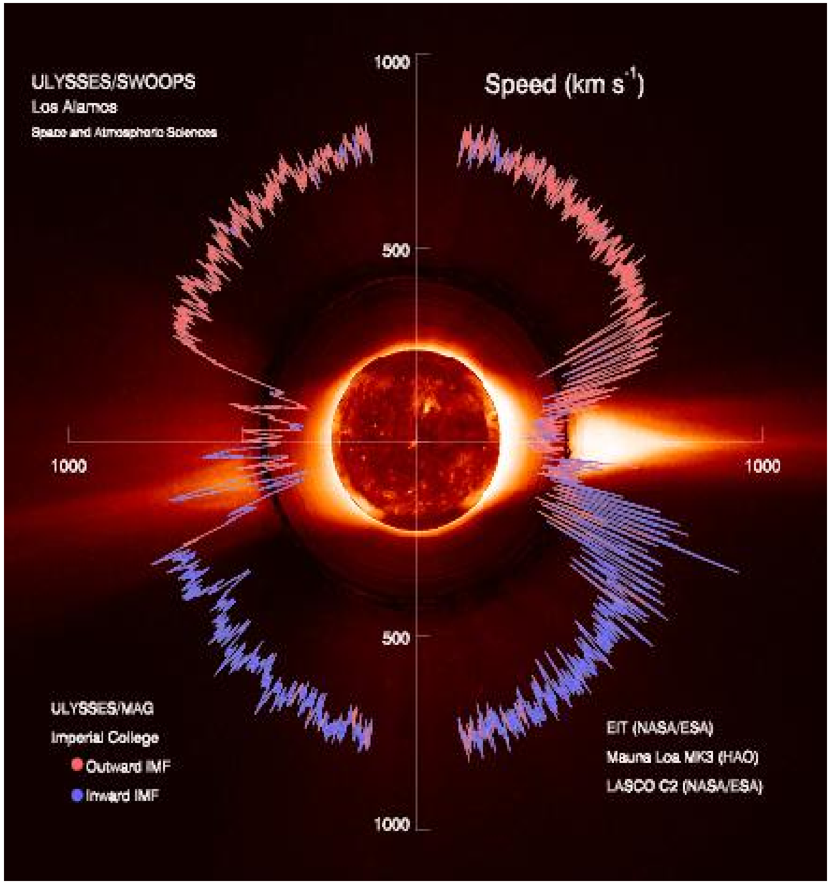
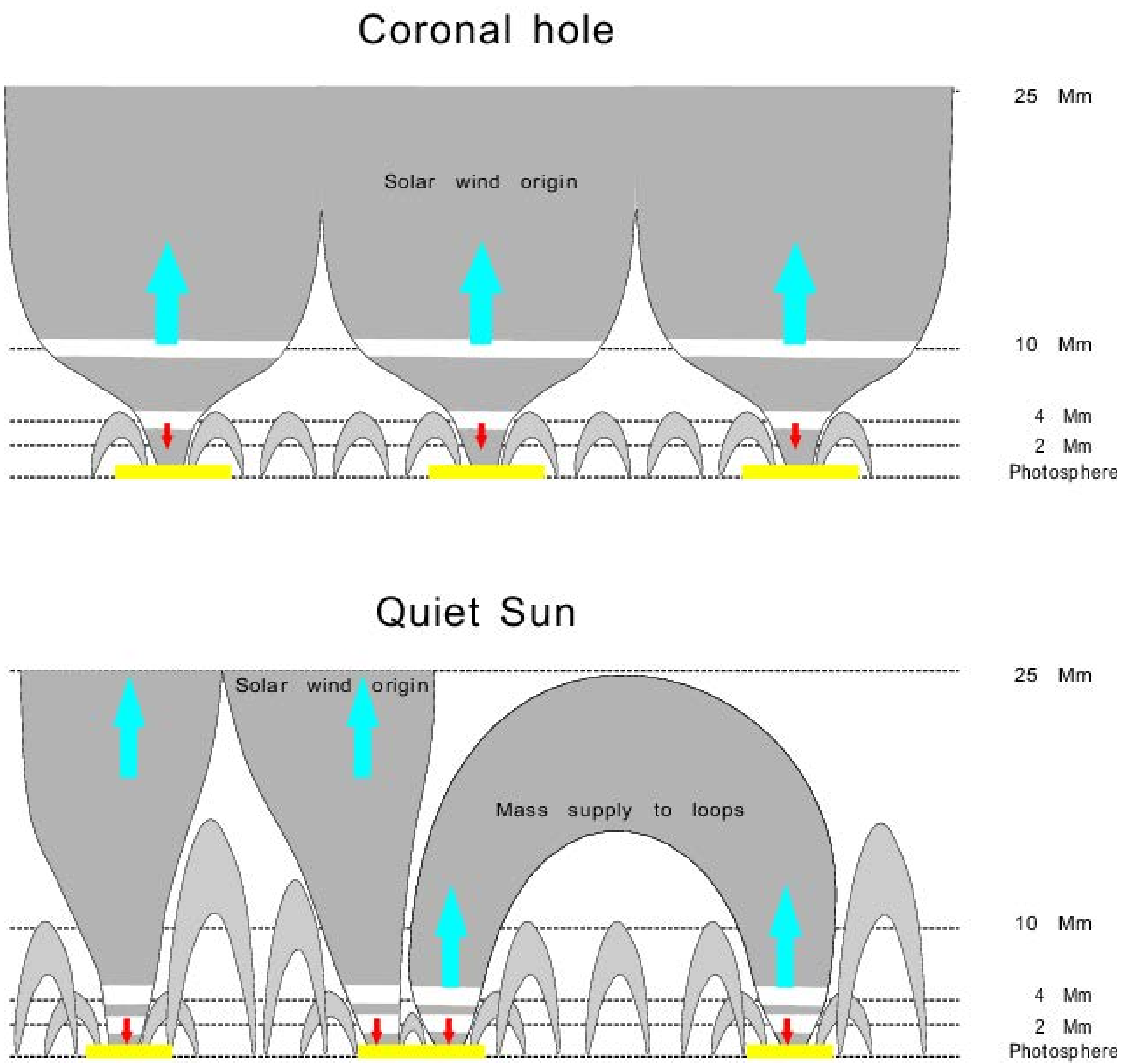
ULYSSES observation of Solar wind





TR structures in CH & QS, is there a difference?



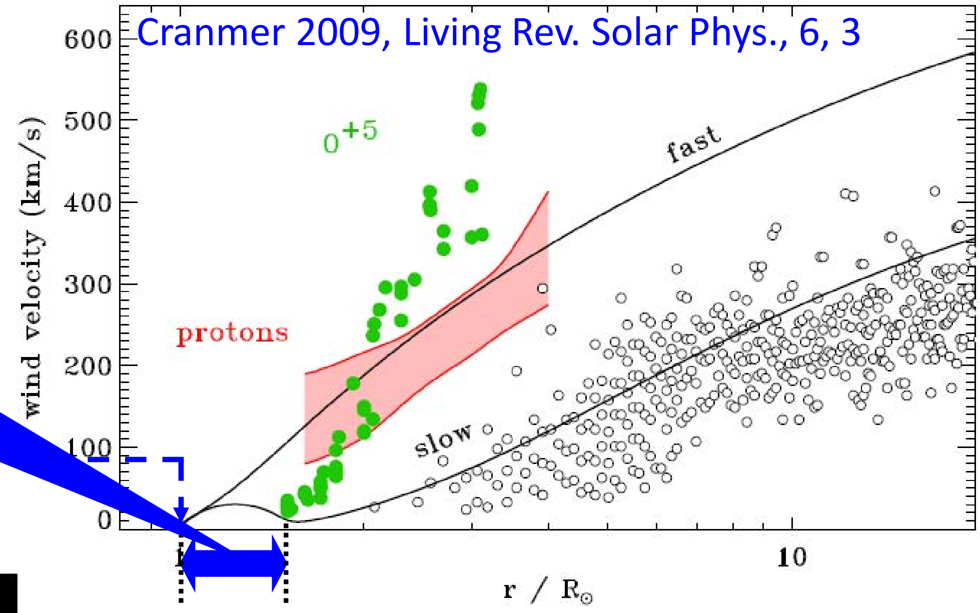
CHs: open funnels, TR higher and thicker, expand very strongly

Tian et al. 2010, New Astron. Rev., 54, 13

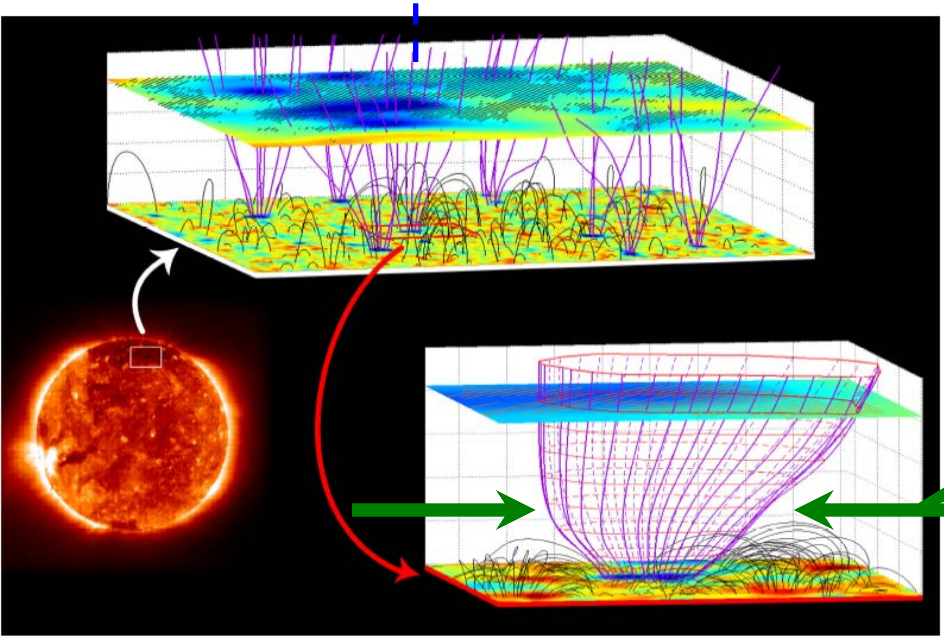
He et al. 2010, Adv. Space Res., 45, 303

Fast wind from magnetic funnels

Initial acceleration (from ~5 km/s to ~100 km/s)



Solar wind mass supply through supergranule-scale magnetoconvection in the chromosphere & TR

