

Coronal oscillations and seismology

Dipankar Banerjee

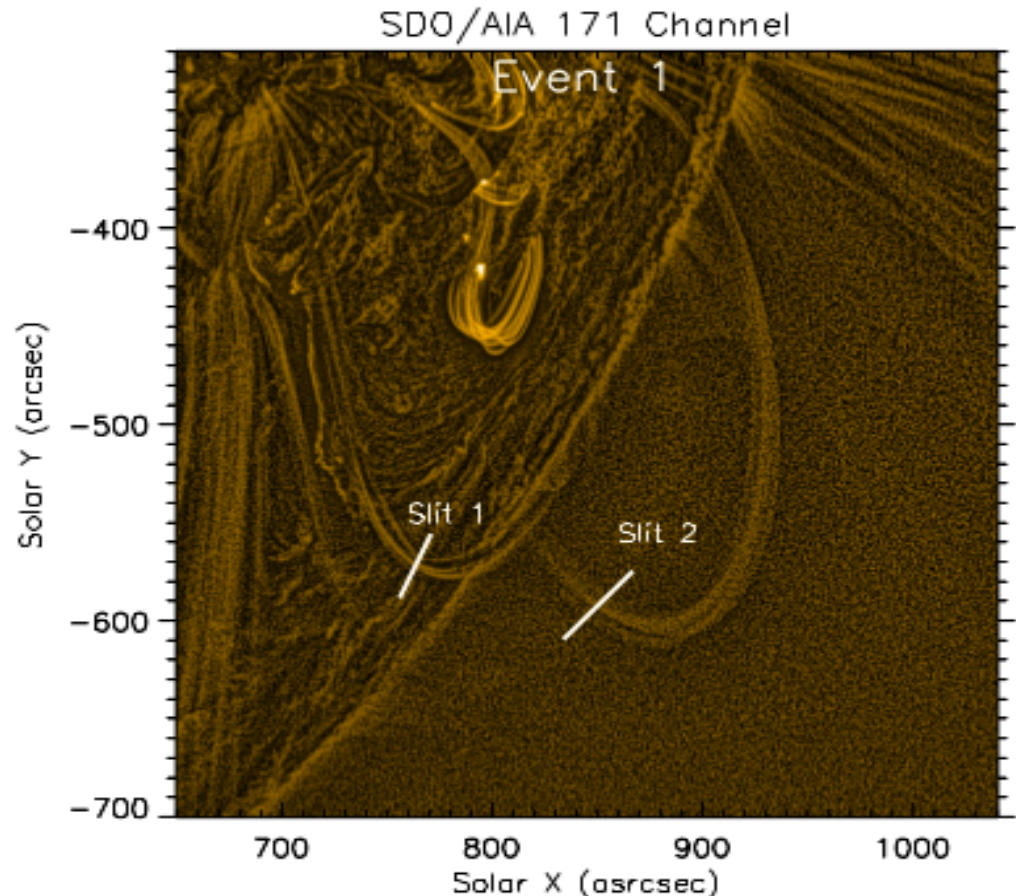
Indian Institute of Astrophysics

Transverse oscillations in coronal loops: Role of the driver

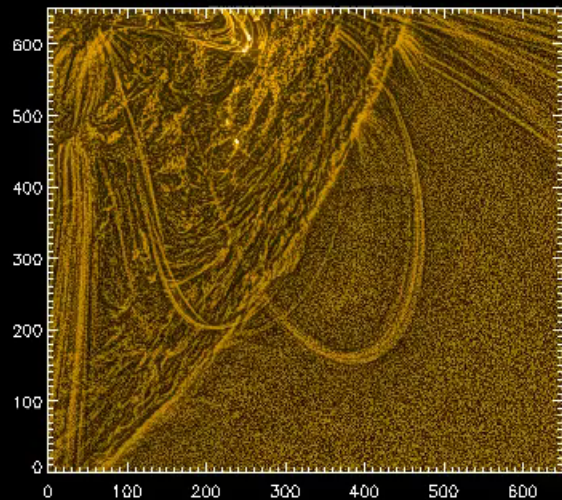
Sudip Mandal, V. Pant, E. Verwichte, D. Banerjee

Transverse oscillations (more specifically kink oscillations) in coronal loops are one of the most common phenomena found in the solar corona. After the high resolution, high cadence observations from SDO, it becomes very evident that these oscillations are a unique tool to measure the magnetic field at coronal heights.

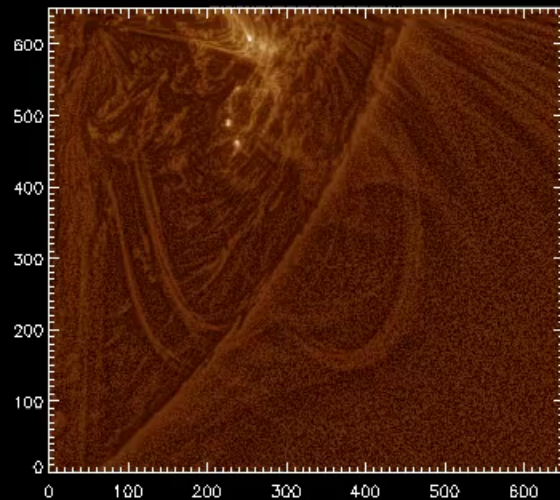
Recent study by Anfinogentov (2015) shows that the period of these oscillations are linearly dependent on the loop length. Now, these oscillations are categorized broadly into two classes: Decay and Decayless. Now it is very often seen that the driver of these oscillations are different for the decaying and decayless cases. In our analysis with 4 datasets obtained from SDO/AIA we have tried to establish the connection of these decay and decayless cases with their driver operation.



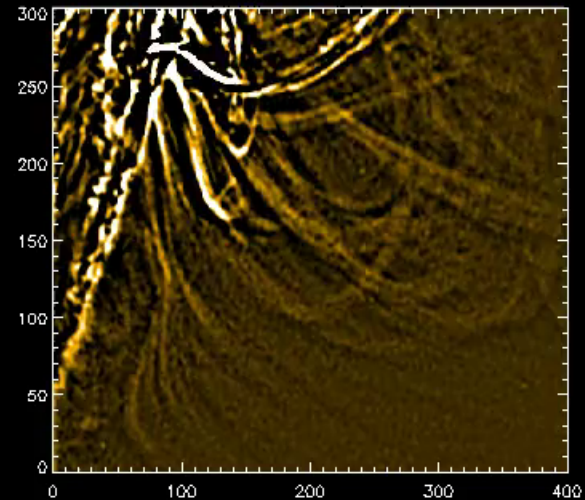
Event1 171 channel



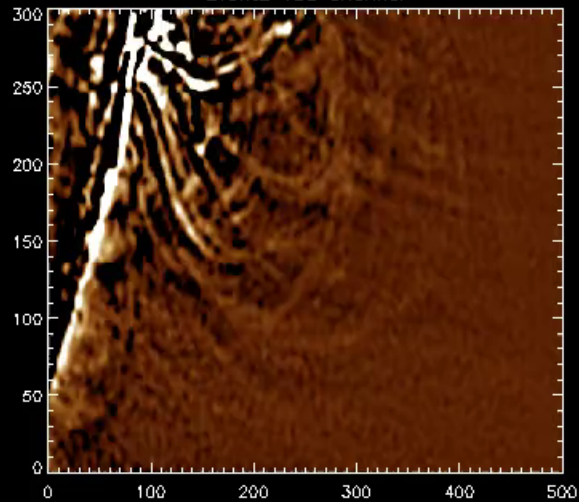
Event1 193 channel



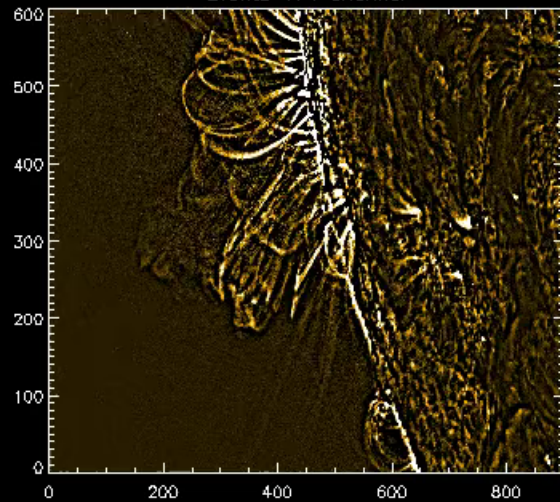
Event2 171 channel



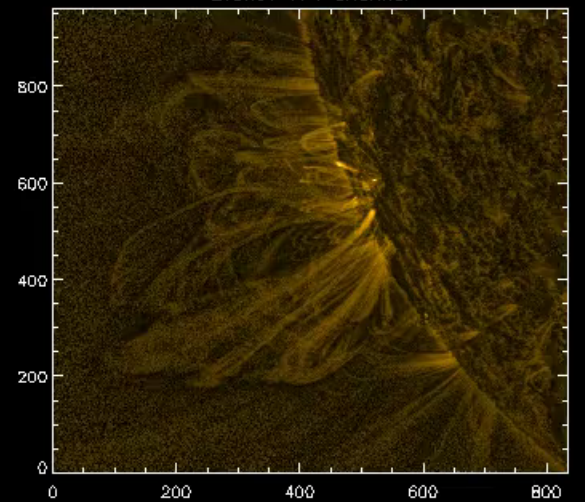
Event2 193 channel



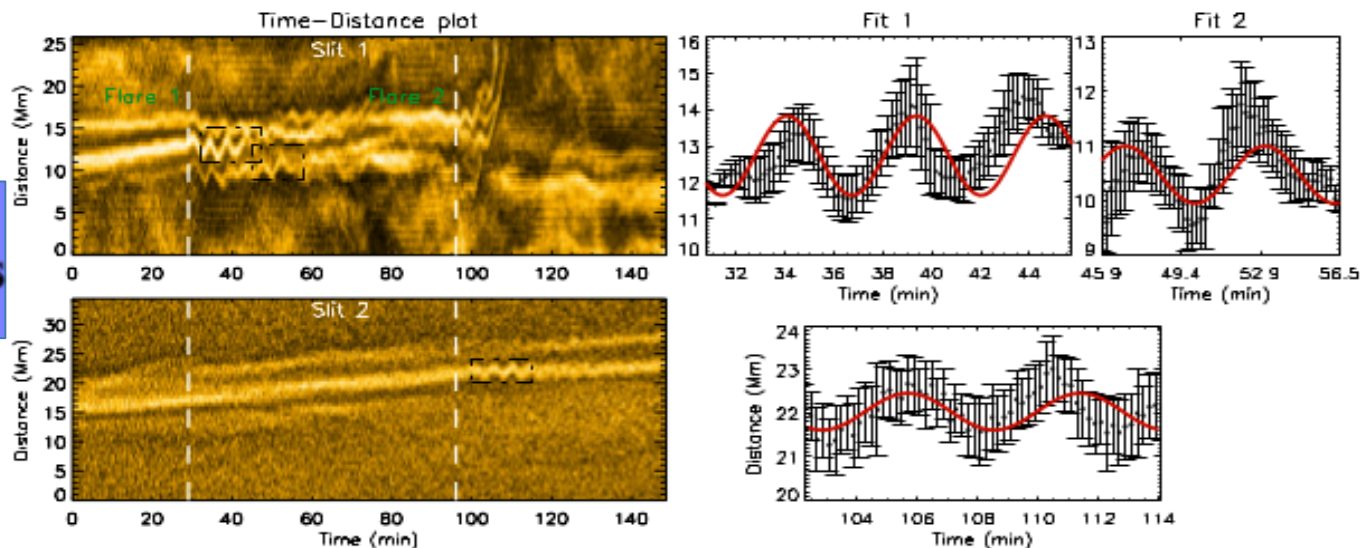
Event3 171 channel



Event4 171 channel

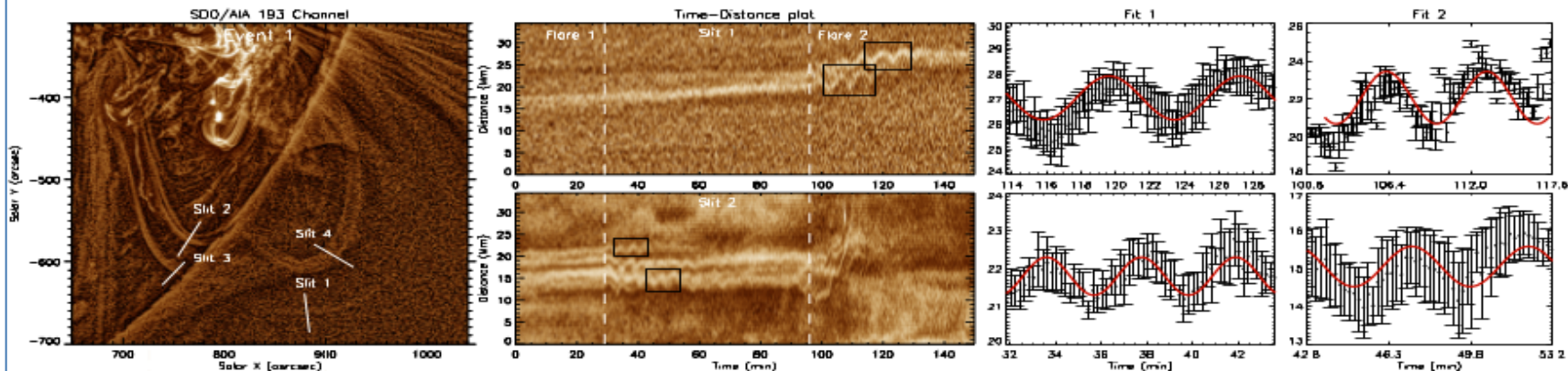


Decayless oscillations

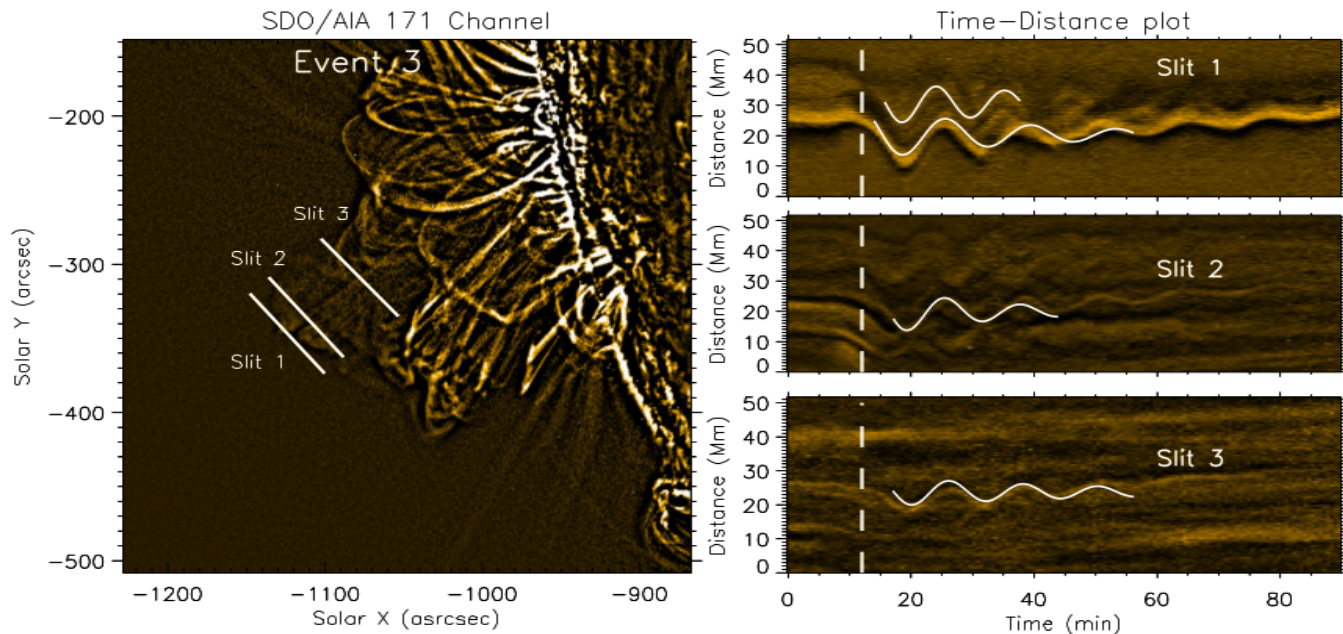


These oscillations are “similar to” decayless cases but they stay only for some time span and then vanishes . Thus it raises the question about the nature of these oscillations as in the classical decayless events one sees the oscillations lasting for longer time frames without any change in the amplitude.