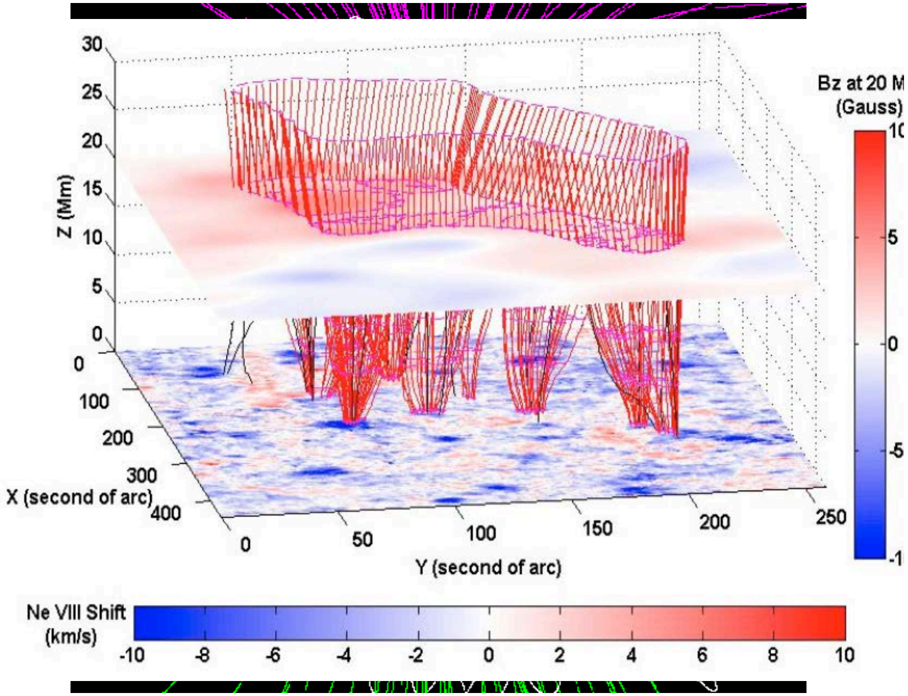


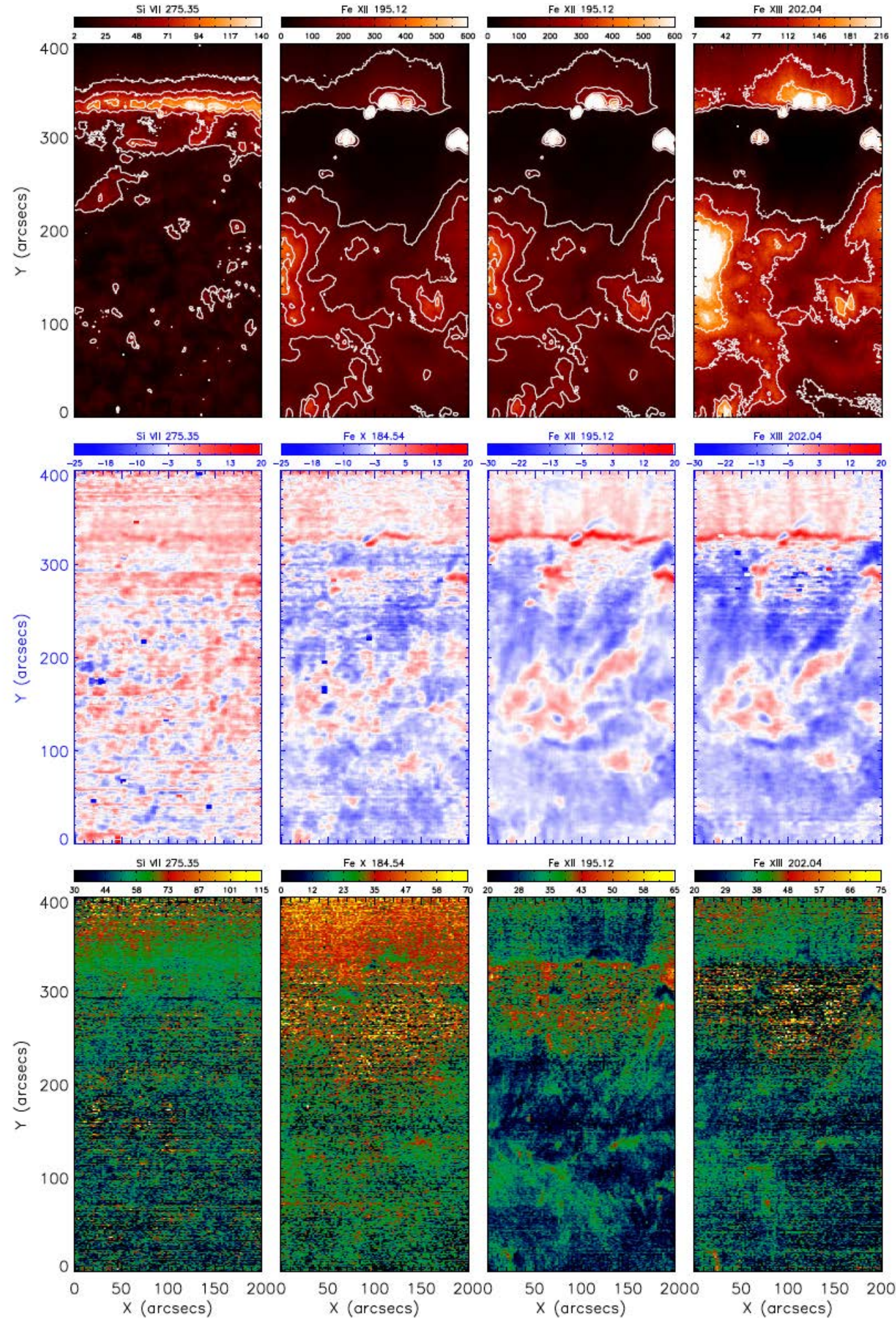
Tu et al. 2005, Science, 308, 519

Tu et al. 2005, Solar Wind 11

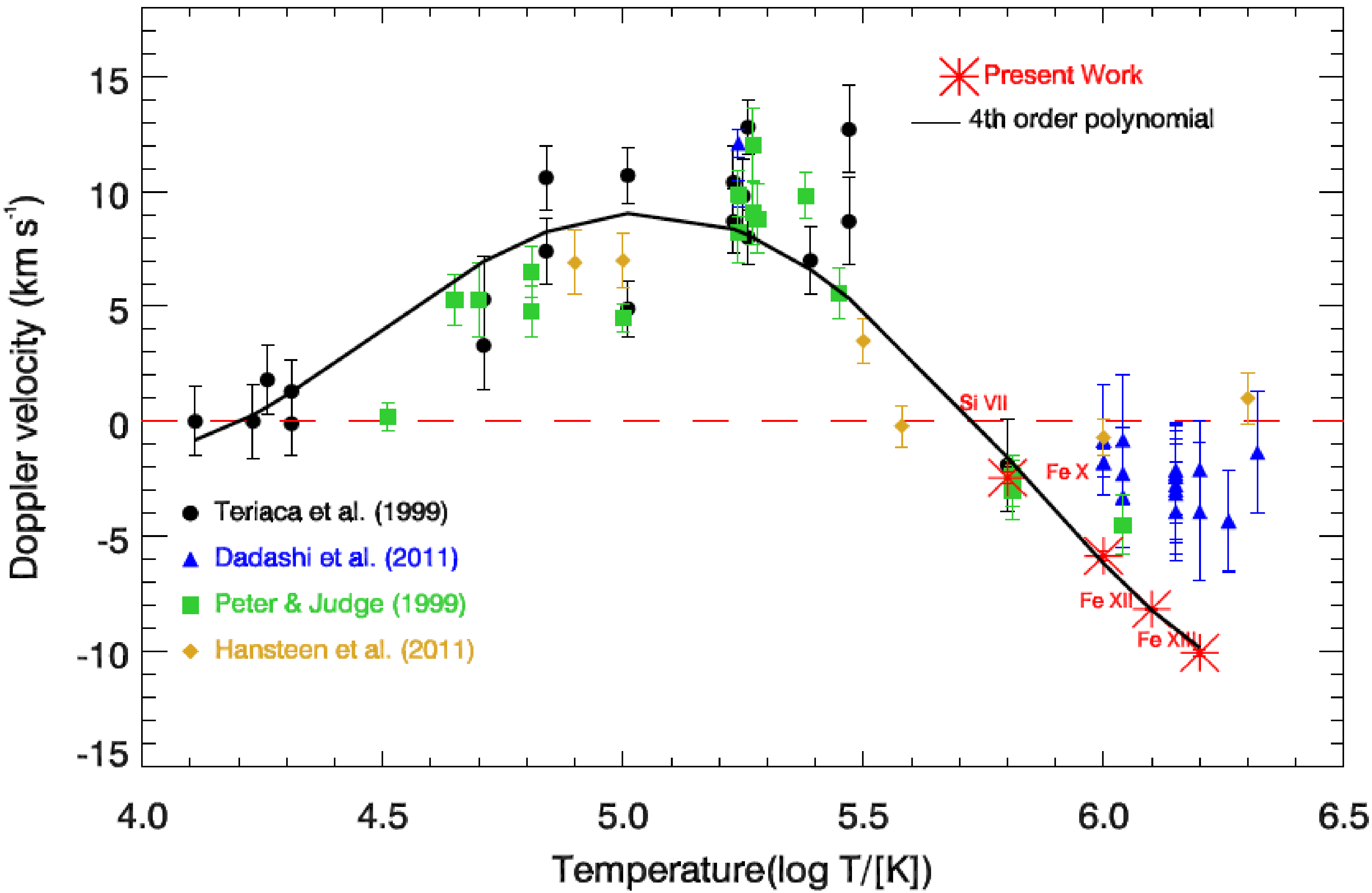
Initial acceleration of the fast solar wind

- Blueshift in TR and coronal lines, increases with T
- Blueshift patches converge as T increases





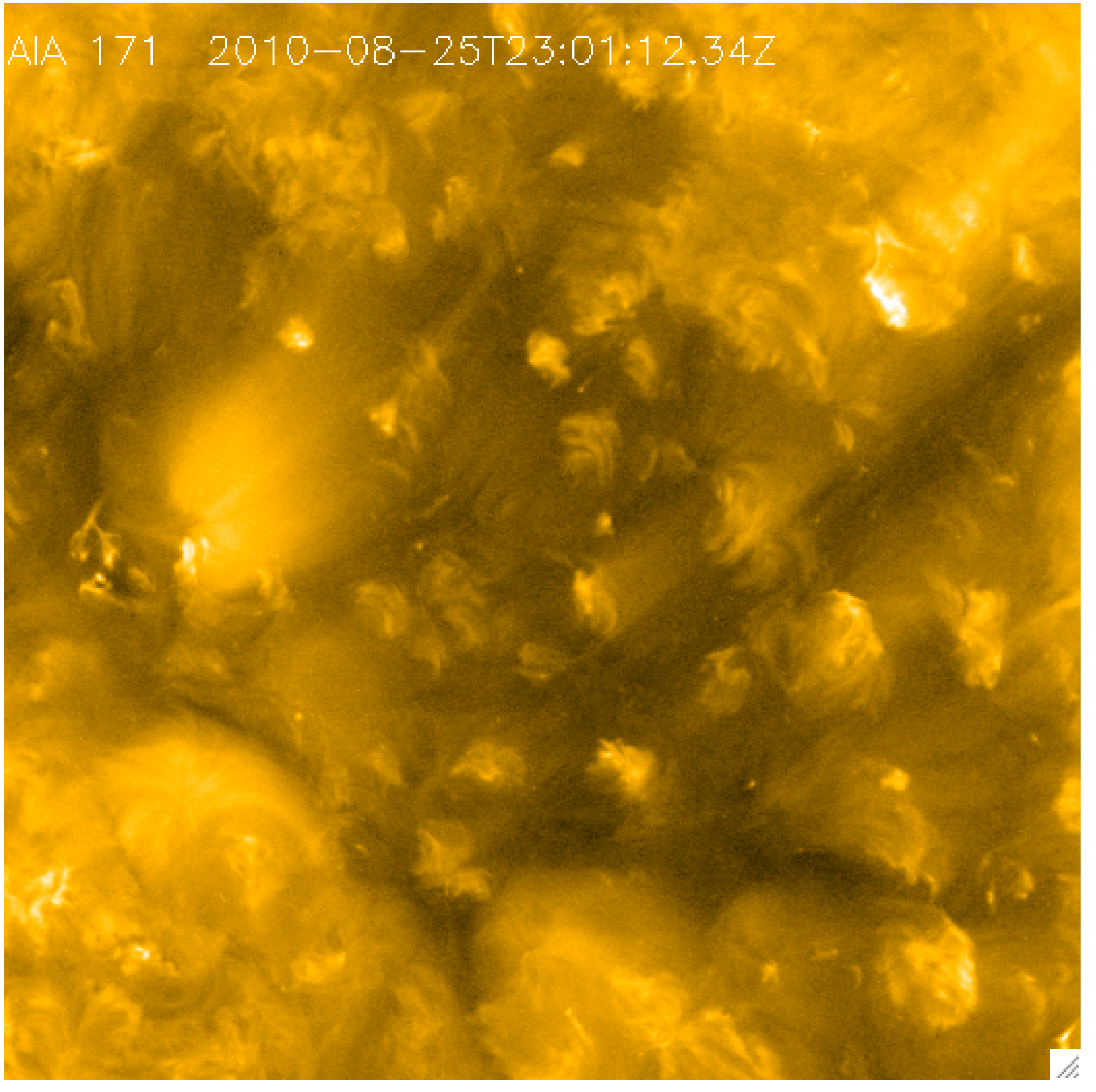
Tian et al., A&A, 478, 915, 2008



Kashyap, Banerjee & Srivastava 2015

Ubiquitous high-speed outflows in CHs ?

- AIA observations reveal unprecedented details inside CHs
- Plumes, PDs and Alfven waves are present in CHs
- Mass flux density: 1.67×10^{-9} g cm^{-2} s^{-1} if using log(Ne/cm^{-3})=8 and v=100 km s^{-1}, mass flux two orders higher than that of solar wind
- Energy flux of coronal Alfvén wave ($f\rho\langle v^2\rangle v_A$) is a significant portion of or comparable to that needed to power the quiet corona and solar wind (100 W m^{-2})



Tian et al. 2011, ApJ, 736, 130

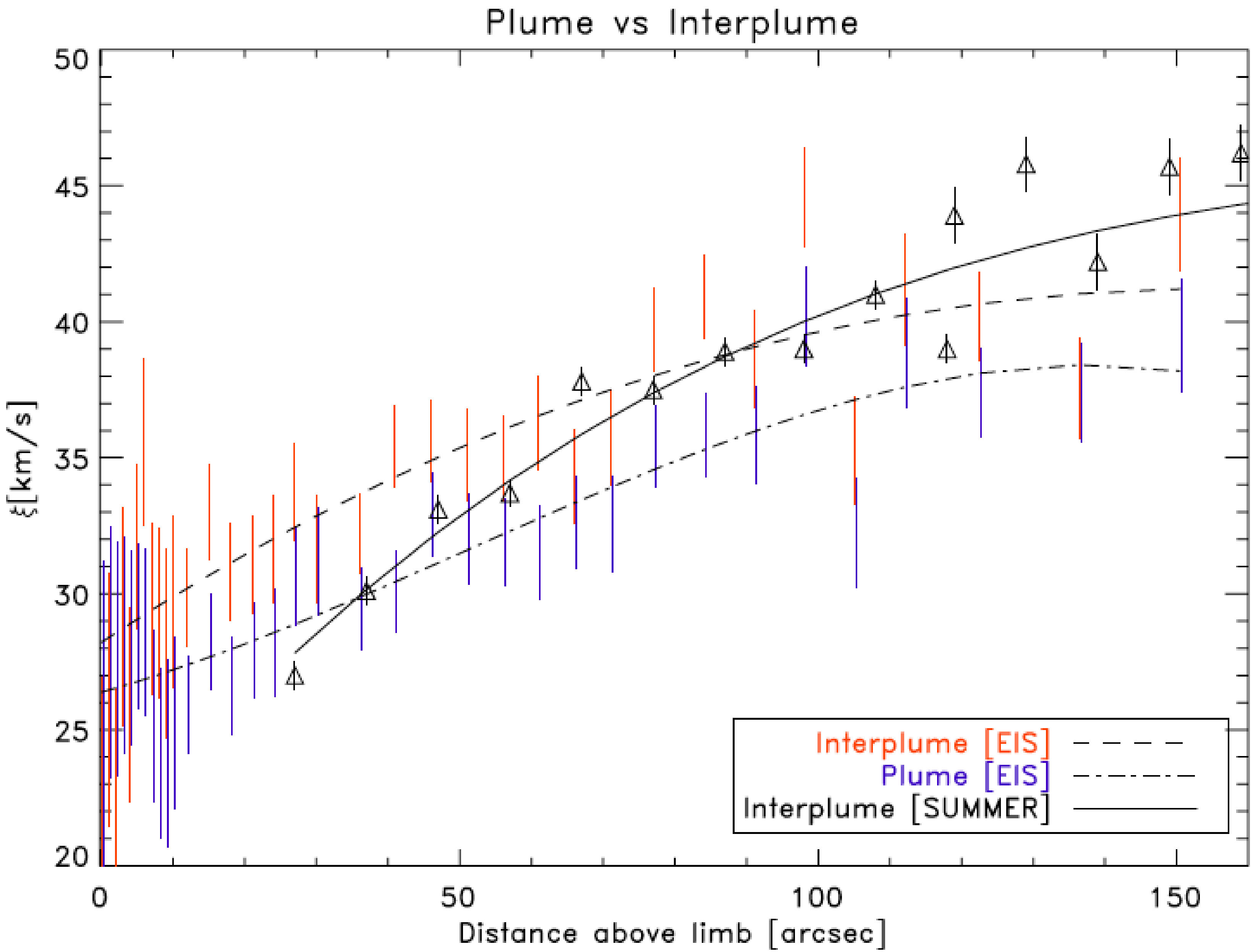


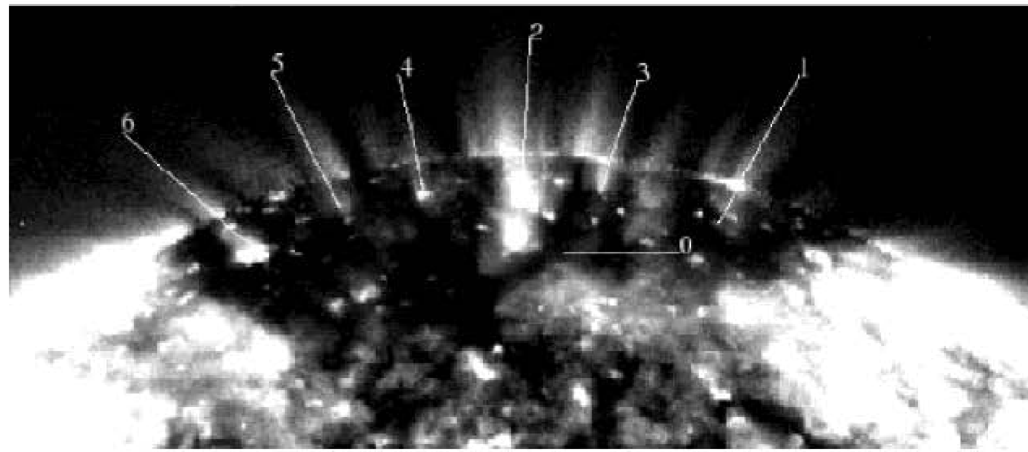
Fig. 6 Variation in nonthermal velocity with height as recorded by Fe XII 195 Å along a polar plume and interplume. The *solid line* corresponds to the nonthermal velocity as derived from Si VIII 1446 Å (Banerjee et al. 1998). The *dashed line* is a third-order polynomial fit. From Banerjee et al. (2009b)

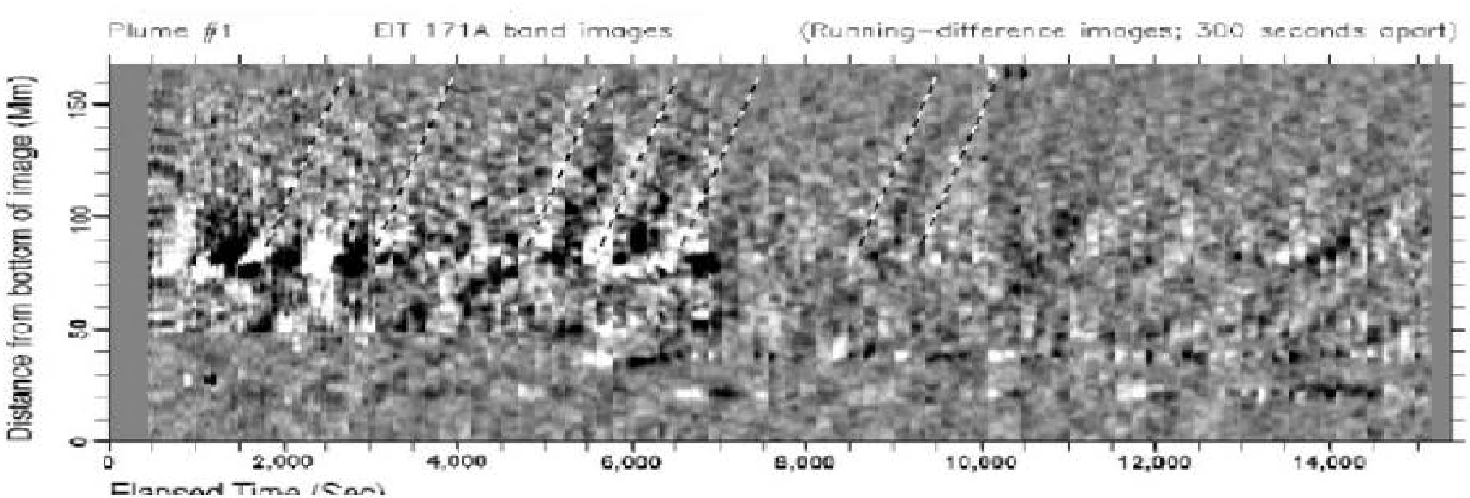
Intensity oscillations

Ofman et al, (1997) first reported the quasi-periodic variations in polar plumes. Deforest & Gurman (1998), found their ubiquitous presence. Ofman et al (1999, 2000) interpreted these disturbances as slow magneto-acoustic waves.