Repeated flares at the base of the loops are the driving agent for this oscillations. We looked at the 193 channel also where we see the same signature.



Decaying Oscillations



The driver in this case is a flare which happened not at the footpoint but very nearby to it.

Key questions to ask:

1. What dictates the oscillations to be decaying or decayless?
2. How does the driver location and type (instantaneous or long duration) affects the period to be propagating through the structure?
3. We found oscillations which are decayless but existing for not so long time. What causes the system to achieve the equilibrium so rapidly?
4. Does the loop topology have any effects towards the decaying or decayless cases?

Braided Solar Coronal Magnetic Structures

THE ASTROPHYSICAL JOURNAL LETTERS, 801:L2 (7pp), 2015 March 1

[doi:10.1088/2041-8205/801/1/L2](https://doi.org/10.1088/2041-8205/801/1/L2)

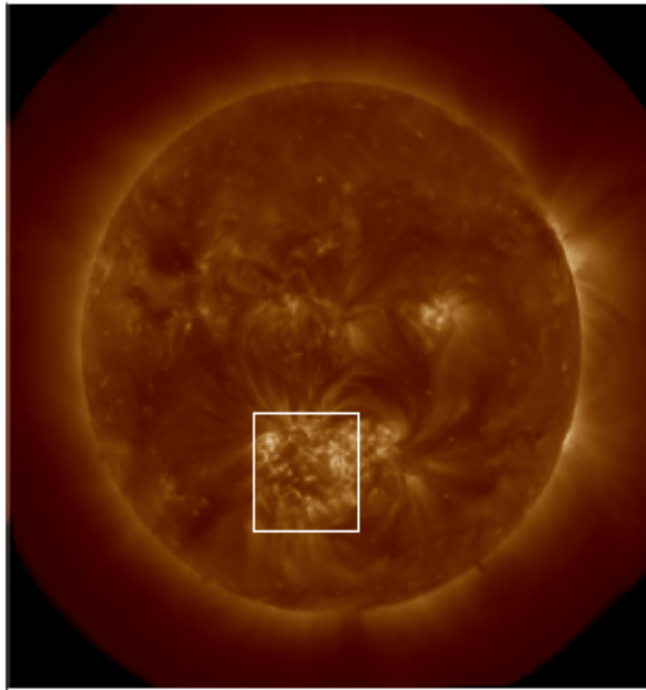
© 2015. The American Astronomical Society. All rights reserved.

FLOWS AND WAVES IN BRAIDED SOLAR CORONAL MAGNETIC STRUCTURES

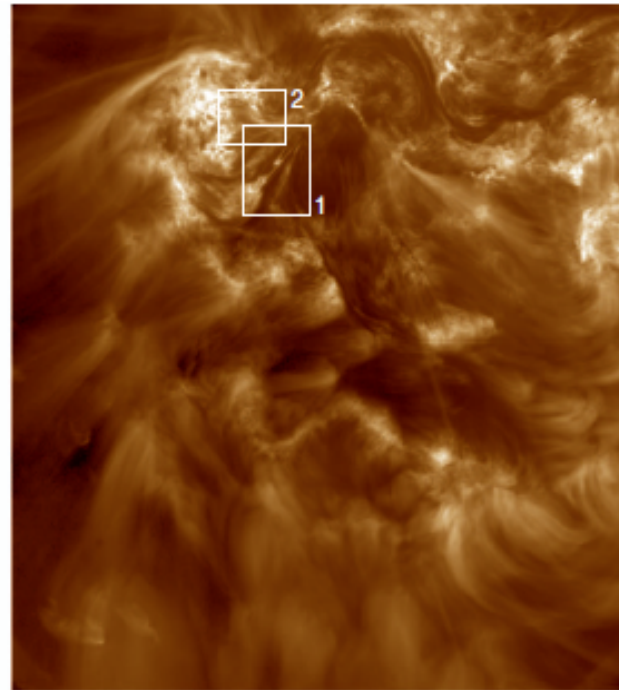
V. PANT¹, A. DATTA^{1,2}, AND D. BANERJEE^{1,3}

High Resolution Coronal Imager (Hi-C)

- Launched on 11 July, 2012
- Spatial Resolution $\sim 0.2''$ (AIA $\sim 1.2''$)
- Temporal resolution ~ 5.5 sec (AIA ~ 12 sec)



AIA 193 A image



Hi-C 193 A image

Cirtain et al, 2013

Multi scale normalized gaussian filter

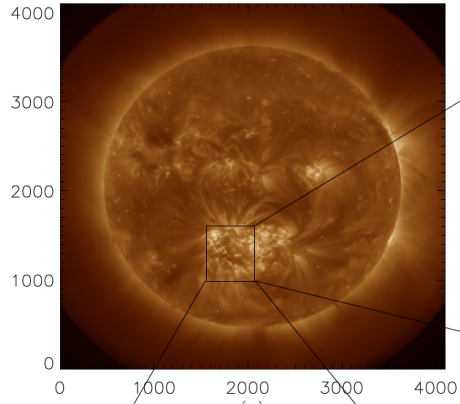
Unsharp mask

- I (unsharp mask) = $I - I * G(\sigma)$
- $G(\sigma)$ is the gaussian of width σ (low pass filter).

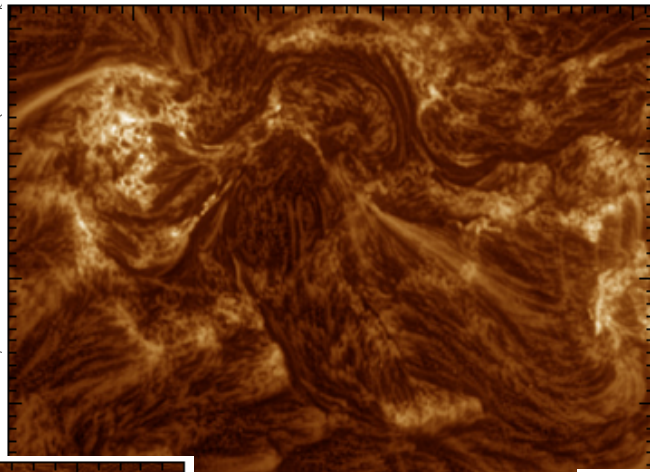
Multi scale Gaussian mask

- First implemented by Huw Morgan (2014)
- Gaussian of different widths are convolved with image to enhance features at different scales
- Enhance the noise too
- We first remove the noise by isolating high frequency using unsharp mask algorithm.
- We iterate this process 3 times to isolate the uncorrelated noise looking at fourier transform.
- We subtract noise filtered image from original image and then applied multiscale gaussian filter (see, Pant et al, 2015)

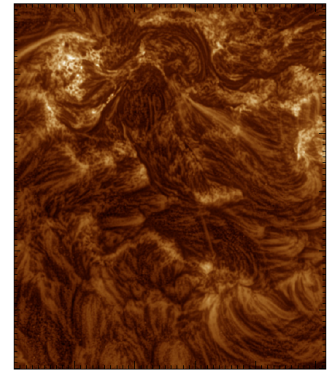
SDO-AIA-193 2012-07-11T18:55:06.84



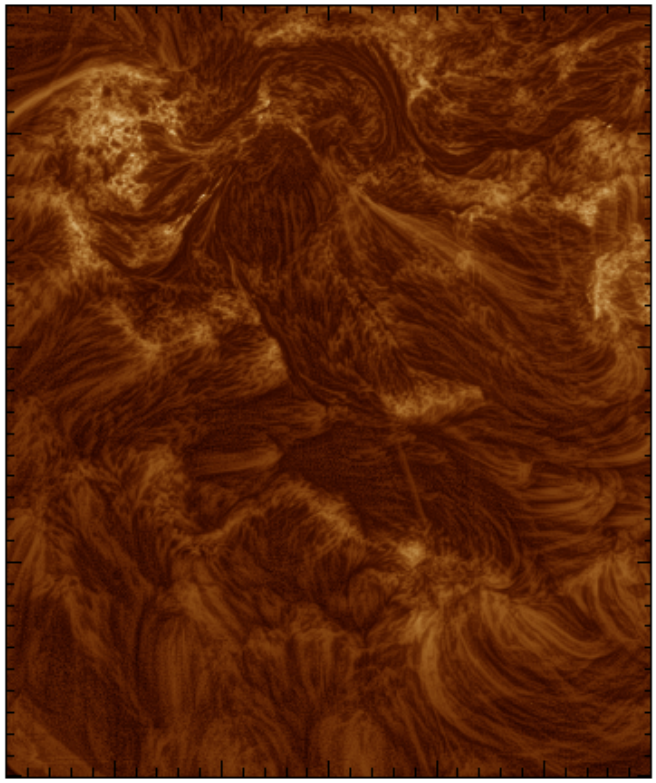
(a)



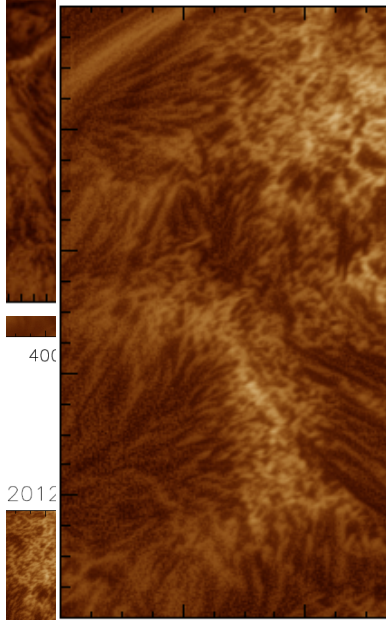
AIA-193 2012-07-11T18:55:06.84



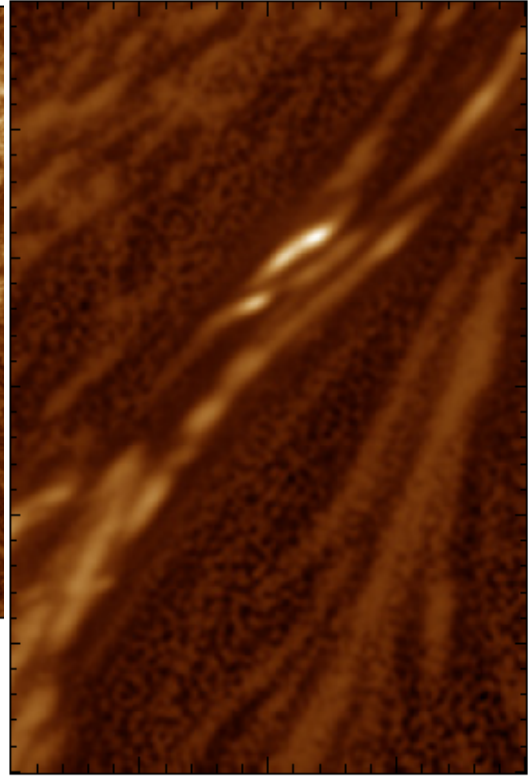
(c)



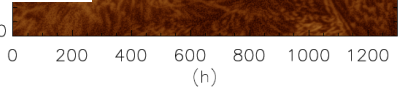
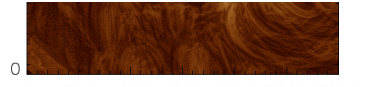
(g)



(h)

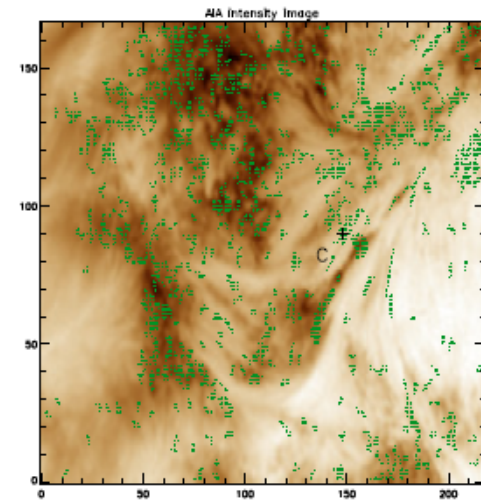
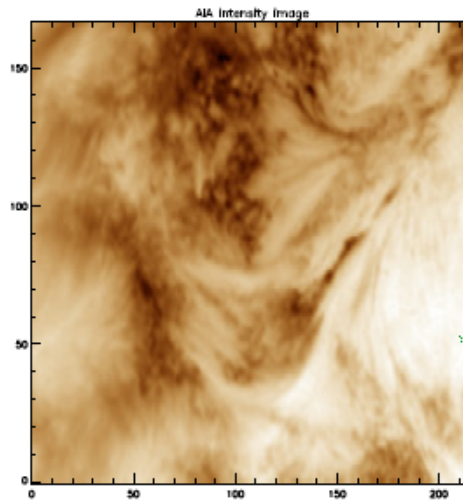
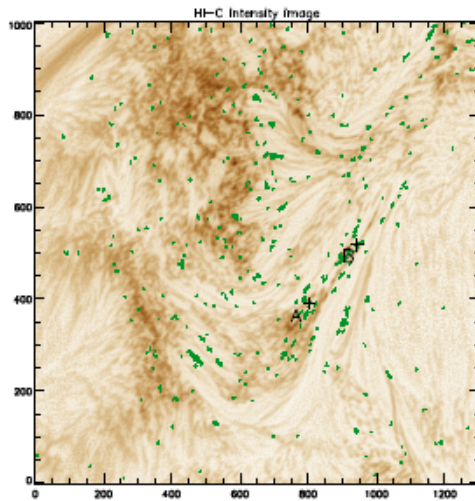
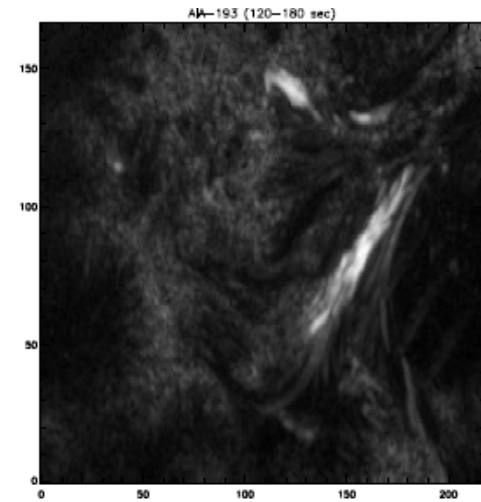
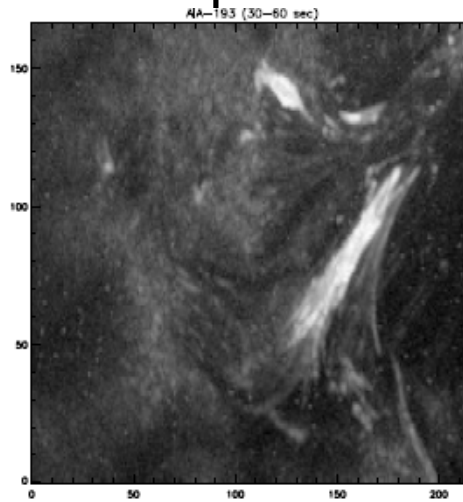
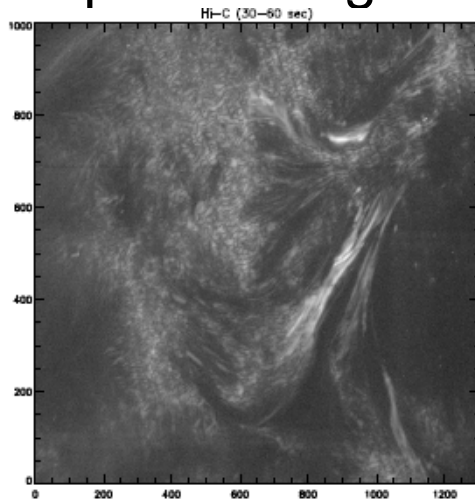


(i)