Polar plumes – South pole
From SoHO/EIT 1996 Mar 7
Using 171 Fe ix/ Fe x channel

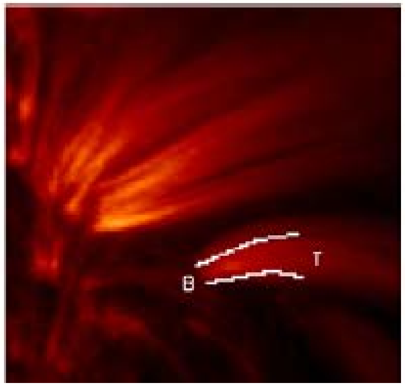
Periodicities: 10-15 min.
Speeds: 75 to 150 km/s.



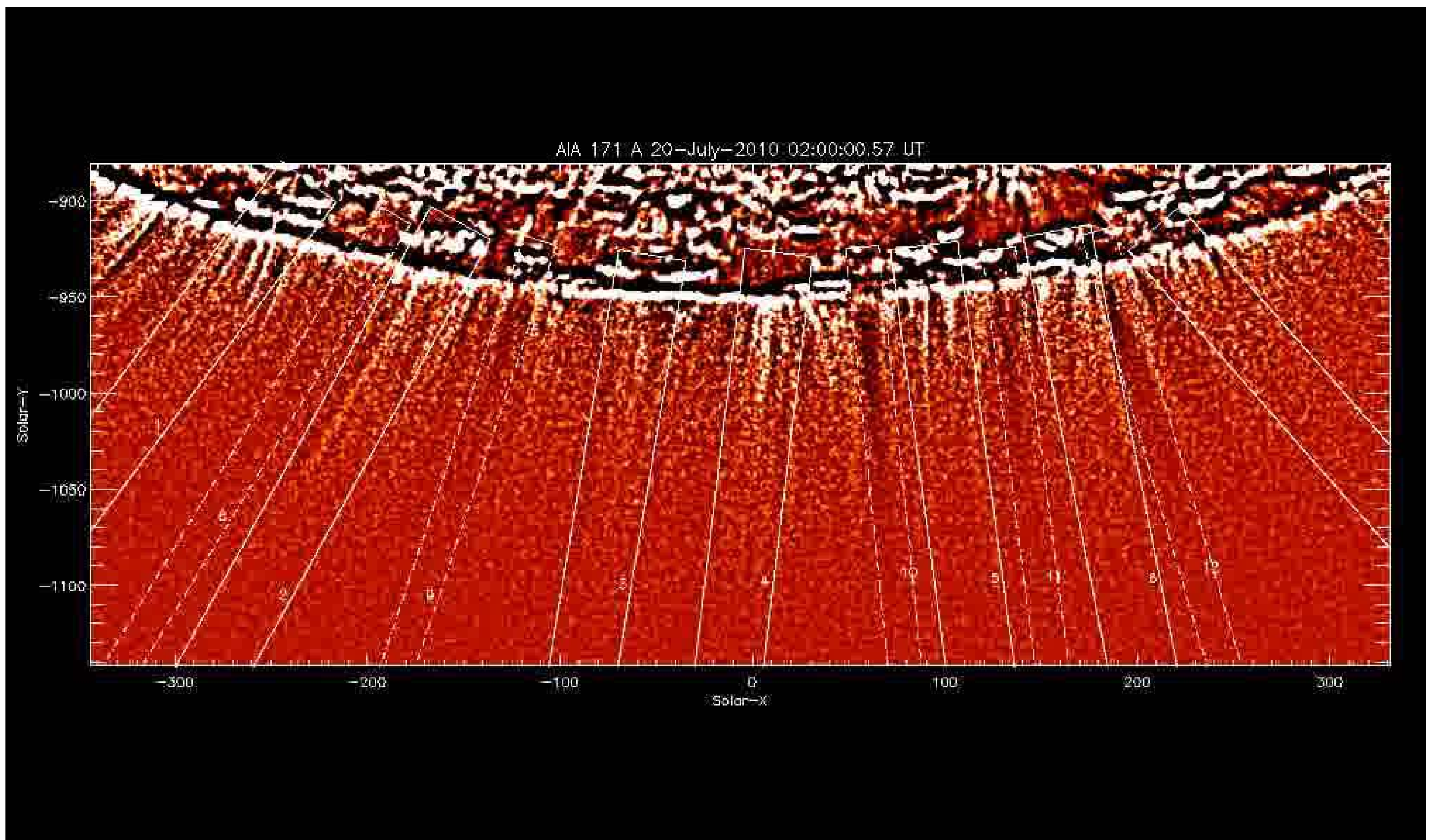


De forest & Gurman (1998)

Propagating slow waves in open structures



Parameter	Average	Range
Oscillation Period, P	284.0 ± 10.4 s	145–550 s
Propagation Speed, v	99.7 ± 3.9 km s^{-1}	$O(45)$–$O(205)$ km s^{-1}
Relative Amplitude, A	$3.7\% \pm 0.2\%$	0.7–14.6%
Detection Length, L_d	8.3 ± 0.6 Mm	2.9–23.2 Mm
Energy Flux, F	313 ± 26 erg cm^{-2} s^{-1}	68–1560 erg cm^{-2} s^{-1}



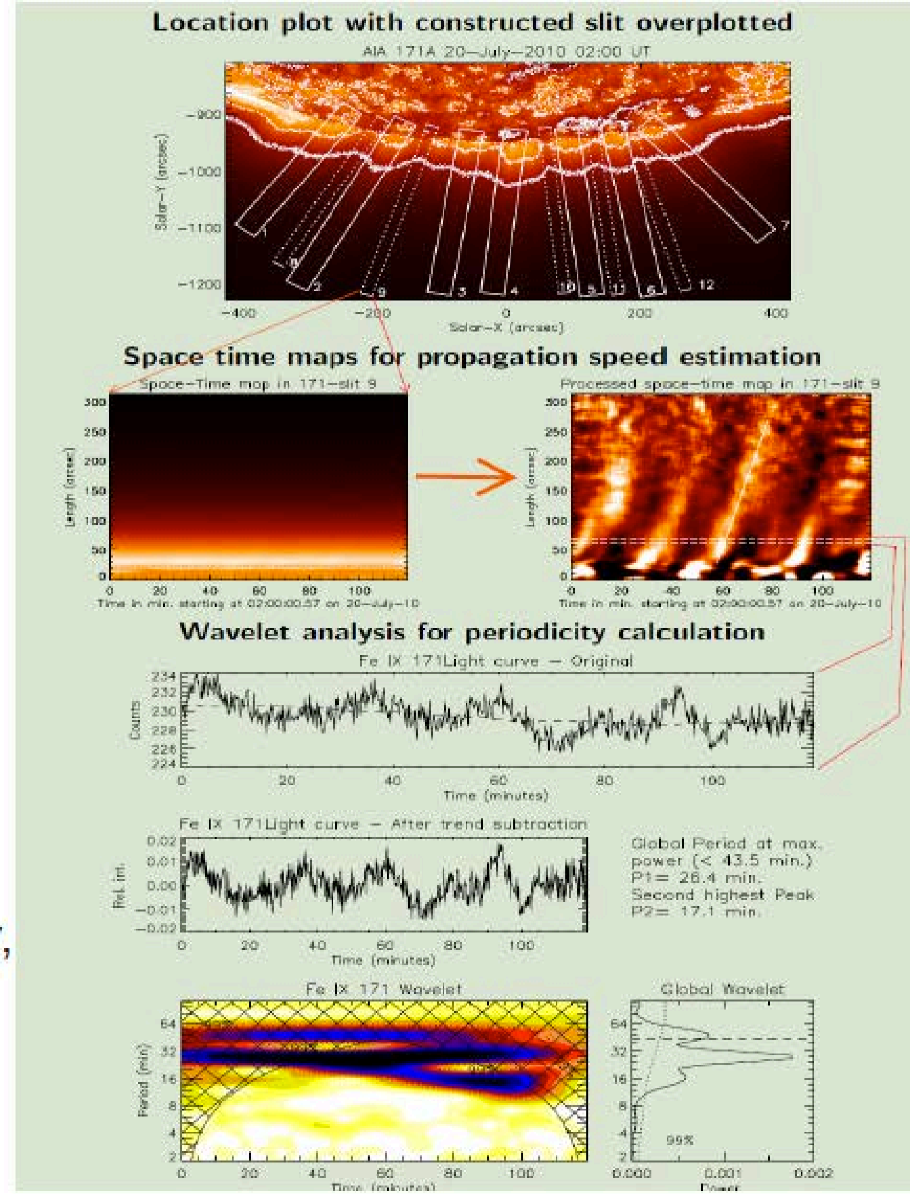
PD's in polar plumes revisited..

Motivation:
Waves or flows?
Preferred channels – Inter plumes or plumes?

Data:

- Location --->South polar region
- Duration ---> 2 hours
- Spatial resolution---> 0.6 arcsec
- Cadence----> 12s

Analysis:
Images from three coronal channels of AIA/SDO, centered at 171 Å, 193 Å and 211 Å, with their peak temperatures at 0.8 Mk, 1.25 Mk and 1.6Mk respectively, are used in this analysis. The adjacent figure illustrates the techniques used for the detection of intensity oscillations and estimation of propagation speeds and periodicities.



Krishna Prasad, S. et al., (2011)

Slow waves: Detections

- Small amplitude propagating intensity disturbances were extensively studied with imagingtelescopes in open/extended loop structures close to active regions (Berghmans & Clette 1999; De Moortel et al. 2000; King et al. 2003) and also in polar plumes (Deforest & Gurman 1998; McIntosh et al. 2010; Krishna Prasad et al. 2011).

- There were some spectroscopic observations as well by several authors using CDS onboard SOHO (Ireland et al. 1999; O'shea et al., 2001) and more recently using SUMER and EIS (Banerjee et al. 2009; Gupta et al. 2010)

- Based on some of the observed properties all these authors interpreted the observed oscillations in terms of slow magneto-acoustic waves.

- Wang et al. (2009) observed low frequency (12 & 25 min) oscillations for the first time, both in intensity and Doppler shift using EIS supporting this nature.
- De Pontieu & McIntosh (2010) report oscillations in line width in addition to the intensity and Doppler shift and they cautioned on the ambiguous detection of high speed up-flows as slow waves.
- Recent observations indicate that the effect of up-flows is more prominent close to the foot points of the supporting structure and the slow waves dominate away from the base (Nishizuka & Hara, 2011, Tian et al. 2012).
- Slow waves were also found to be omnipresent at longer periods (Krishna Prasad et al. 2012).