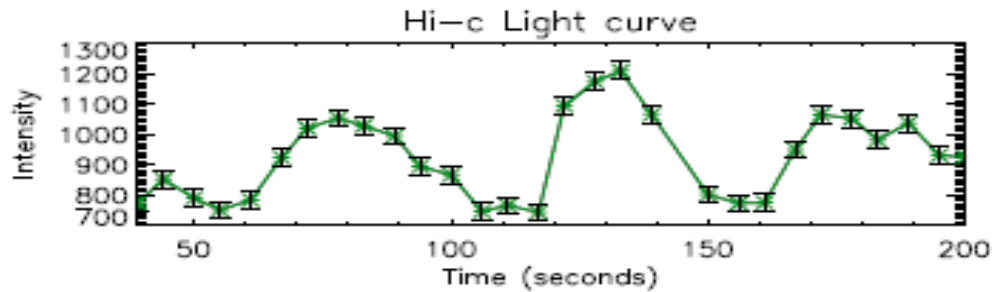
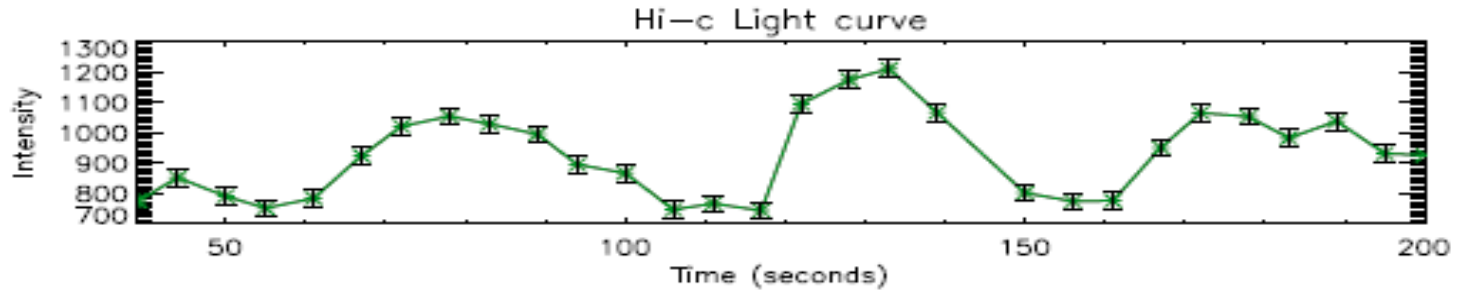


Power Maps and Periodic disturbance

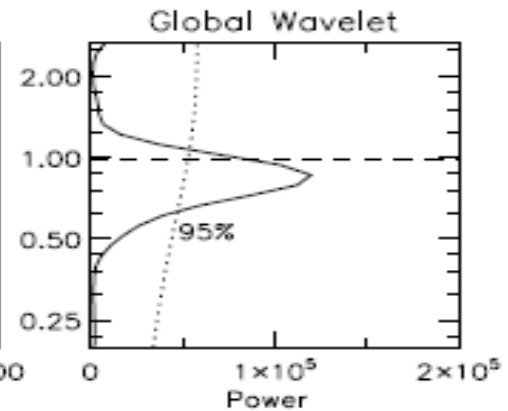
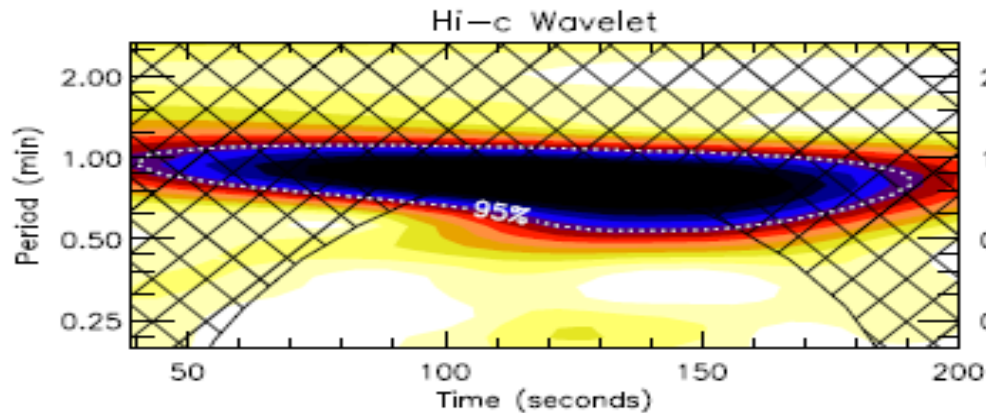
- Performed wavelet transform at each pixel location and computed the global wavelet power.



Wavelets Map at one pixel location 'a'

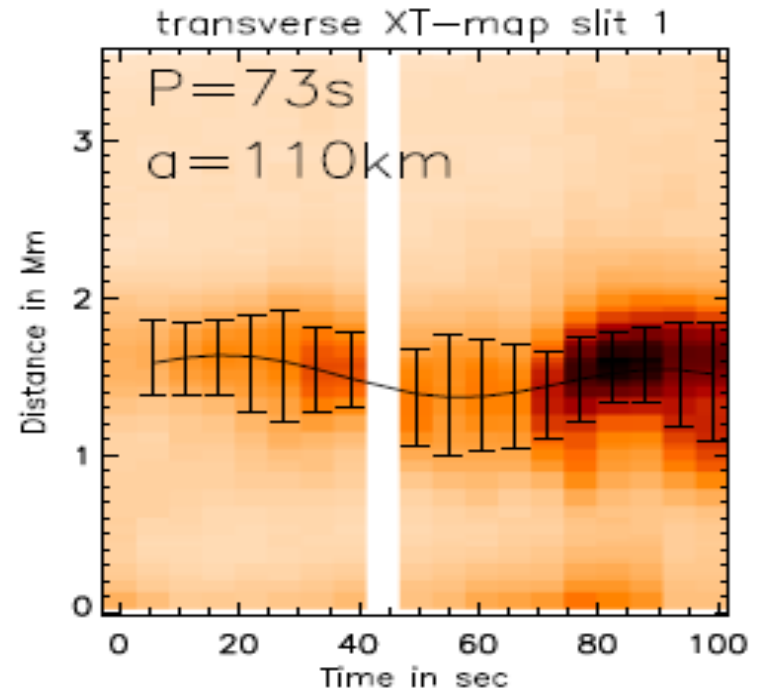
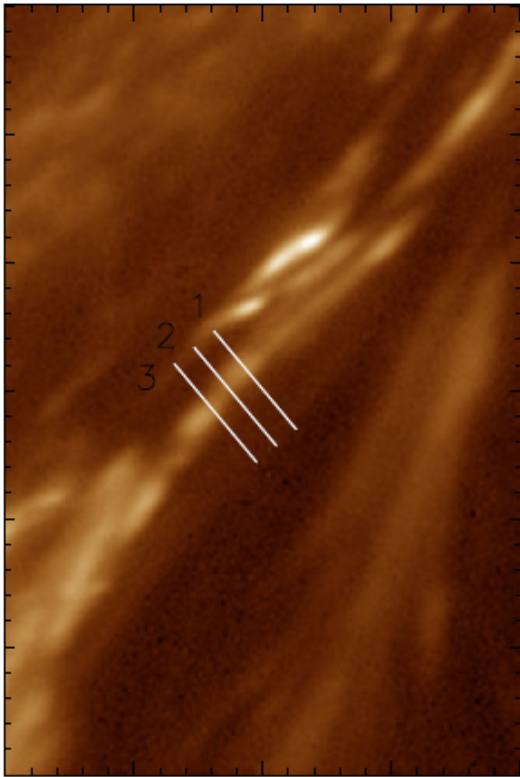


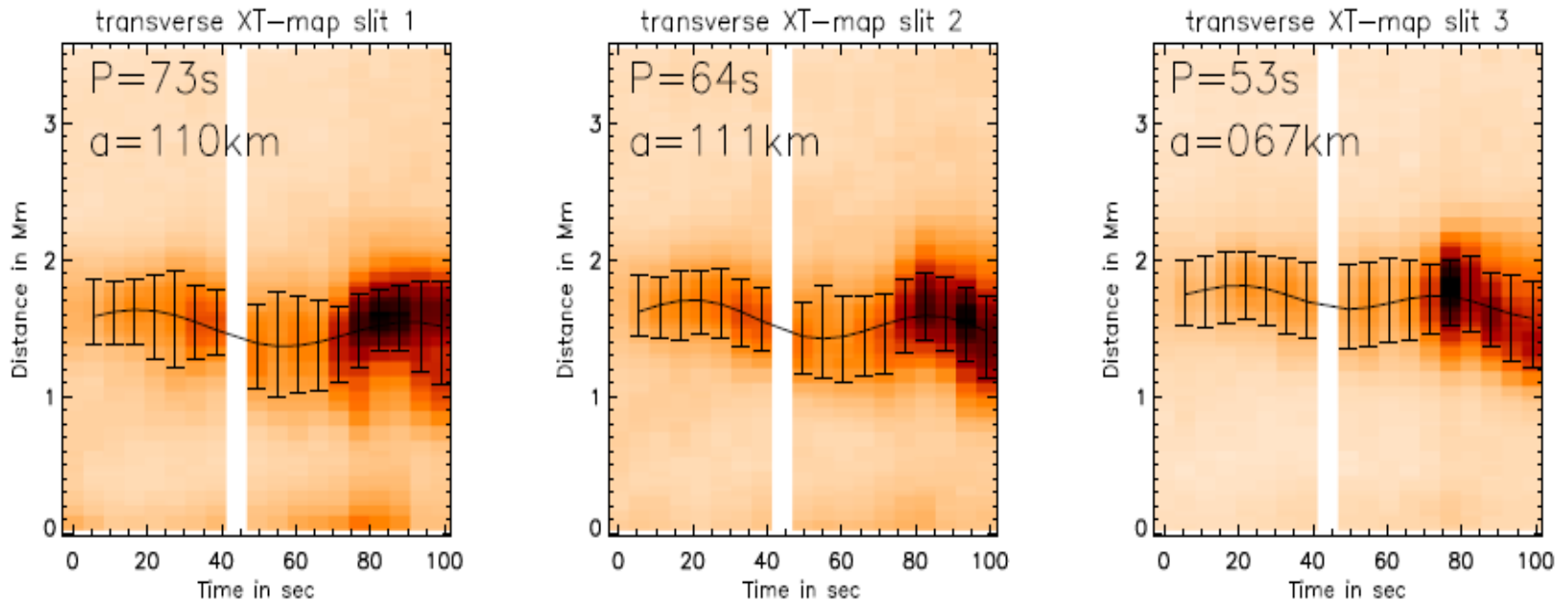
Global Period at max.
power (< 58.80 sec.)
P1 = 51.821 sec.
Second highest Peak
P2 = 12.955 sec.



- Green contours represent the significant power.
- 30-60 sec periodicity is present in Hi-C but absent in AIA
- 120-180 sec periodicity is seen in AIA FOV
- Significant power is present over moss region and braided magnetic region
- Power enhancement may be due to repetitive flows (in braided region) or magneto acoustic waves (in moss region).
- High temporal resolution of Hi-C enables us to estimate power at small temporal scales
- High spatial resolution of Hi-C allowed us to resolve the regions of significant power at higher frequency
- AIA having low temporal and spatial resolution couldn't detect power at such smaller scales

Transverse Waves in Braided Structures





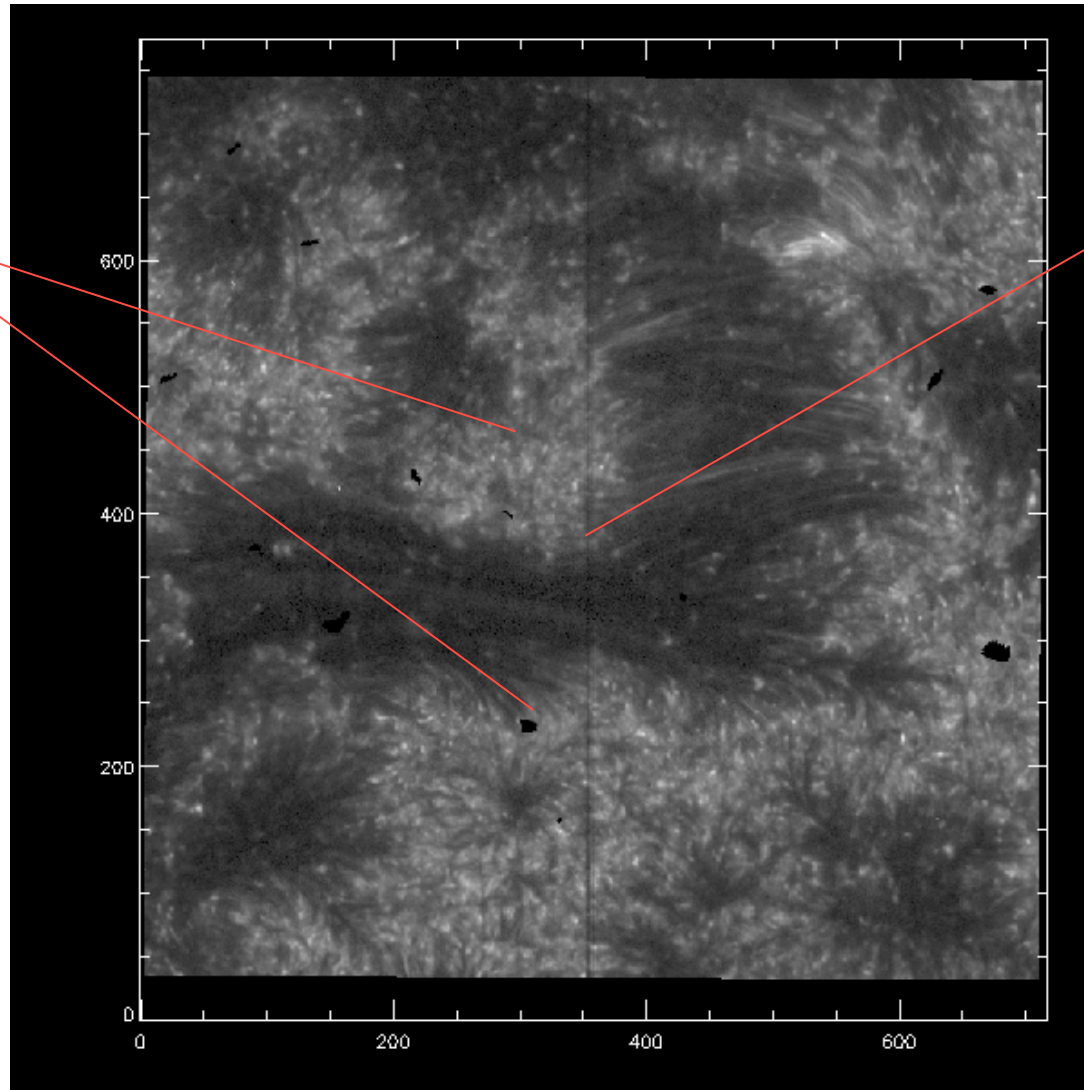
- Velocity amplitude = 11 ± 11 km/s
- Short period large amplitude oscillations are found at braided region
- Higher than what was predicted by McIntosh et al.
- Indicates that active region corona hides a lot more energy than predicted.
- High speed significant outflows as a result of reconnection and transverse waves happen almost at same time
- Who is triggering what??
- Reconnection \rightarrow waves OR waves \rightarrow Reconnection in tangled magnetic field

High frequency dynamics of moss using IRIS

Active
Region
Moss

Advantages

- High spatial and temporal resolution
- Looks at Transition region
- TR is not covered in AIA in high resolution

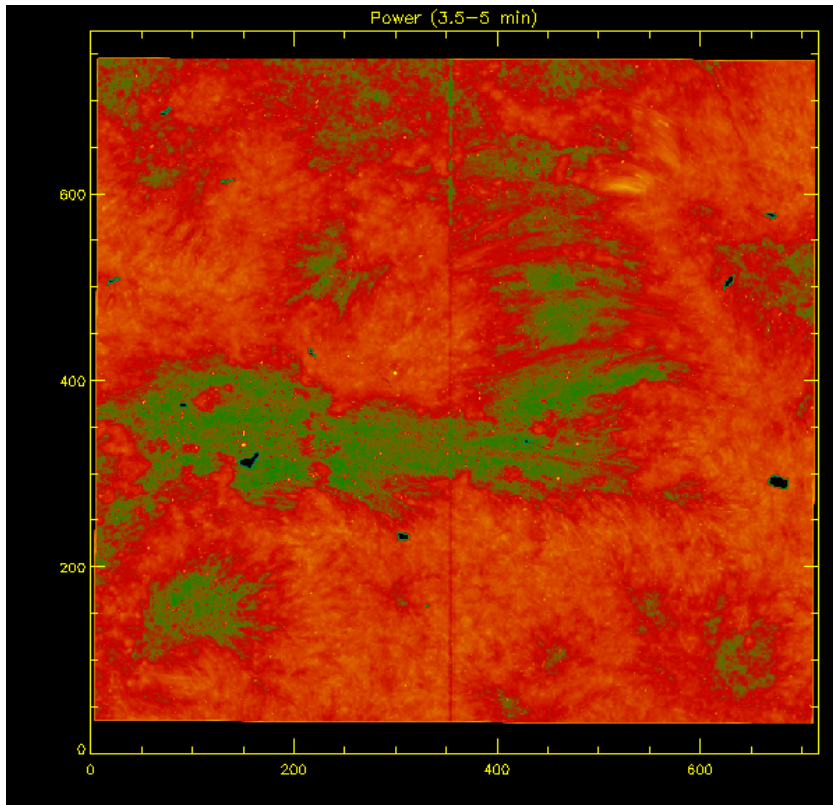


IRIS slit

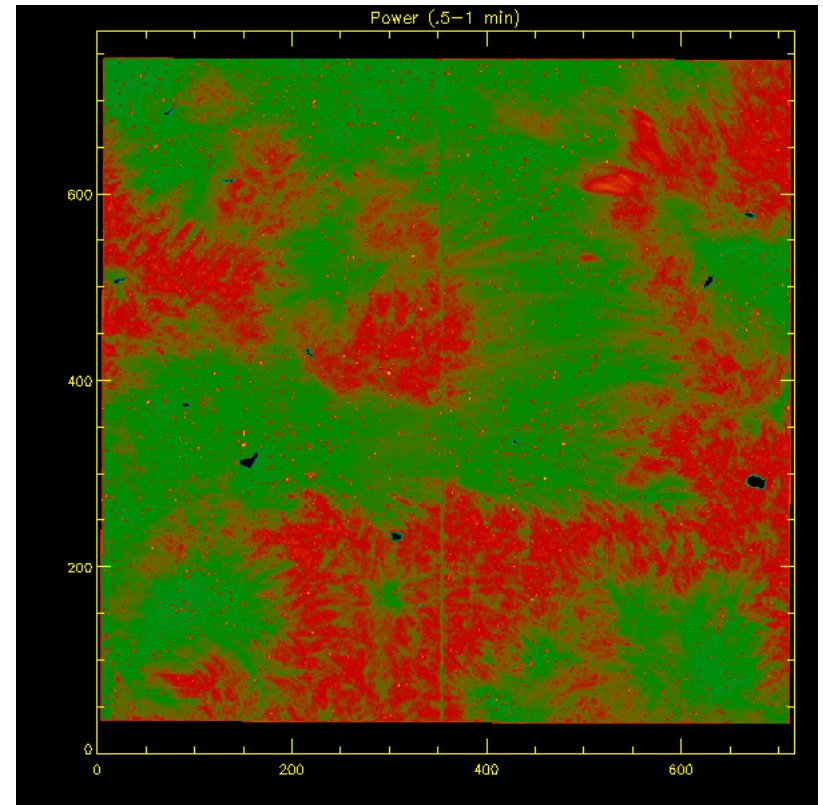
- Cadence of SJI is 12 sec
- Spatial Resolution is 0.166"/pixel

IRIS 1400 A

Power Maps using SJI 1400 A



3.5-5 min

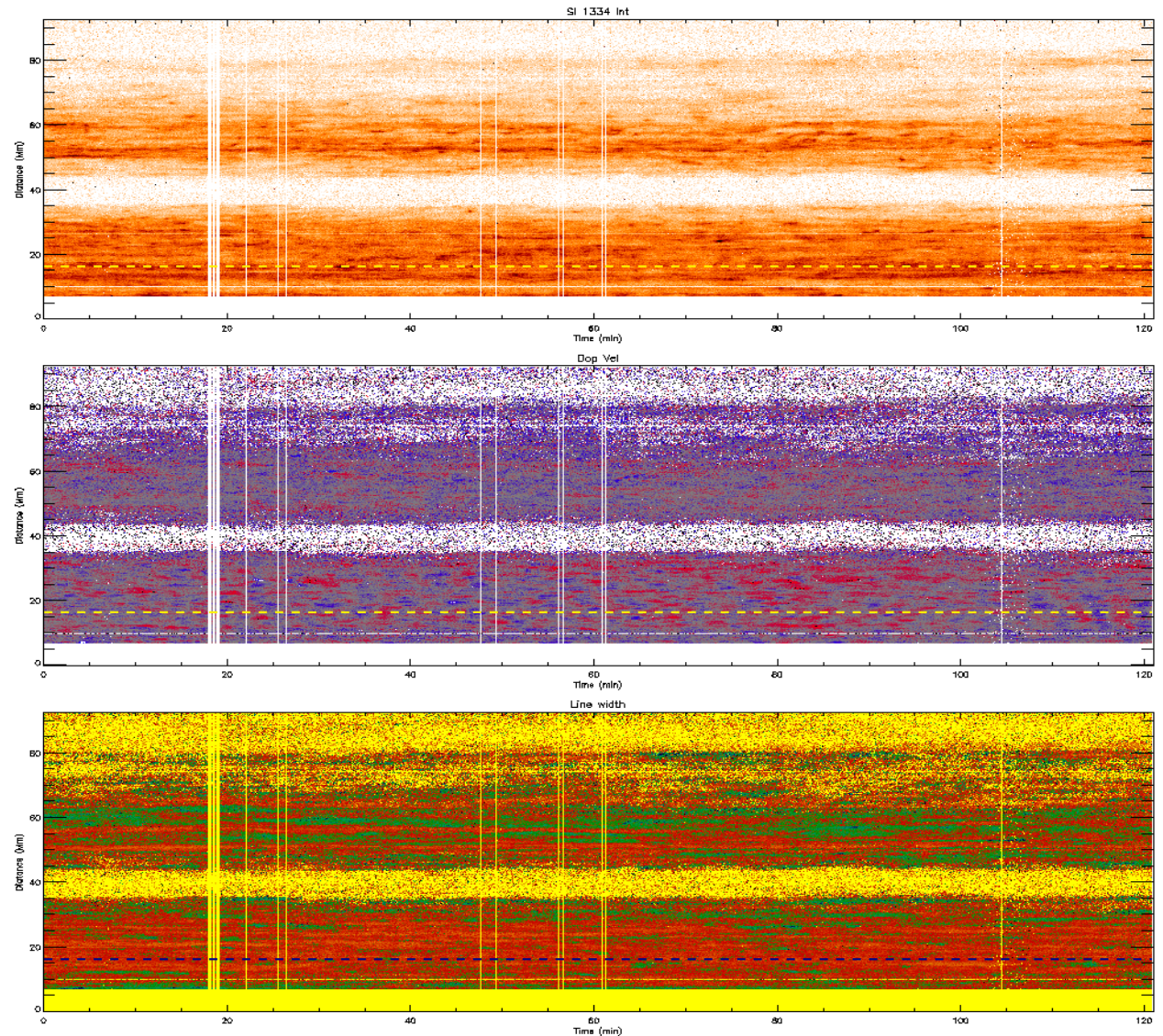


0.5-1 min

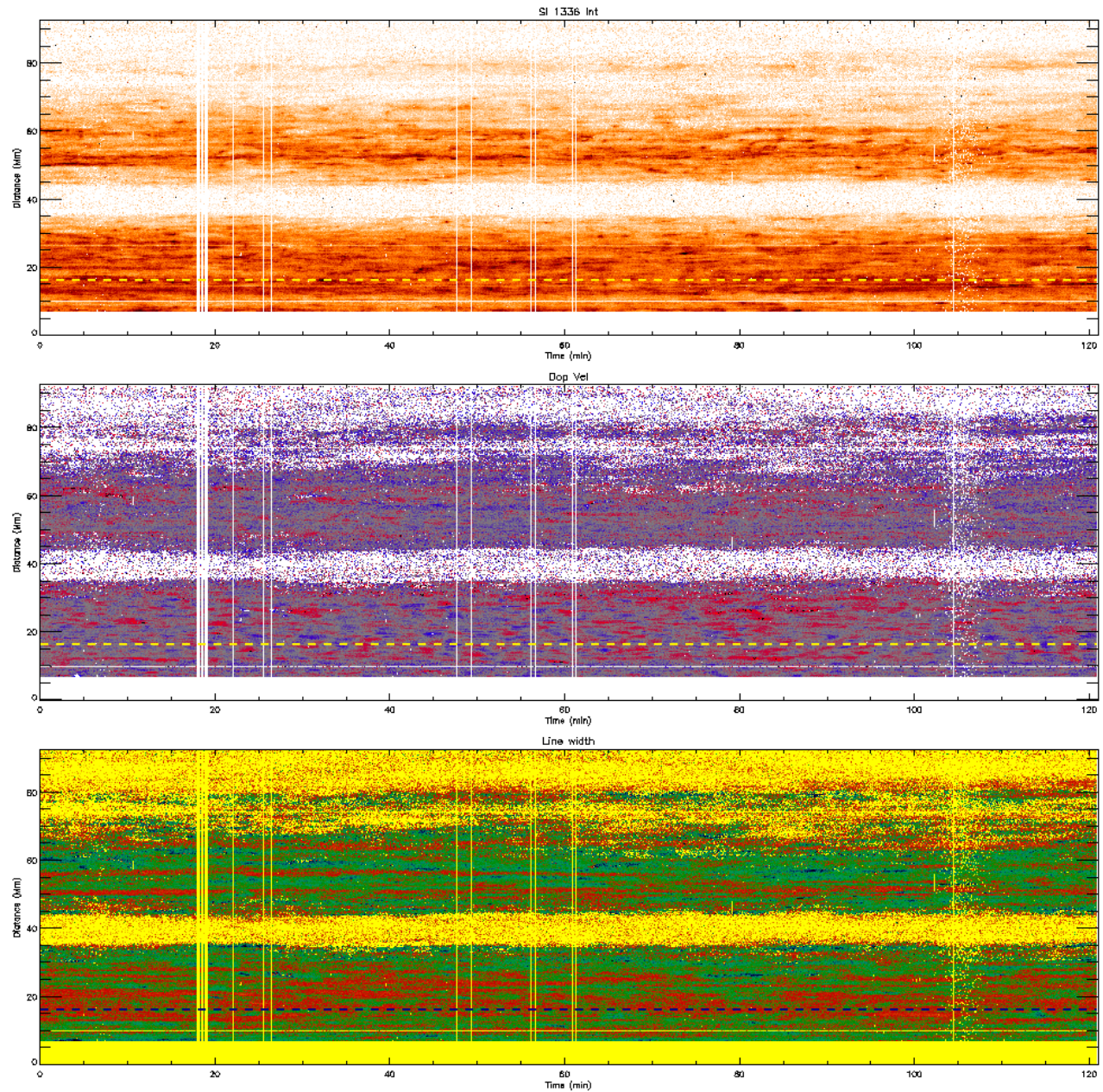
- Able to detect high periodicities due to low spatial resolution.
- Since cadence is 12 sec thus periodicities < 30 sec are not seen
- This result matches with Hi-C where we see similar behavior.

Spectroscopic analysis

- Sit and stare mode for ~ 2 hours
- Step cadence is 3.3 sec
- Suitable for high frequency analysis
- Used Si IV (1402 A), C II (1334, 1336 A)



C II 1334 A

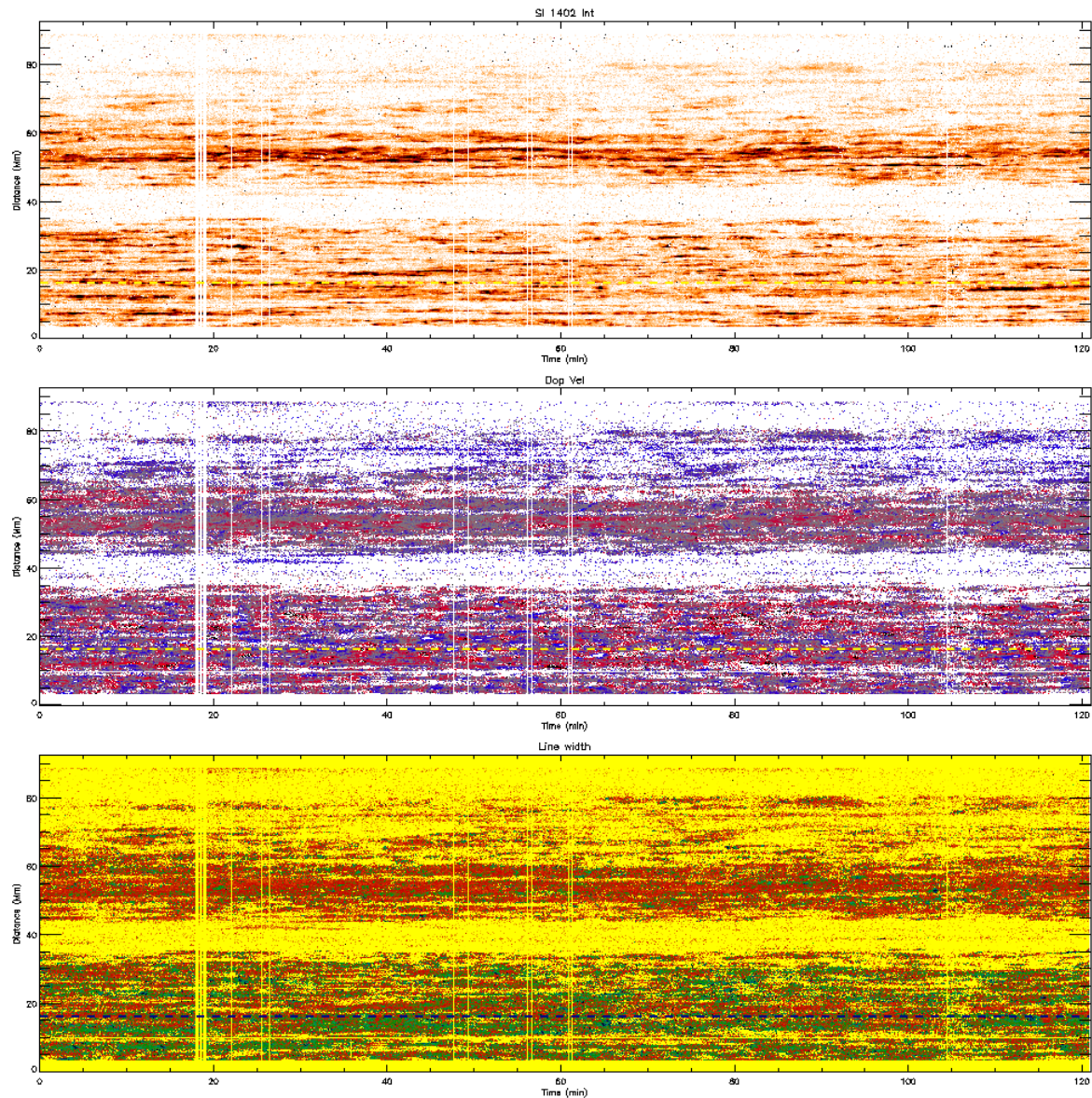


Dashed line represent the position used for obtaining intensity, Doppler velocity and line width curves