Observational properties and current ambiguities

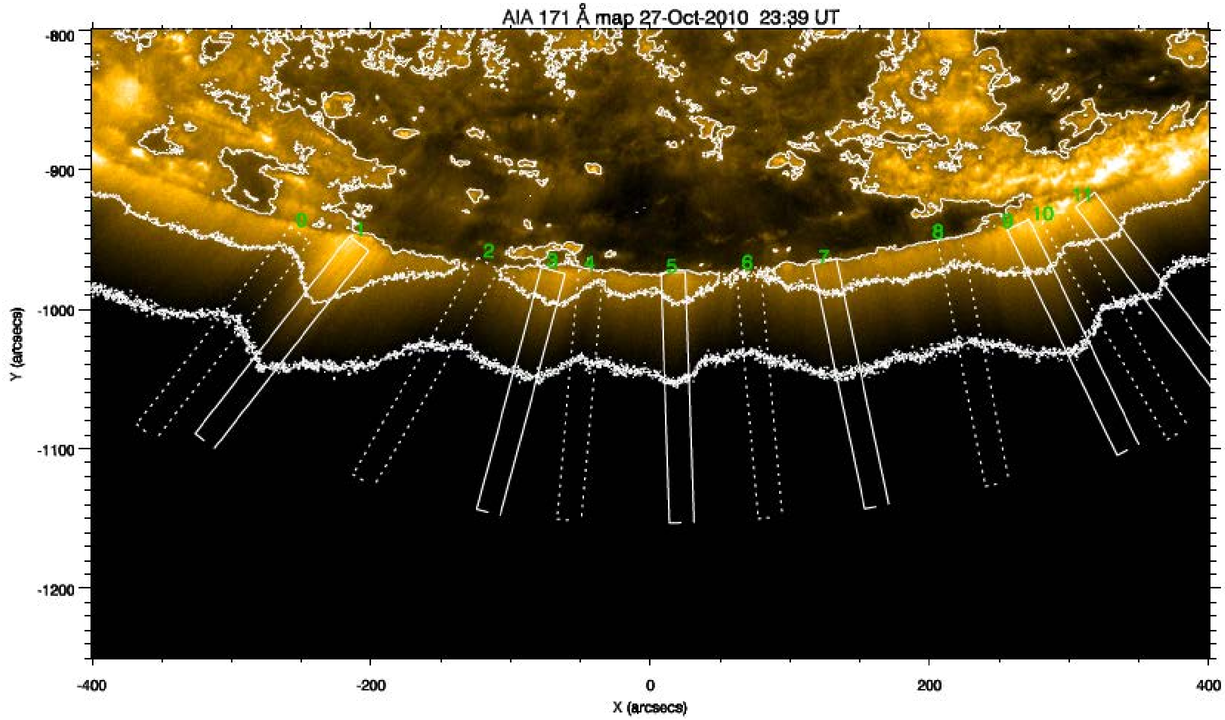
Periodicities: Similar. No Knowledge on the driver. P-mode leakage? Spicular flows? Source of low frequency oscillations is not known. Impulsive heating?

Propagation speeds: Acoustic? Temperature dependence? No shocks? Suffers from the projection effects and error in measurement.

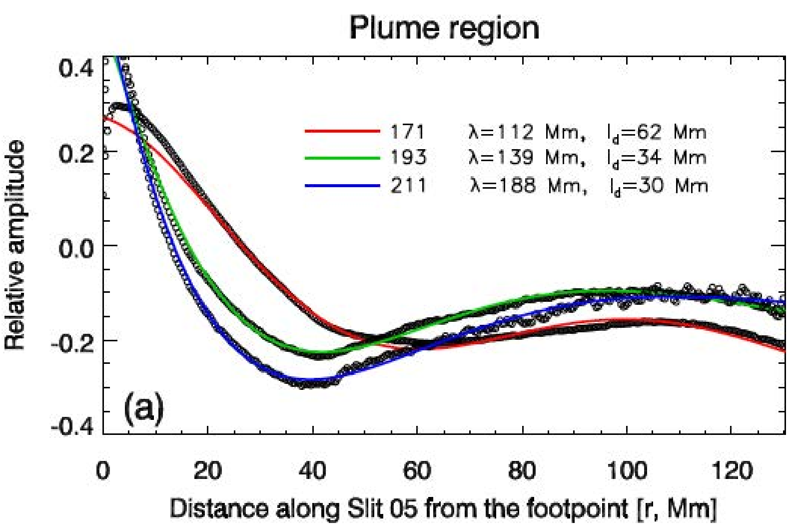
Oscillation Amplitudes: Temperature dependence? Possible for flows? Simultaneous measurements in multiple channels is required.

Disappearence after some height: Damping? Dispersed flows? Or material fallen back? Frequency dependence of the detection length might be the key.

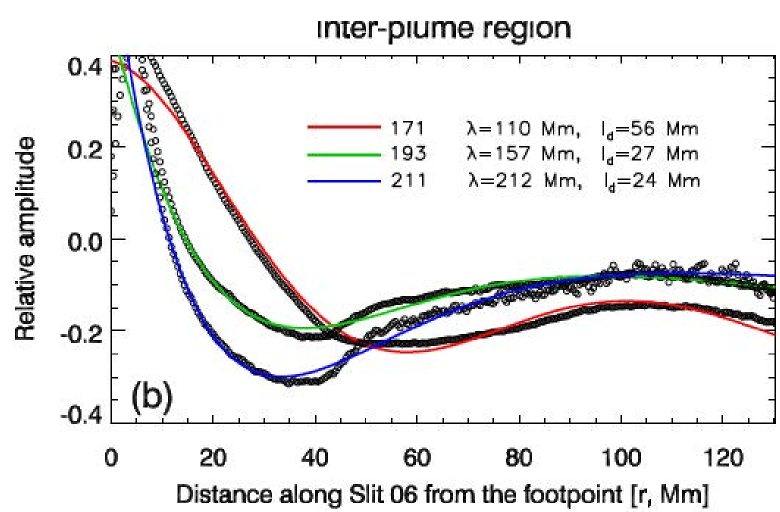
Asymmetry in line profiles: Not observed always. LOS effects? Suffers from low signal-to-noise affects. Gupta et al. (2012) observed minimal R-B asymmetry in the PD's which can be reproduced by adding random noise to simulated profiles. The effect is predominantly observed at loop foot points.



AIA 171 Å map 27-Oct-2010 23:39 UT
Y (arcsecs)
X (arcsecs)
-800
-900
-1000
-1100
-1200
-400
-200
0
200
400
0
1
2
3
4
5
6
7
8
9
10
11



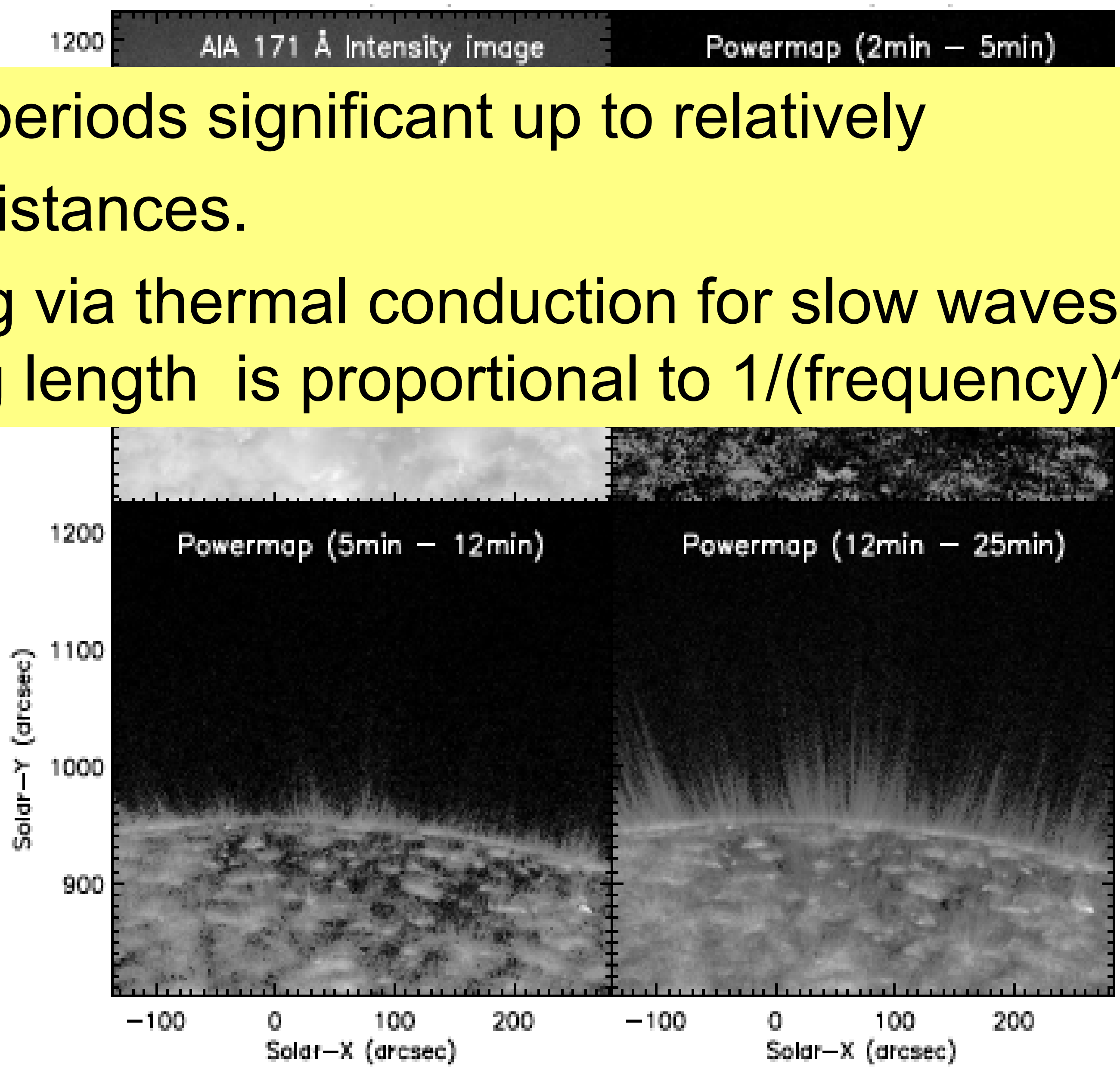
Plume region
171 λ=112 Mm, l_d=62 Mm
193 λ=139 Mm, l_d=34 Mm
211 λ=188 Mm, l_d=30 Mm
Relative amplitude
Distance along Slit 05 from the footpoint [r, Mm]
(a)



Inter-plume region
171 λ=110 Mm, l_d=56 Mm
193 λ=157 Mm, l_d=27 Mm
211 λ=212 Mm, l_d=24 Mm
Relative amplitude
Distance along Slit 06 from the footpoint [r, Mm]
(b)

Su 2014

Polar regions



Longer periods significant up to relatively larger distances.

Damping via thermal conduction for slow waves - damping length is proportional to 1/(frequency)^2 ?