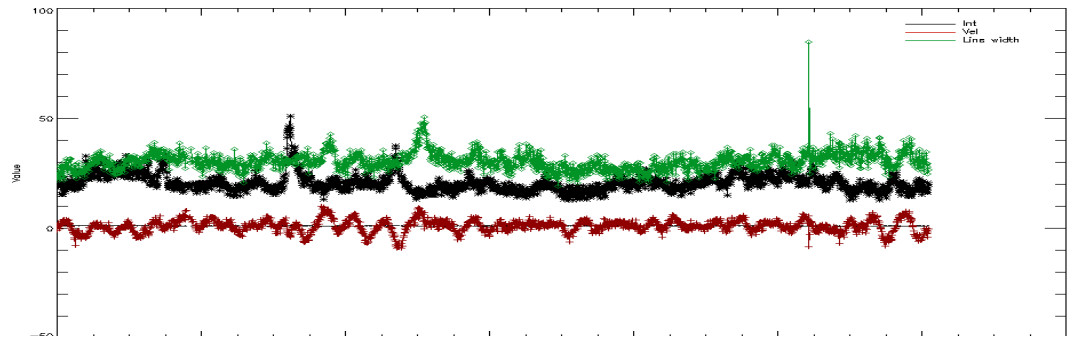
C II 1336 A

- While C II 1334 A and 1336 A looks same, Si IV 1402 looks quiet different
- More noisy
- Structures are not continuous
- Not compact as C II
- Dynamics is quiet different at different height scales

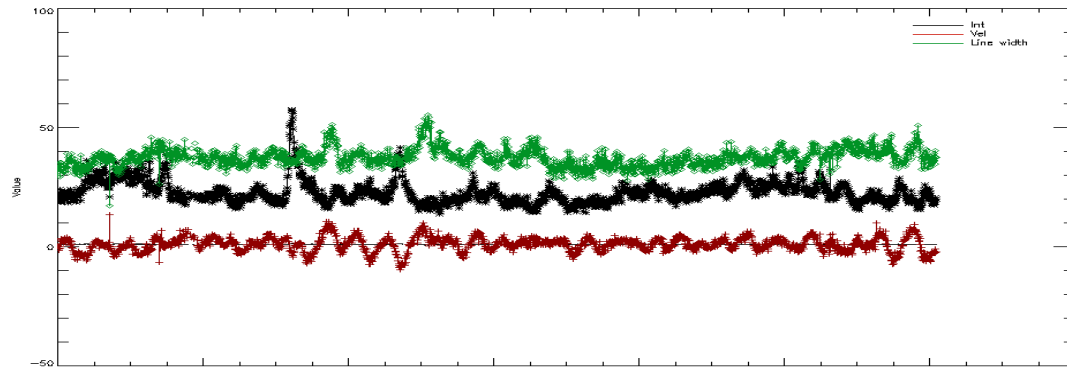
Si IV 1402 A



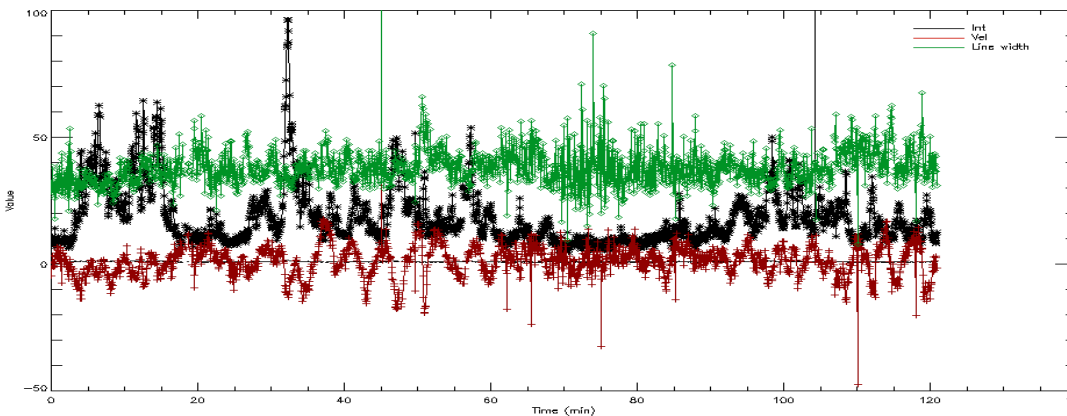
- Variation of line parameters with time at the location marked with dash line
- At most occasions intensity anti-correlate with Doppler velocity and line width
- Periodic disturbances are noted
- Horizontal black line represents the error in intensity.
- Plots for 1334 A, 1336 A and 1400 A are co-spatial.
- We find periodicity of 4.5-5 min
- Could be P-mode leaking through the flux tubes at active region moss ??



1334
A

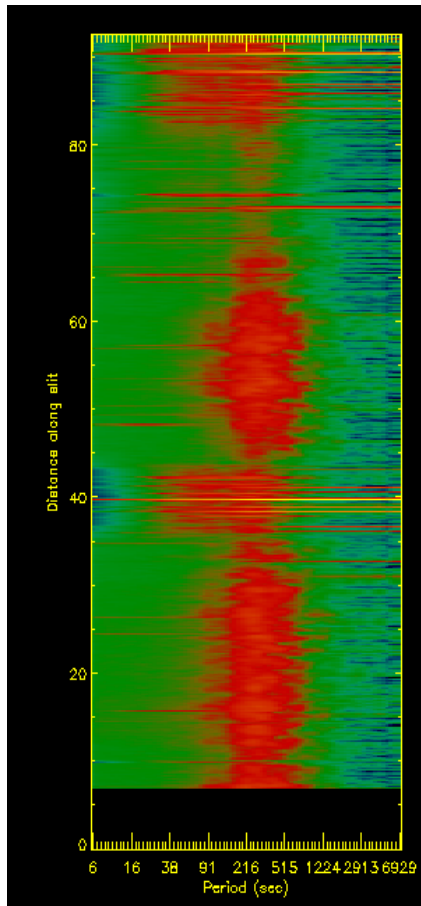


1336
A

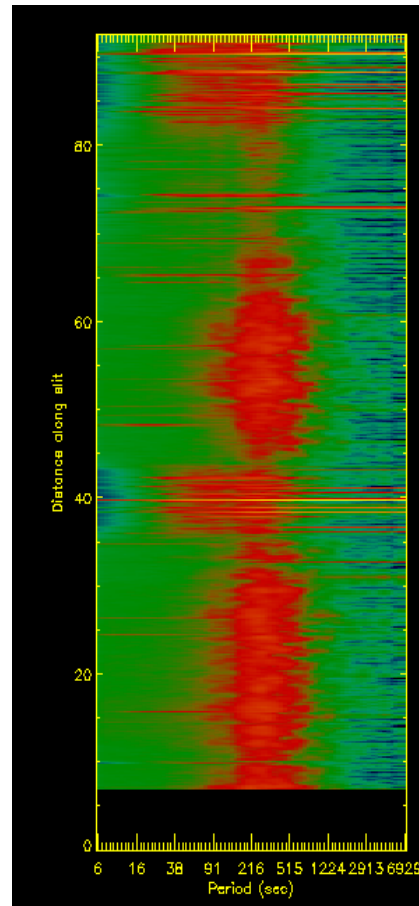


1402
A

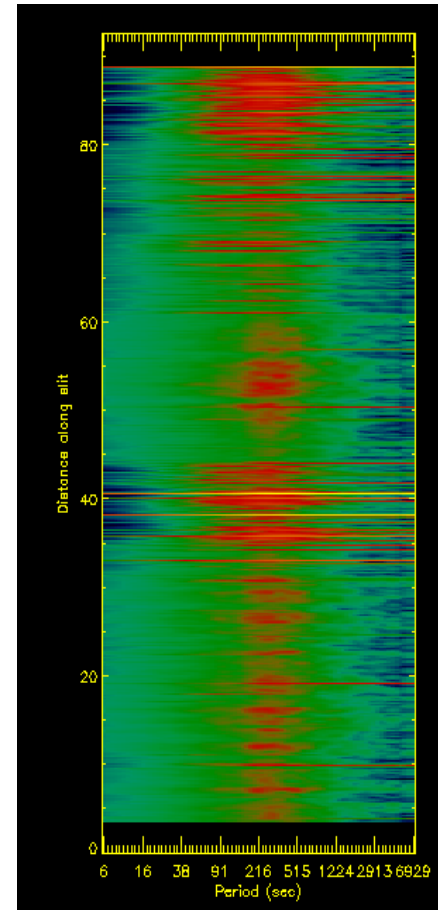
Power map at slit positions



1334 A

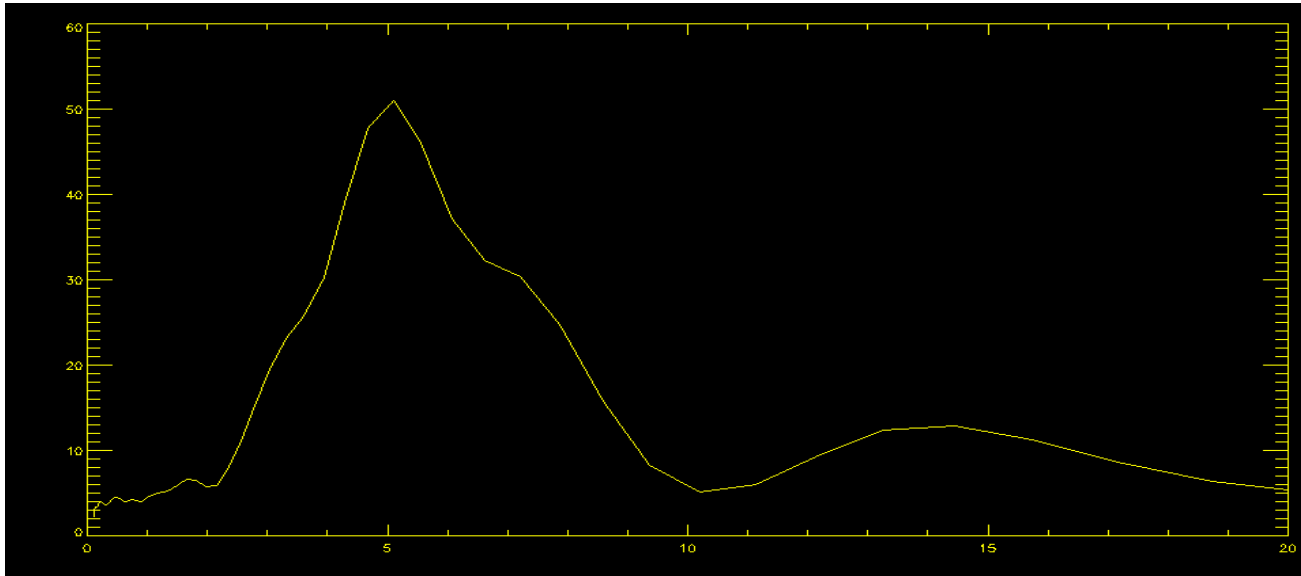


1336 A



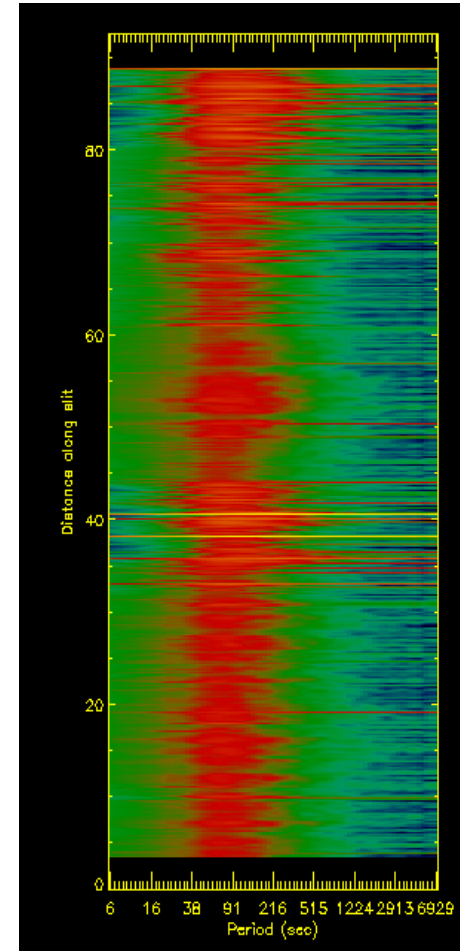
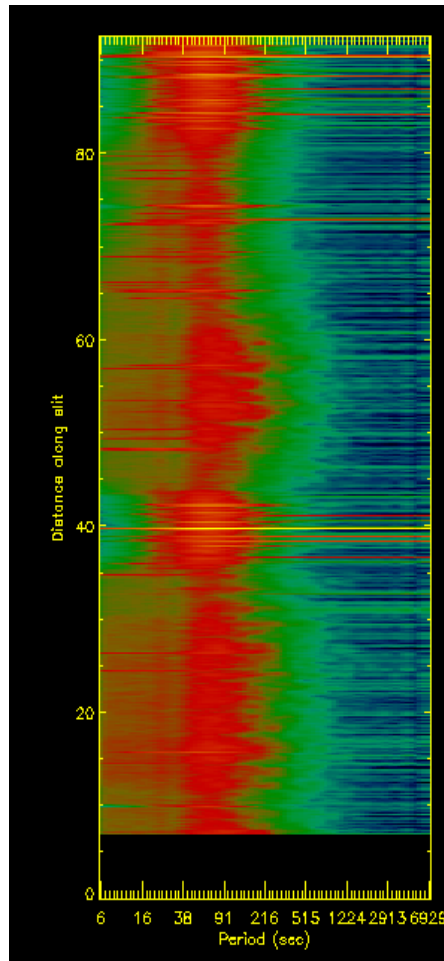
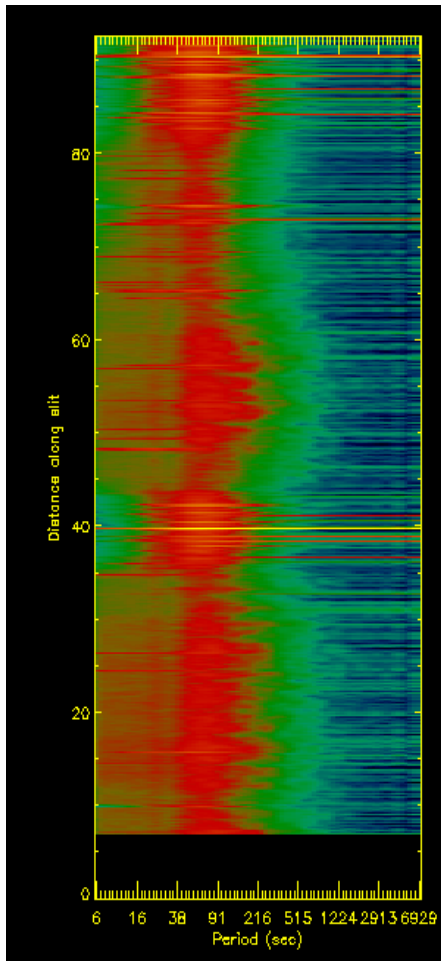
1400 A

- 4-5 min periodicity is quiet evident
- 1400 A the power is concentrated more in some rows. This picture is consistent with the intensity maps

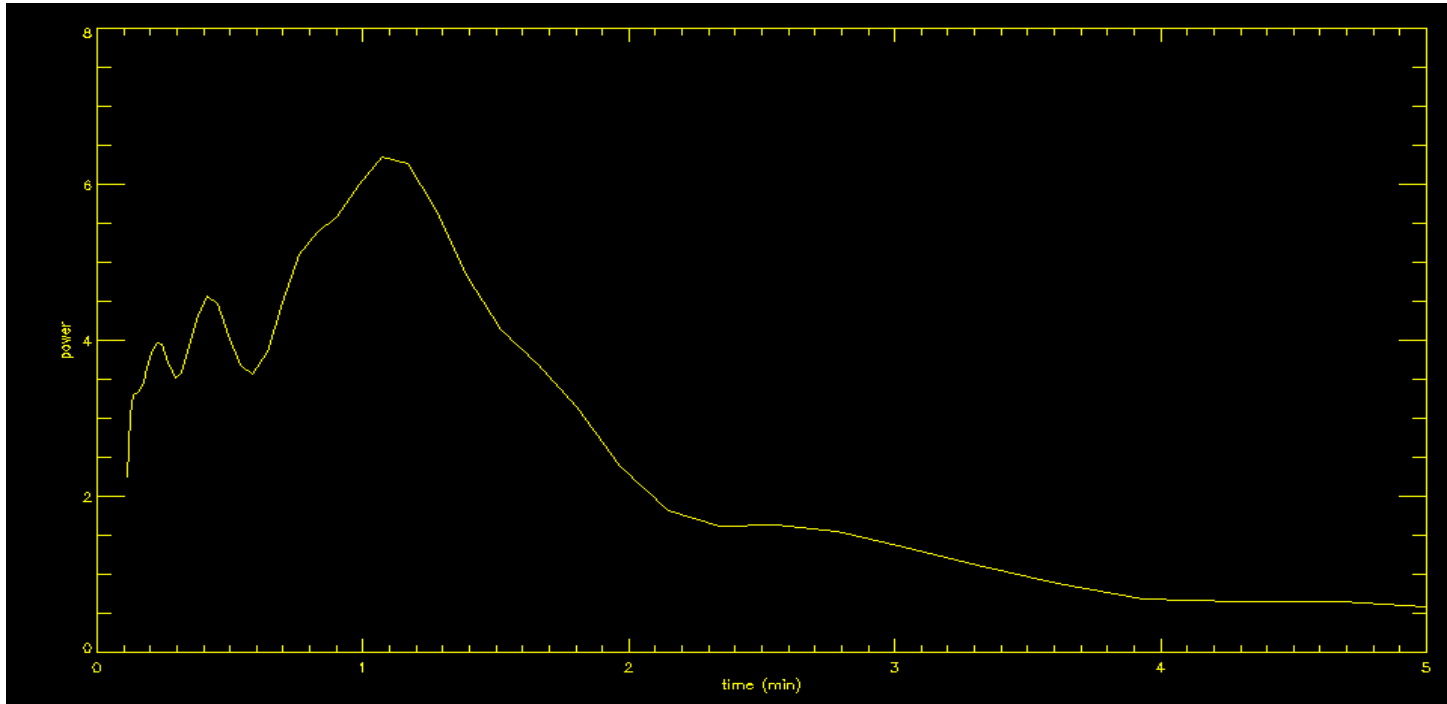


- Global wavelet at the position marked with dashed line. Power peaks at 5 min
- The power enhancement is also seen at higher frequency (low period)
- The power at 5 min has to be suppressed in order to bring out power at higher frequency

Subtracting the larger periodicity

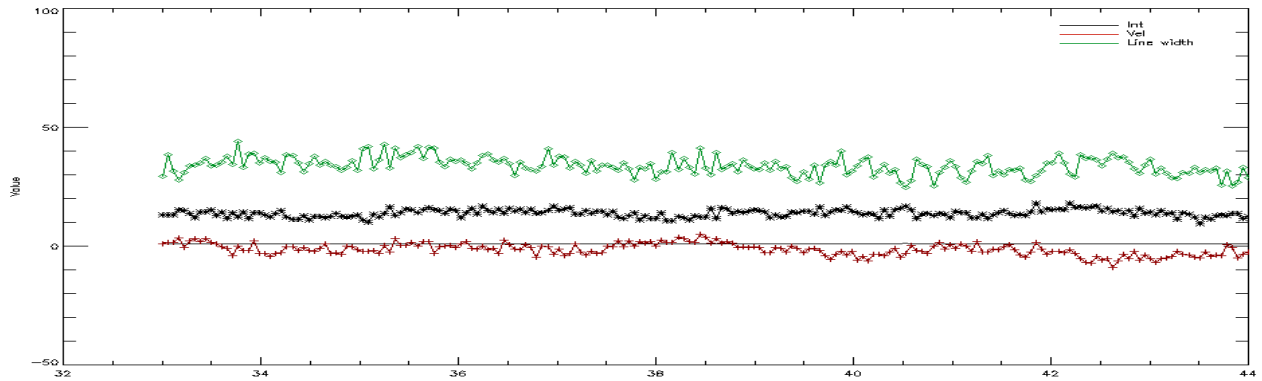


- After de-trending, the power becomes significant at high frequency
- 0.5-1 min periodicity becomes quiet evident

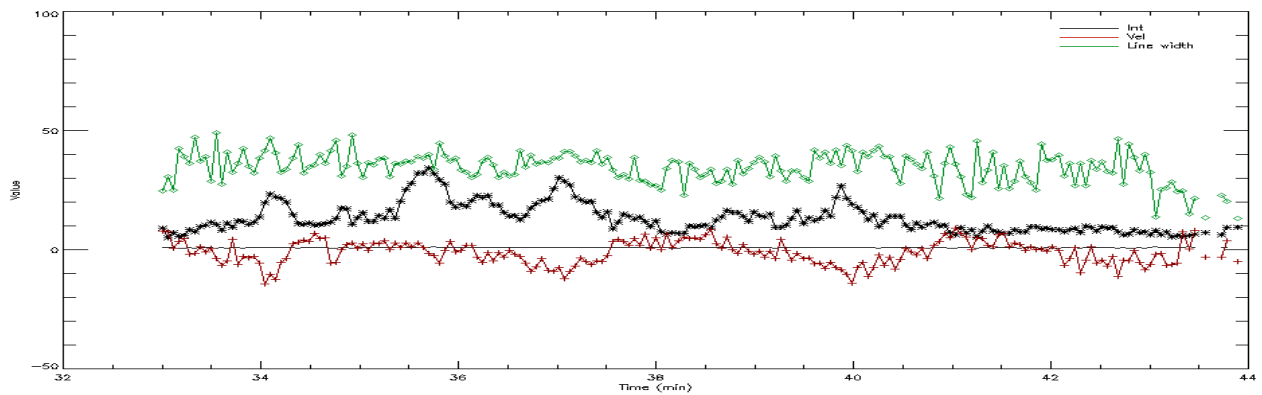


- Global wavelet at dashed position after suppressing the power at lower frequencies (de-trending)
- Power enhancement is seen ~ 1 min
- Still power bumps are present ~20-30 sec.
- These small periodicities are not present throughout thus specific region has to be selected.

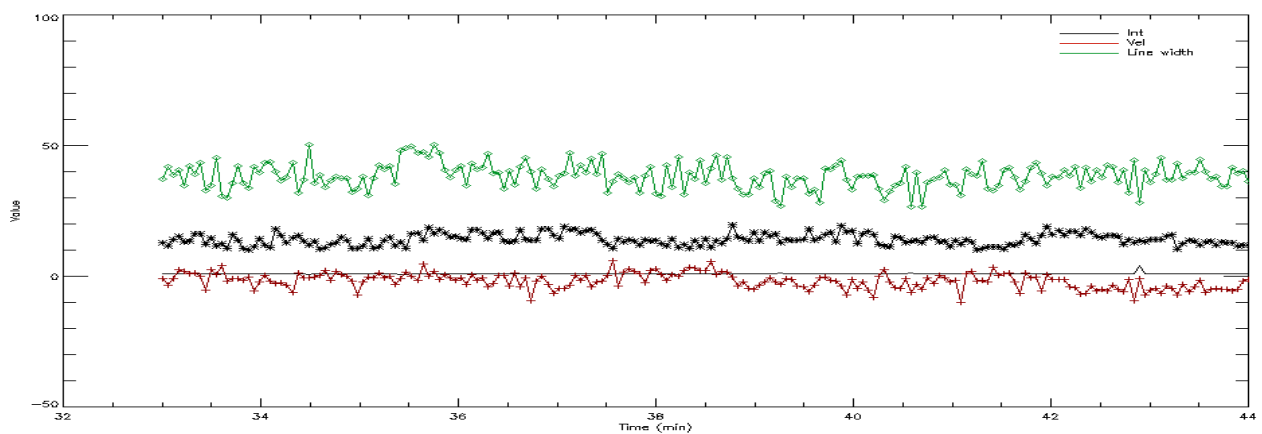
- Variation of line parameters at shorter time scales (34 min – 44 min)
- We see variations at lower time scales
- Global Periodicity of 30 sec to 60 sec
- At some places even lower than 30 sec.
- Intensity anti correlates with Velocity and line width at many positions.



1334 A

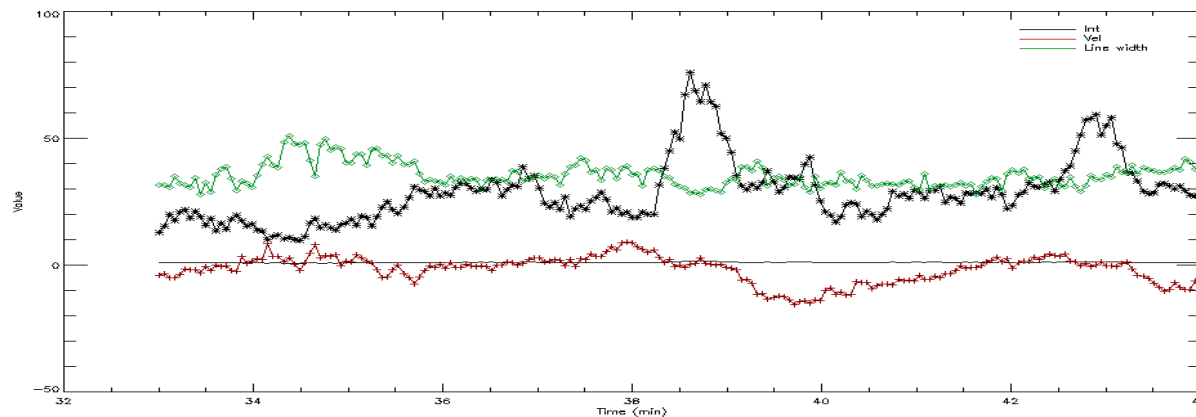
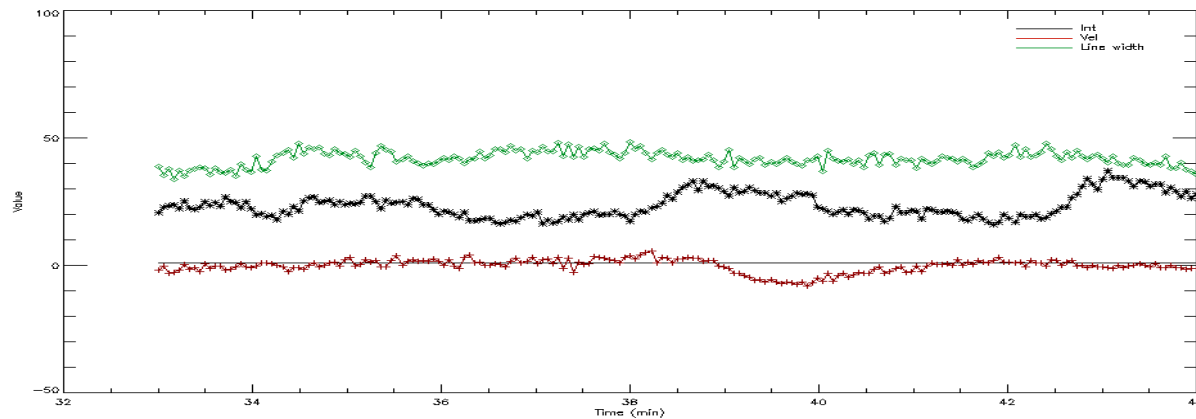
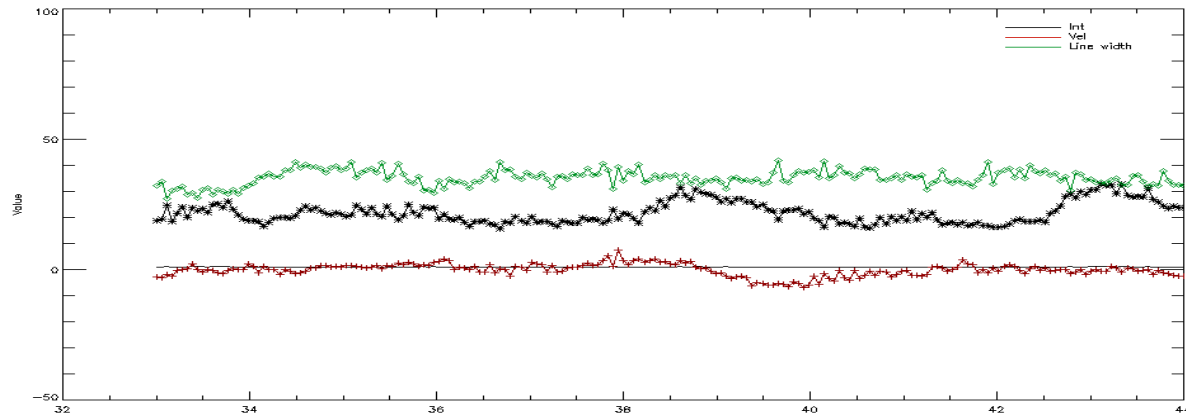


1402 A



1336 A

- Variation of line parameters at another position.
- Small impulsive changes in 1400 A are not seen very well in 1334 and 1336 A
- Large change in intensity is reflected in all three lines
- Large change in intensity \rightarrow very low Doppler shift
- May be heating not reconnection



Conclusions

- 5 min periodicities suggest that p-modes might be leaking in corona through small scale flux tubes present in active region moss
- Higher periodicities are present in active region moss
- Short timescale impulsive events are seen in 1400 Å but not very clearly in 1334 and 1336 Å, which led us to believe that reconnection is happening at higher heights.
- We do see the signature of heating and the intensity at 1400 Å, 133 Å and 1336 Å vary. Which suggest that heating is chromospheric
- To Do
- Shorter time scale variations are waves?
- We do see the shorter scale reconnections (~15 sec).
How much energy is deposited in corona by such events?

Kink waves in rainy loops

Antolin & Verwichte 2011

In phase oscillations

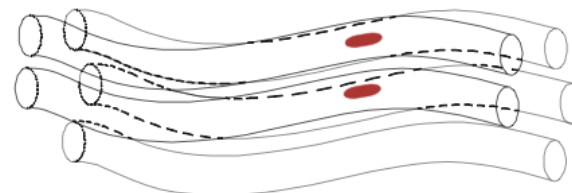
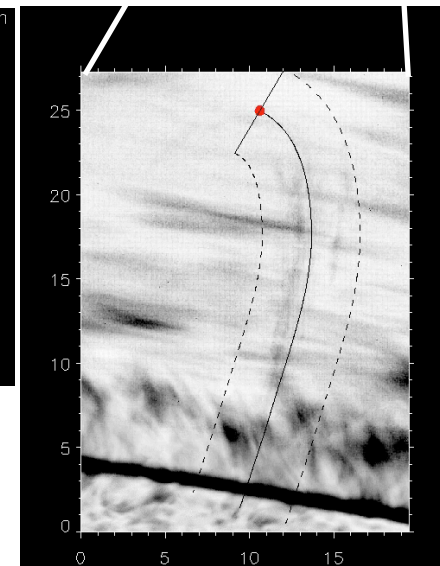
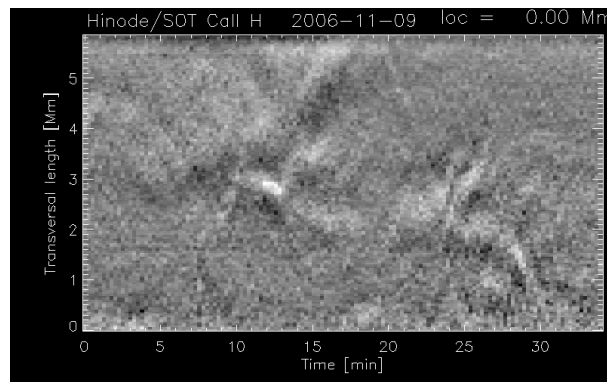
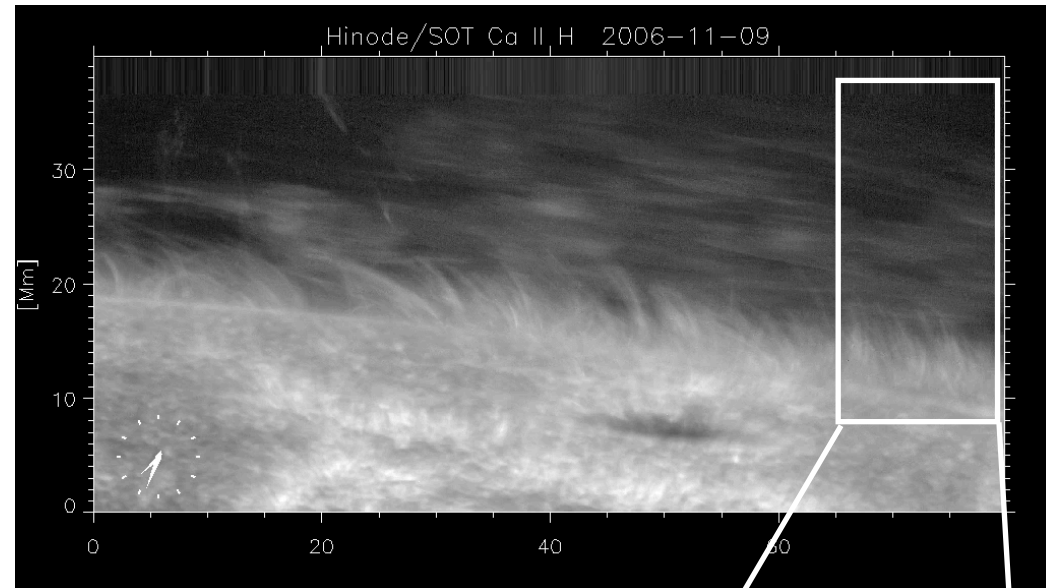
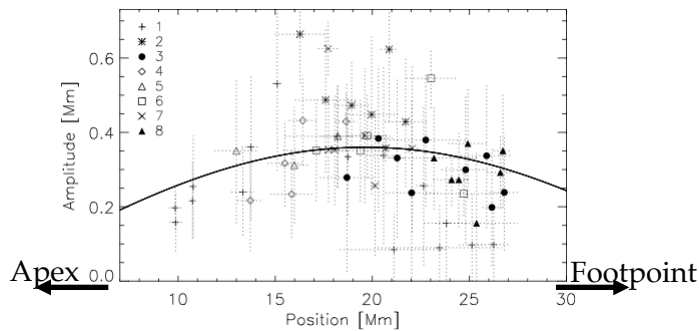
Periods: 100 - 200 s