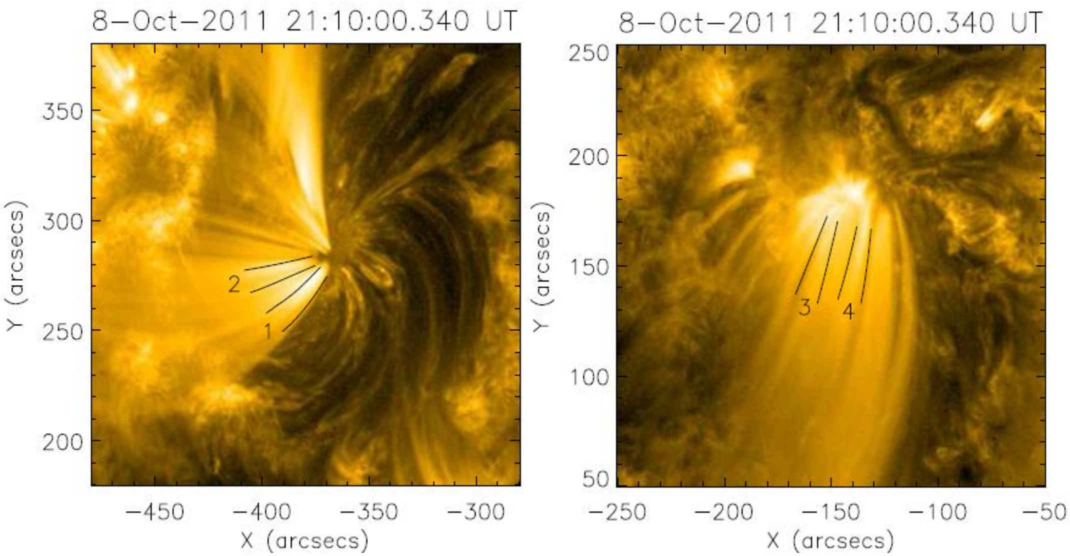
Different mechanisms that alter the amplitude of slow waves

- Thermal conduction
- Compressive viscosity
- Radiation
- Density stratification
- Area divergence
- Loop curvature, phase mixing and coupling with fast mode

Thermal conduction combined with area divergence can account for the observed damping even when the density stratification is present (De Moortel & Hood, 2003; 2004; De Moortel, 2009)

Marsh et al., (2012) observed that for longer periods (~10 minutes) supported by cool (sub-million degree) loops thermal conduction is insufficient to explain the observed damping and area divergence has the dominant effect.

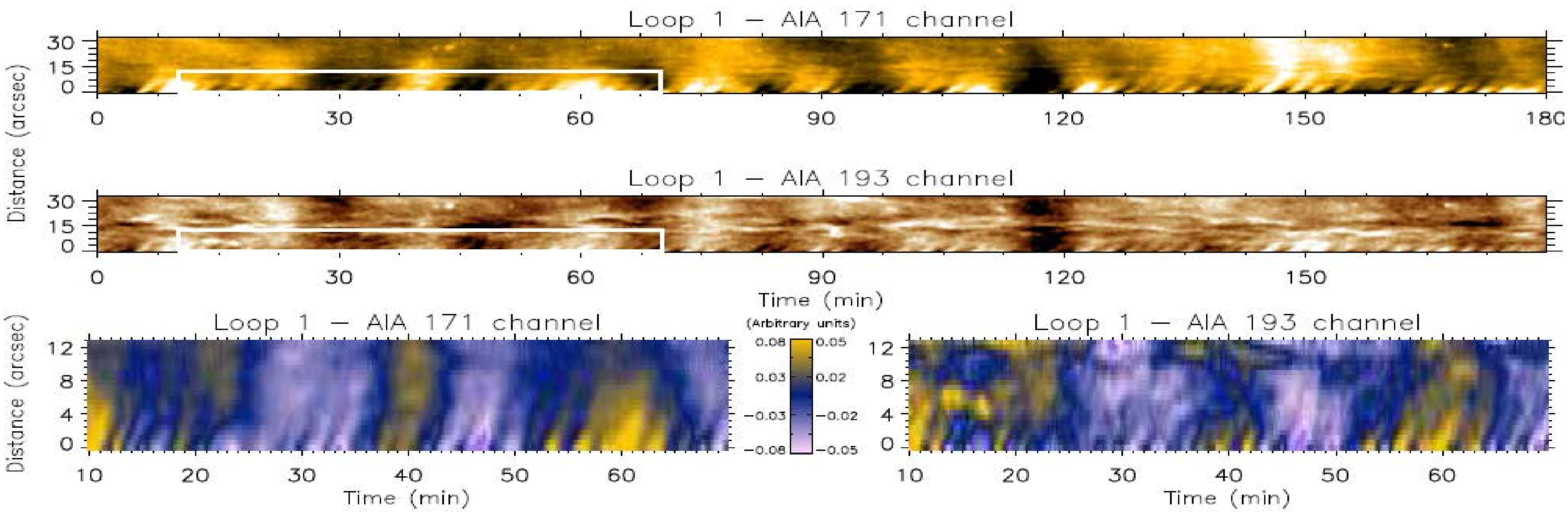
To study the quantitative dependence..



Data duration: ~3 hrs

Cadence: ~12s

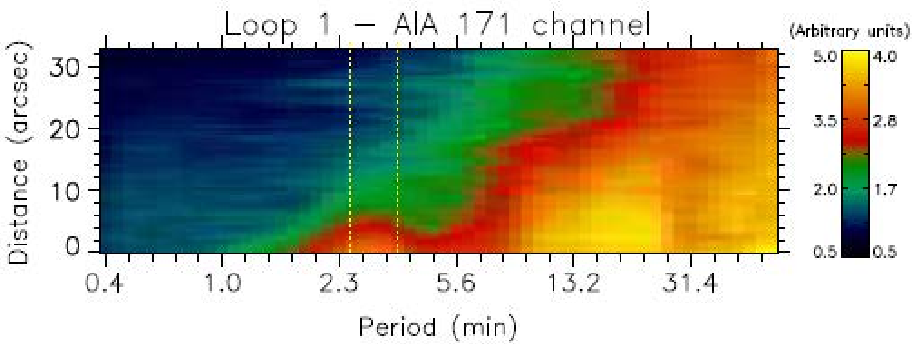
Channels: 171 & 193

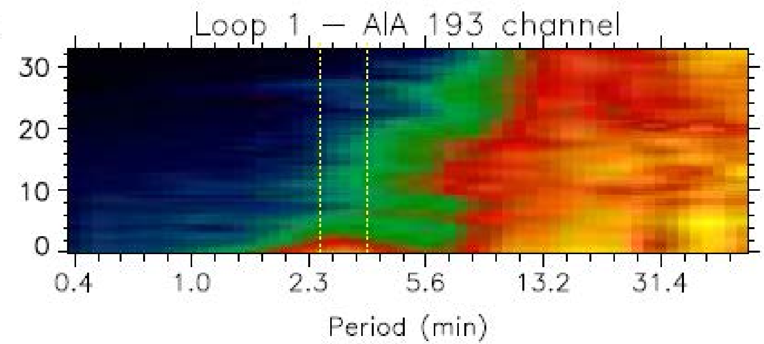


Time –Distance map

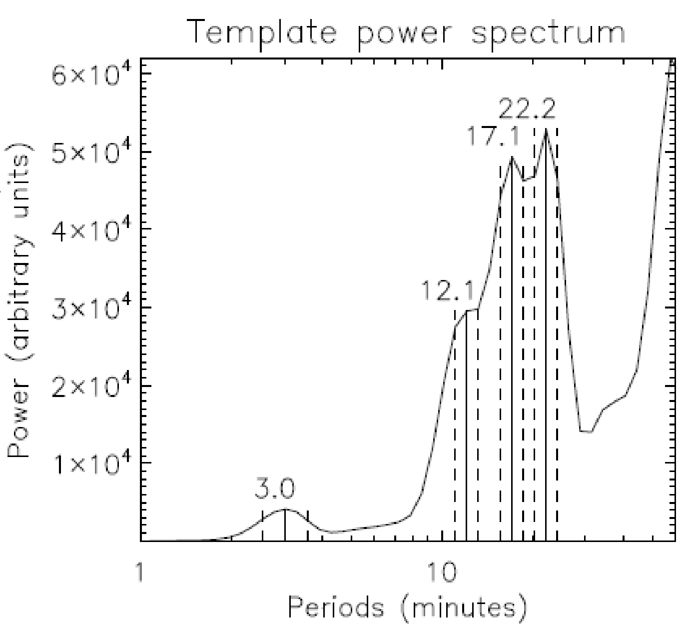
Damping length measurement

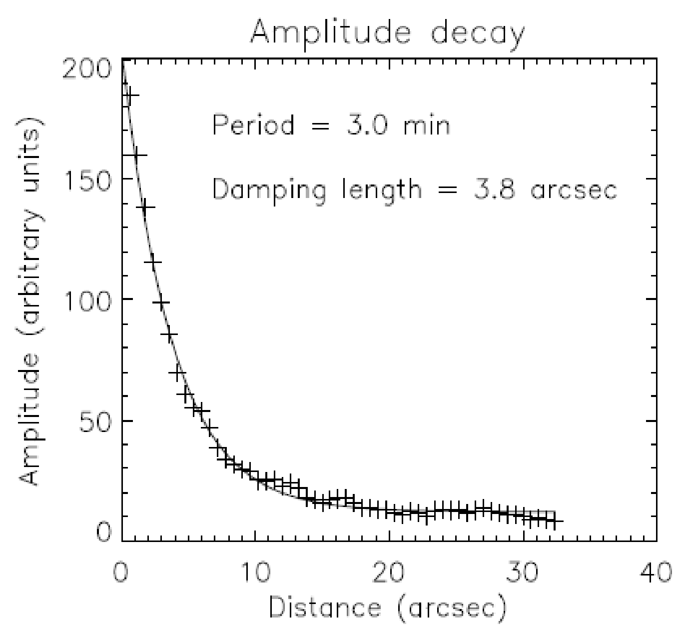
Transformed the time-distance maps into period-distance maps by replacing the time series at each spatial position with its wavelet power spectrum.