Amplitudes: <500 km

standing wave: 1st harmonic

$\lambda=L\sim 80\pm 15$ Mm

Magnetic field: 12 ± 3 G



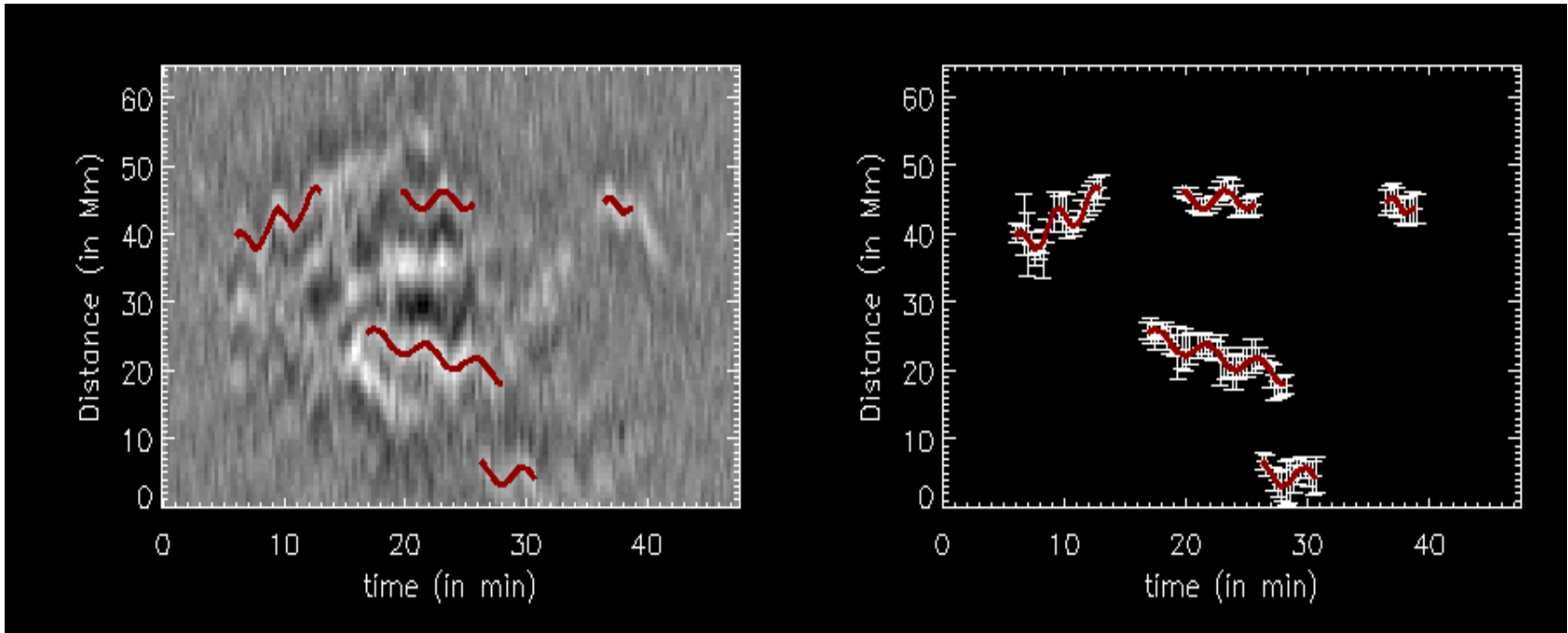
- Multiple kink mode: each strand ~~2009~~ defines a waveguide
- Possible dynamic effect from transverse MHD wave on coronal rain (may explain velocities lower than free fall)

Transverse Waves in Coronal Rain

- Green vertical line represents the location of IRIS slit
- Red boxes represents the slits used to create x-t maps
- Seems to oscillate coherently all along the loop.

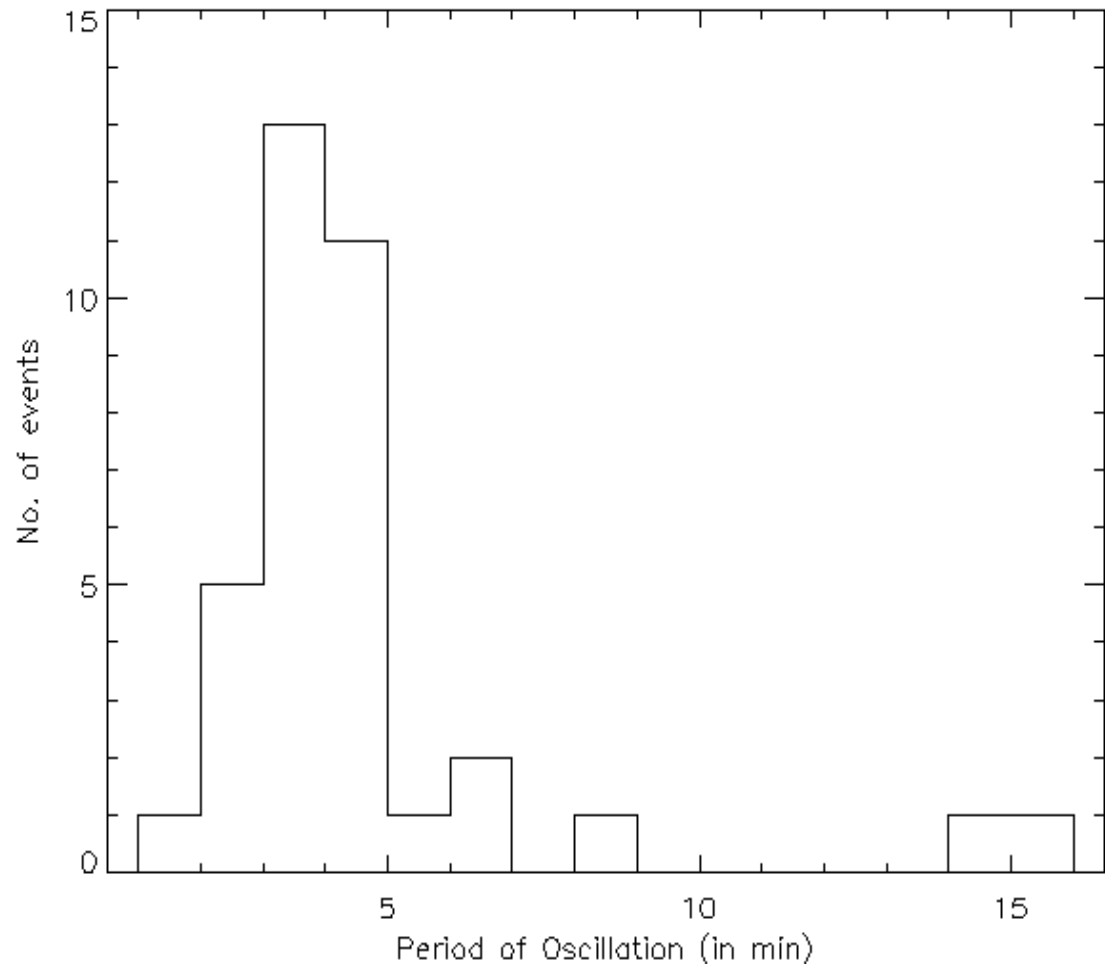


IRIS 1440 A SJI

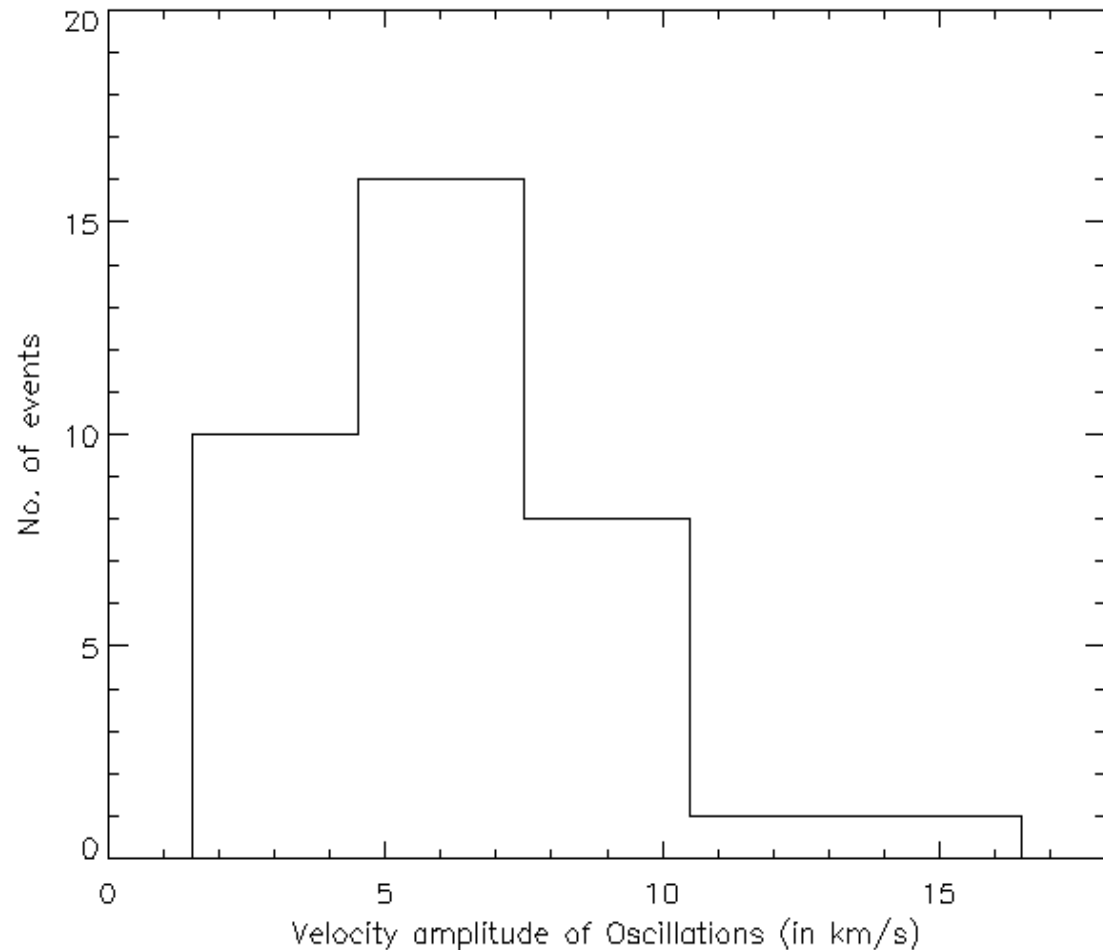


- X-t map for artificial slit 1
- Semi automatedly fit the sinusoidal curves to the oscillations.
- Error bars are estimated by fitting a Gaussian along the column and estimating 1 sigma variation.
- Threads of coronal loops are oscillating in phase.
- More like fundamental mode.
- Coronal rain act as the tracer for the threads of coronal loops
- Looks like decayless but could be possible that coronal rain just left the place and there is no intensity enhancement

- Wide spread in the period of oscillations
- Peaks ~3 min
- Typical period for a coronal loop oscillations
- Some short periodic oscillations are also present



- Velocity amplitude as high as 15 km/s is seen
- High at coronal heights
- Many events with 8-10 km/s
- Such high velocity amplitude oscillations store lot of energy.
- If density and loop length is known, then energy can be calculated



- 4 step raster was taken
- Variation of line parameters of one of the raster positions are shown
- Small rectangular box represents the location of oscillation
- Apart from it there are many oscillations seen at different places