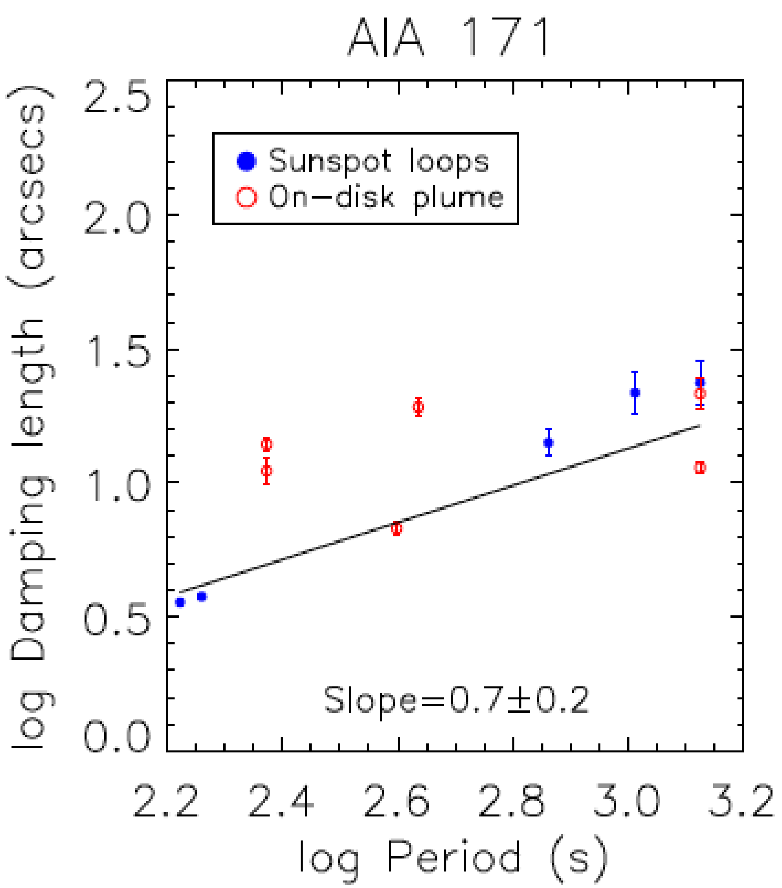
Power spectra for average light curve

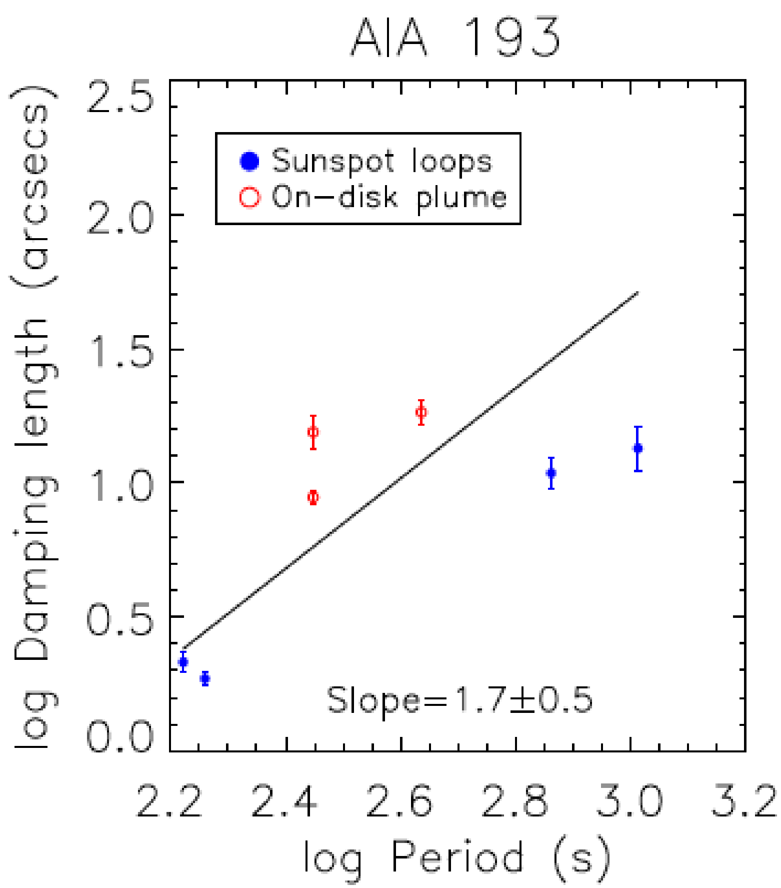




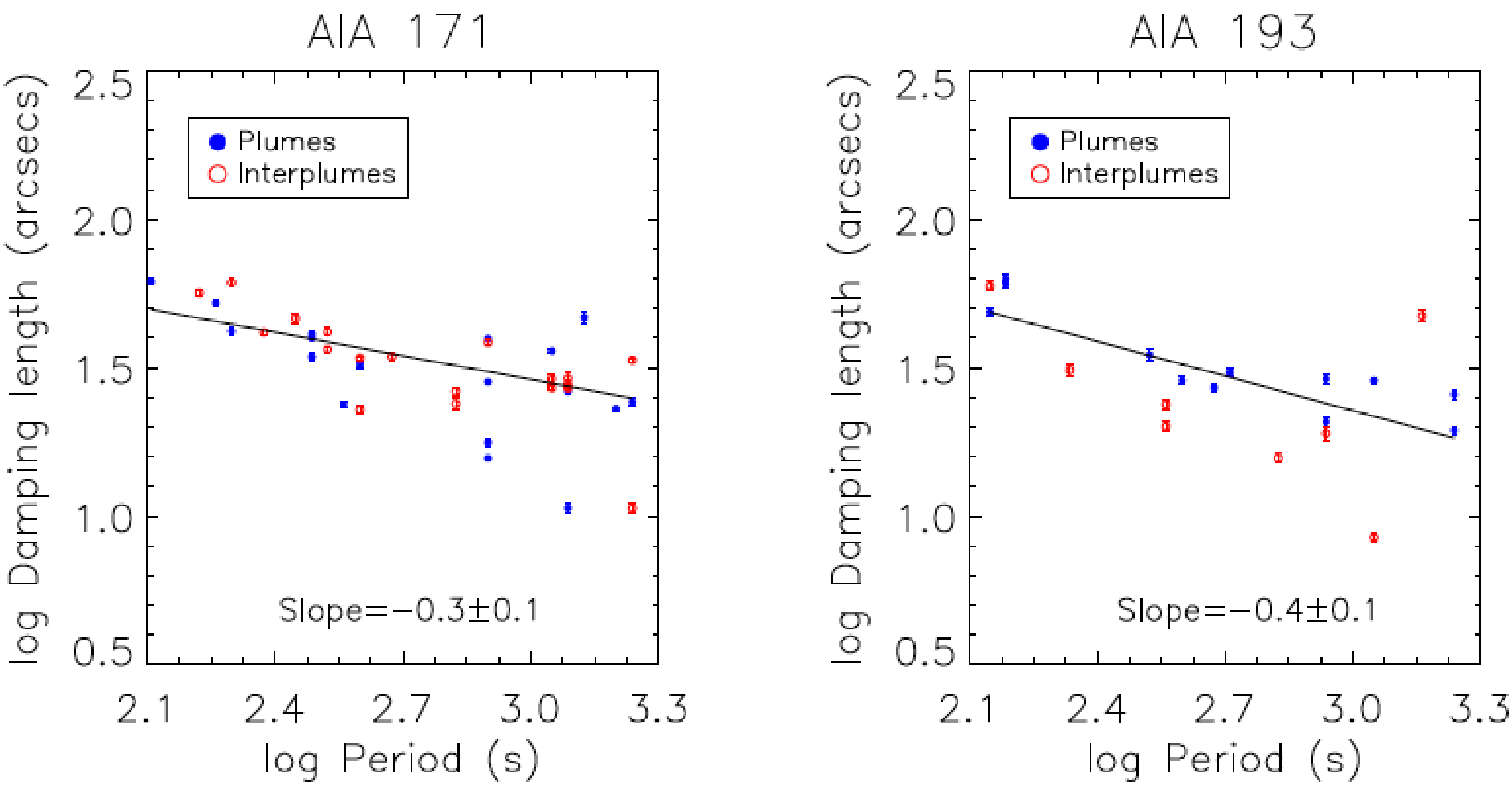
The square root of the power represents the oscillation amplitude.

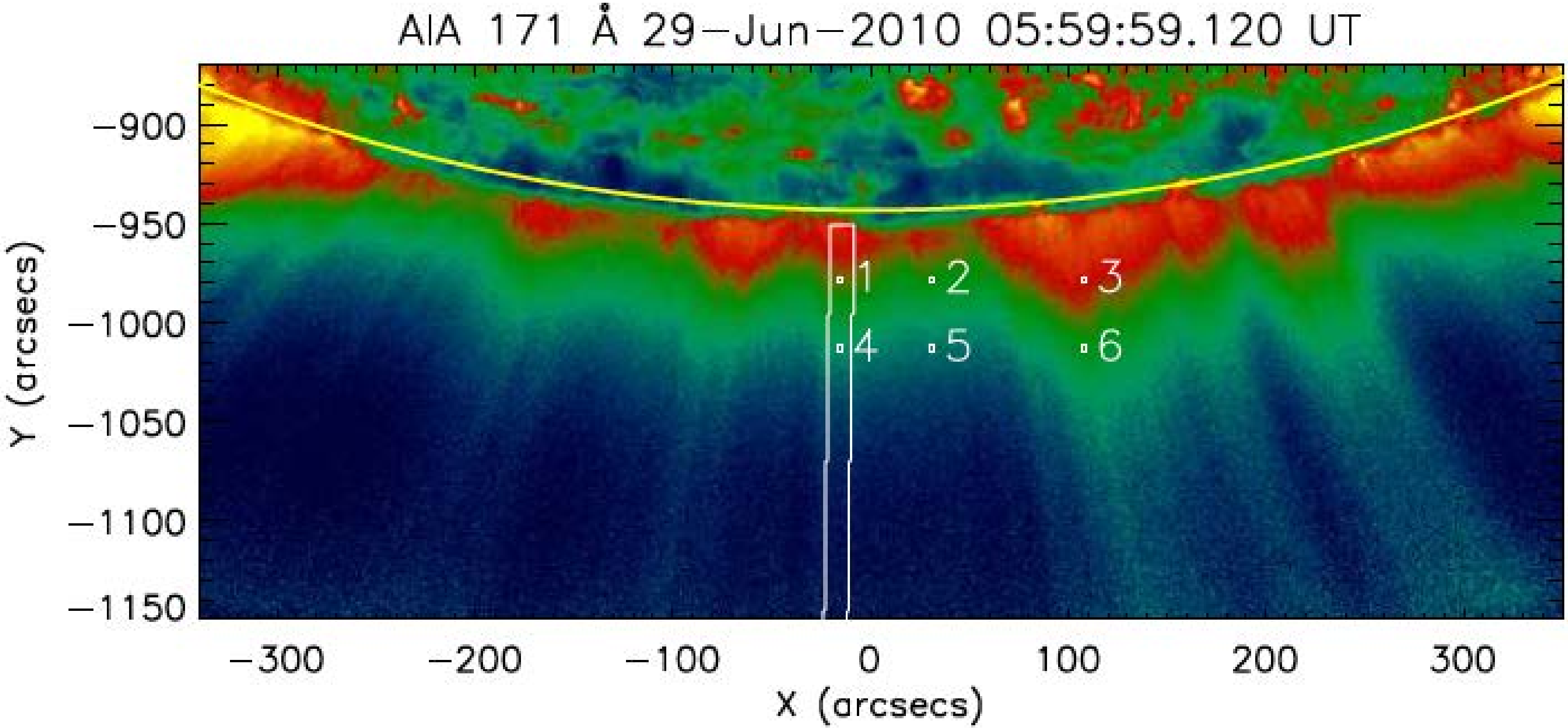
Frequency dependence of damping length in AR loops



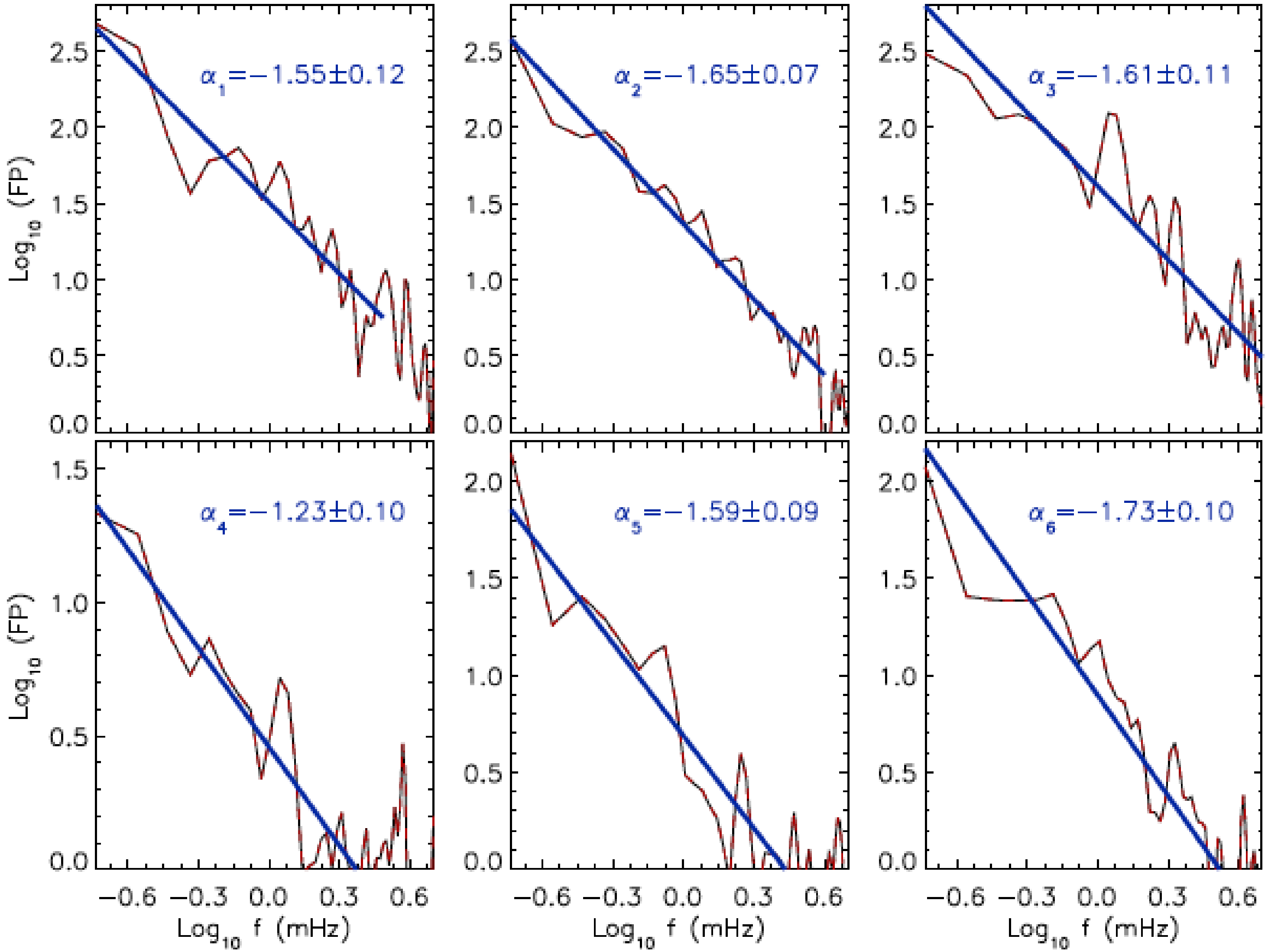


Frequency dependence of damping length in polar plume
r-plume regions





Gupta 2014, A&A



Fourier power distribution with frequency for locations 1–6 marked in previous Fig.

Gupta 2014, A&A

Summary

➔ Slow waves with longer wavelengths travel relatively farther distances before getting damped in all the open structures.

➔ Detailed analysis was done to find the quantitative relation between frequency and damping length of these waves by considering the oscillations with periods between 2 min and 30 min.

- Considering thermal conduction, magnetic field divergence, and density stratification, as the dominant mechanisms that alter the slow wave amplitude, linear theory predicts the variation of damping length as square of the time period. In a log-log scale, this would mean a slope of 2.

- But as we find here, the slopes estimated from the observations are positive but less than 2 for the on-disk region and are negative for the polar region.
- This mismatch between the observed values and those expected from the linear theory, suggests some missing element in the current theory of damping in slow waves. Perhaps, the linear description does not hold good and the slow waves undergo non-linear steepening that causes enhanced viscous dissipation (Ofman et al. 2000).

conclusions

- Viscosity can be effective for the long period waves whose amplitudes are relatively larger and possibly can even explain the negative slopes observed in the polar regions.
- Further studies are required to explore such possibilities and understand the observed frequency dependence.
- Nevertheless, the discrepancy in the results from the on-disk and the polar regions, indicates the existence (or dominance) of different damping mechanisms in these two regions possibly due to different physical conditions.

Krishna Prasad et al. 2014 ApJ, 789, 118

Thank you

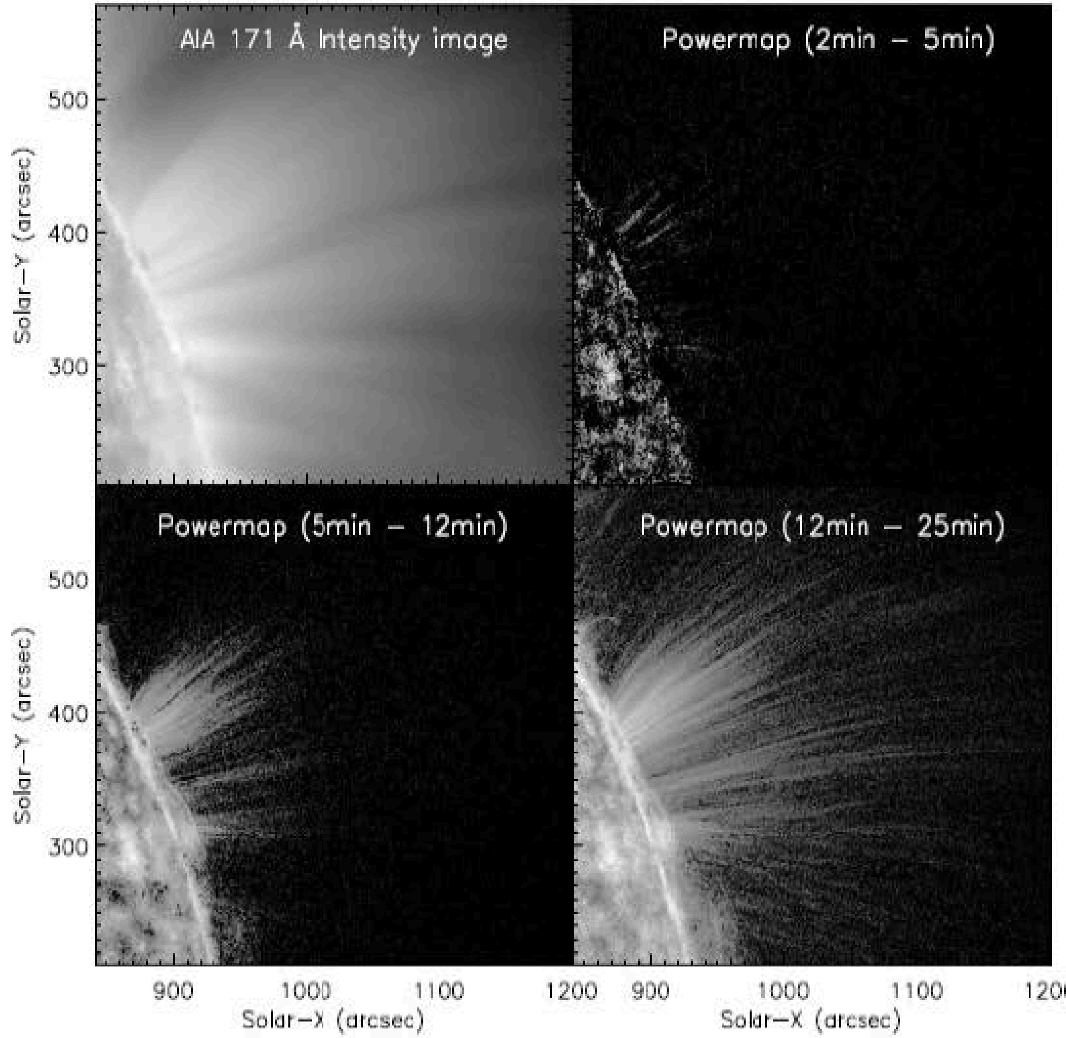
• Power map analysis

- Variations on time scales larger than 30 min is subtracted from each pixel of the image.

- Time series at each pixel is then subjected to wavelet analysis and all the significant power in the desired frequency range is added.

- The intensity values at each pixel are then replaced with the corresponding power values to construct the powermap.

- Off-limb loops



Krishna Prasad, S. et al., (2012)

Ofman et al. 2012

- (3D MHD) modeling of a bipolar AR that contains impulsively generated waves and flows in coronal loops.
- Impulsive onset of flows with subsonic speeds result in the excitation of damped slow magnetosonic waves that propagate along the loops and coupled nonlinearly driven fast mode waves.
- Based on the results of the 3D MHD model we suggest that the observed slow magnetosonic waves and persistent upflows may be produced by the same impulsive events at the bases of ARs.

Persistent Doppler shift oscillations observed with HINODE/EIS in the solar corona: spectroscopic signatures of Alfvénic waves and recurring upflows

Hui Tian[1,*], Scott W. McIntosh[1], Tongjiang Wang[2,3], Leon Ofman[2,3], Bart De Pontieu[4], Davina E. Innes[5], Hardi Peter[5]

two types of oscillations?

- One type is found at loop footpoint regions, with a dominant period around 10 minutes. They are characterized by coherent behavior of all line parameters (line intensity, Doppler shift, line width and profile asymmetry), apparent blue shift and blueward asymmetry throughout almost the entire duration. Such oscillations are likely to be signatures of quasi-periodic upflows (small-scale jets, or coronal counterpart of type-II spicules), which may play an important role in the supply of mass and energy to the hot corona.
- The other type of oscillation is usually associated with the upper part of loops. They are most clearly seen in the Doppler shift of coronal lines with formation temperatures between one and two million degrees. The intensity variation is often less than 2%. These oscillations are more likely to be signatures **of kink/Alfven waves rather than flows.**