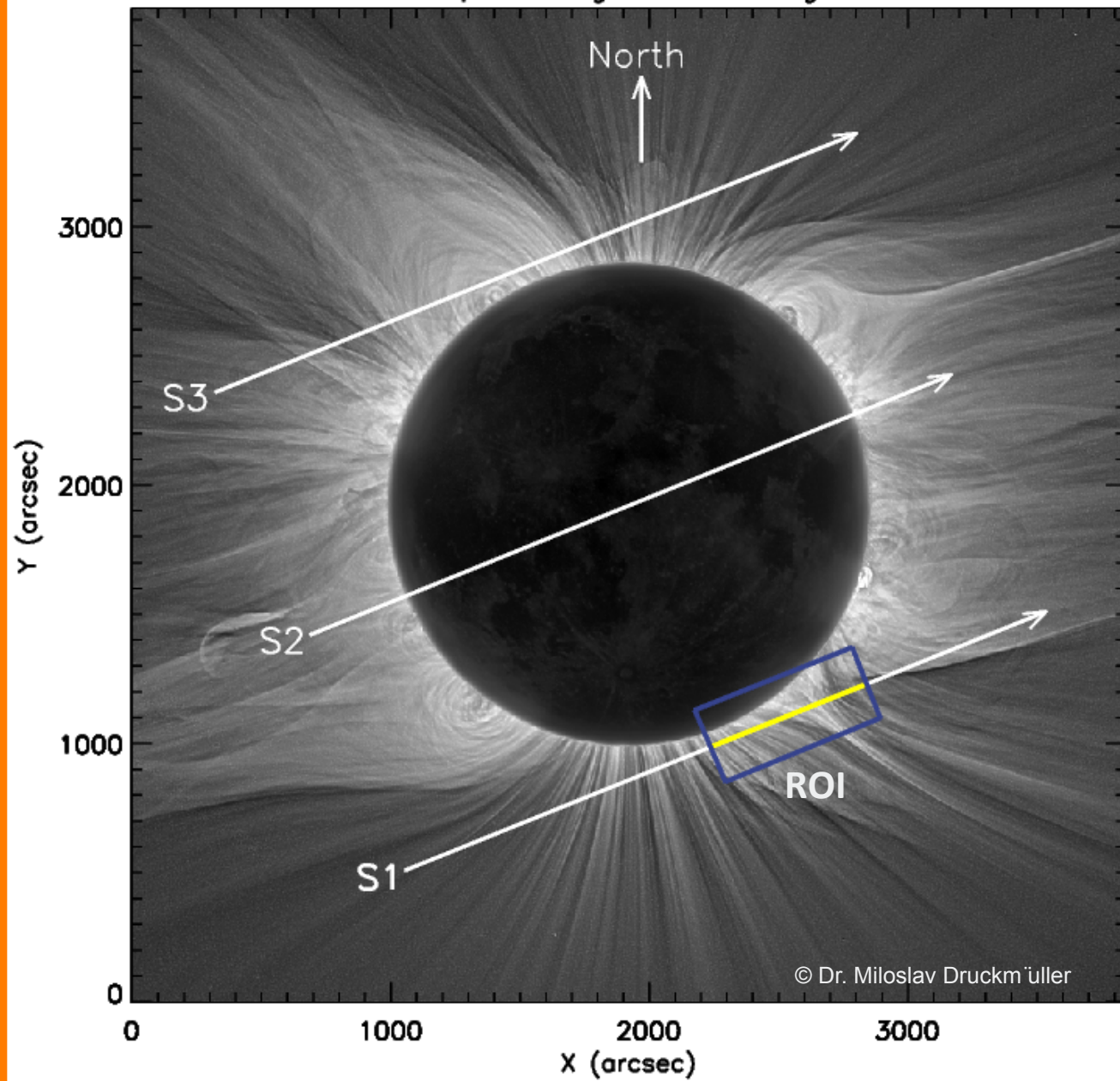


Si 1394 A line variation parameters

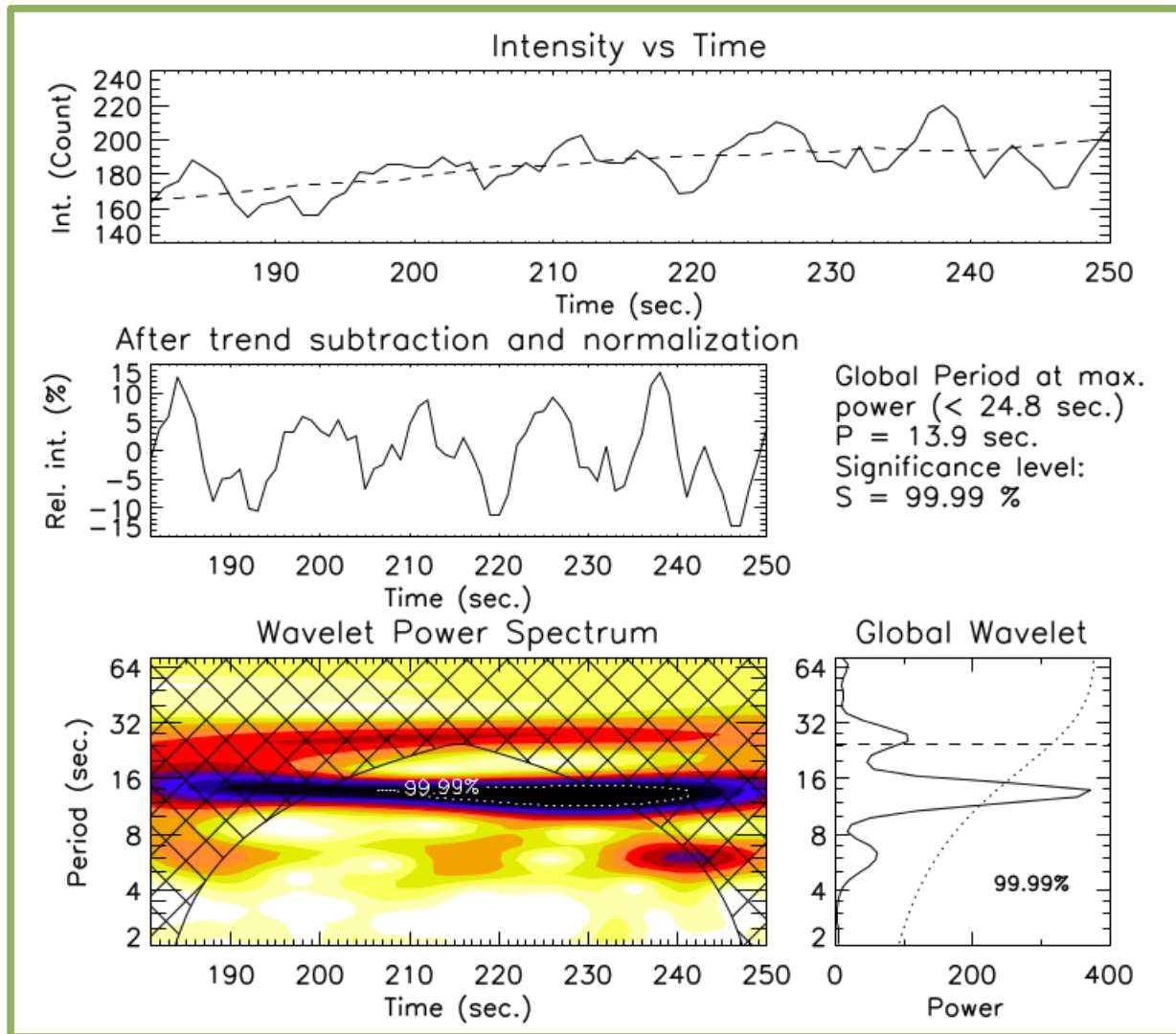
Multi-slit spectroscopic observation of high-frequency oscillations in the corona during a total Solar eclipse

- ◆ A high resolution spectroscopic observations of corona was made during the total solar eclipse of 11th July, 2010 at Easter Island, Chile.
- ◆ The aim of the experiment was to detect “high- frequency oscillations” in the solar corona while observing the strong coronal emission line Fe XIV and Fe X.
- ◆ We will focus only on the red line (Fe X). Spectra was obtained with 1.013 s (exposure time of 1 s).

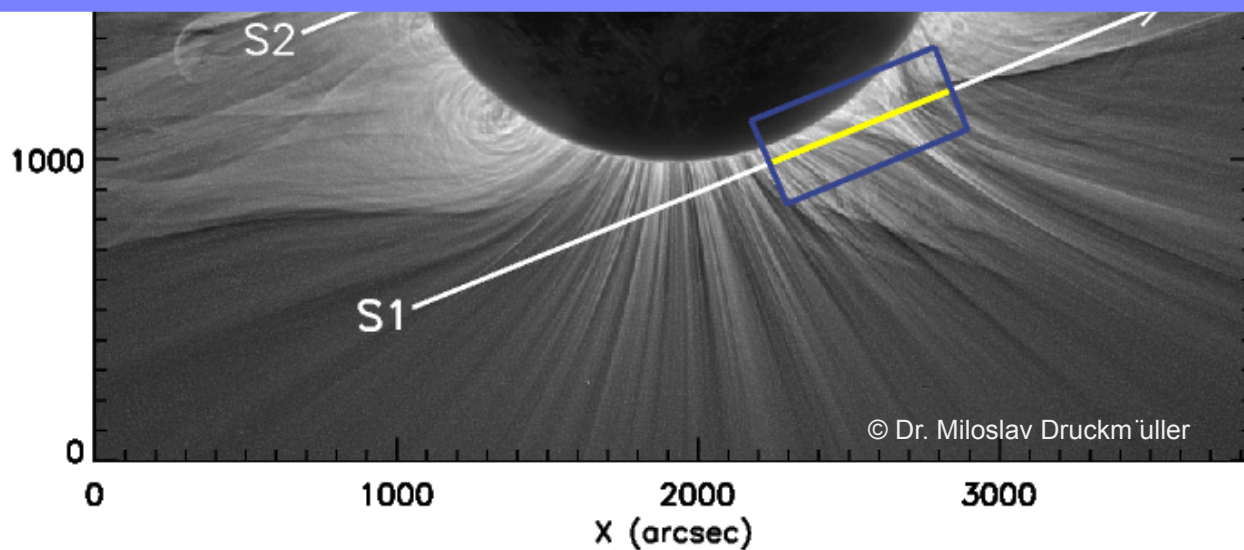
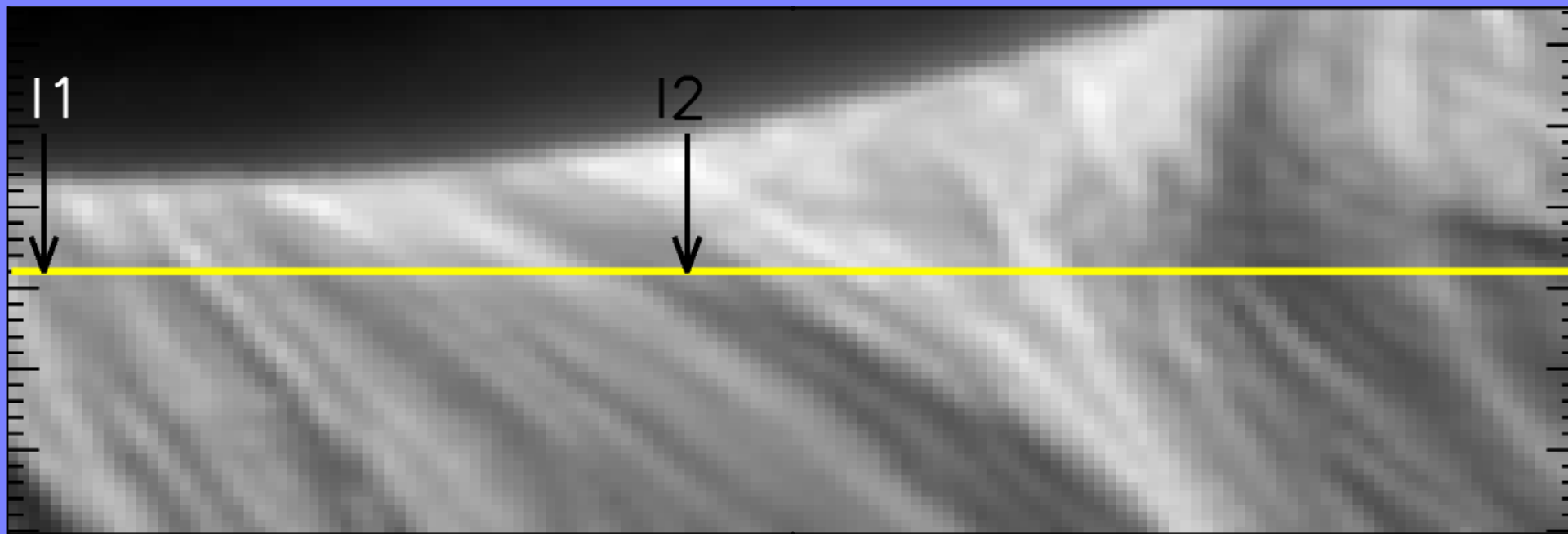
Eclipse image in white light



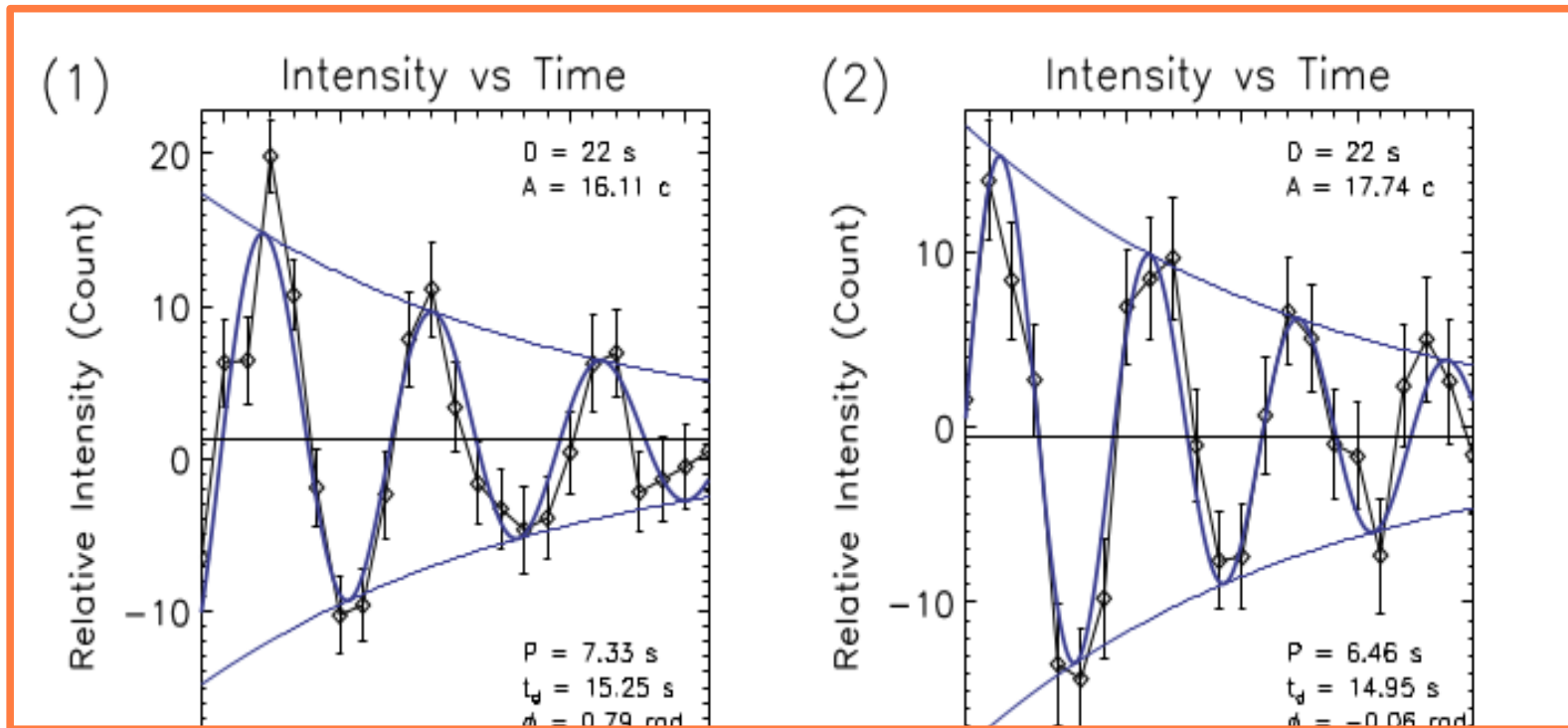
High-Frequency Intensity Oscillations



Eclipse image in white light



Damping of Intensity Oscillations



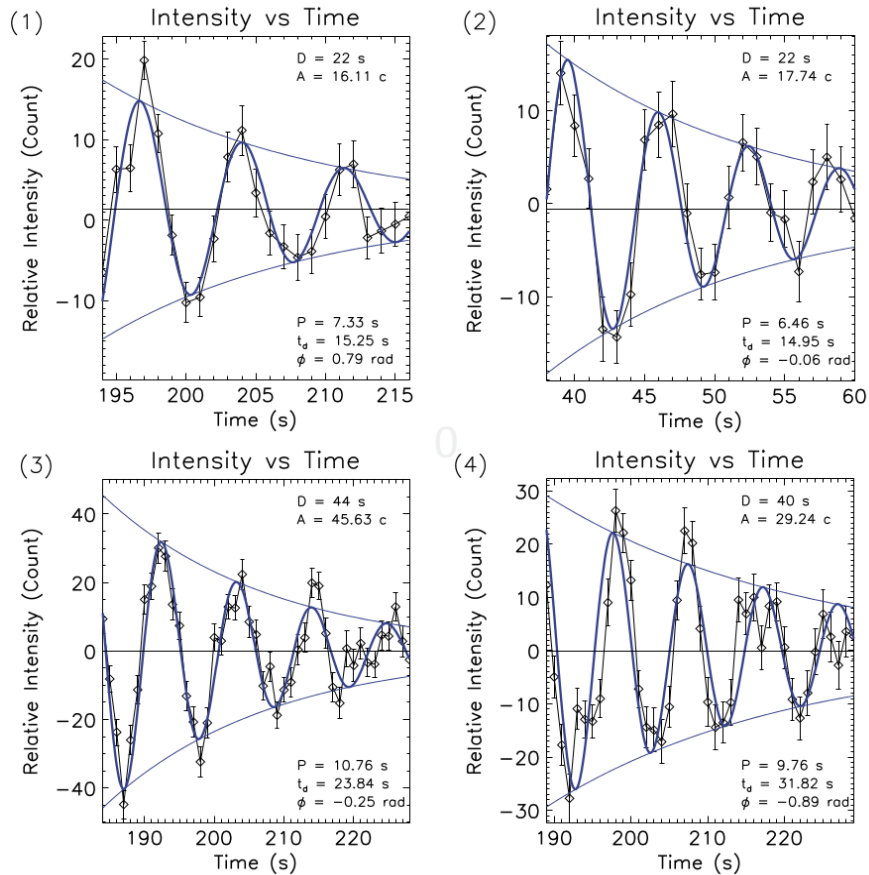
Important Results

- First time detection of the damping of the “high-frequency oscillations” with periods around 10 s.
- “High-frequency wave” damping might make a significant energy contribution for coronal heating as predicted by Porter et al. 1994 and Laing et al. 1995.

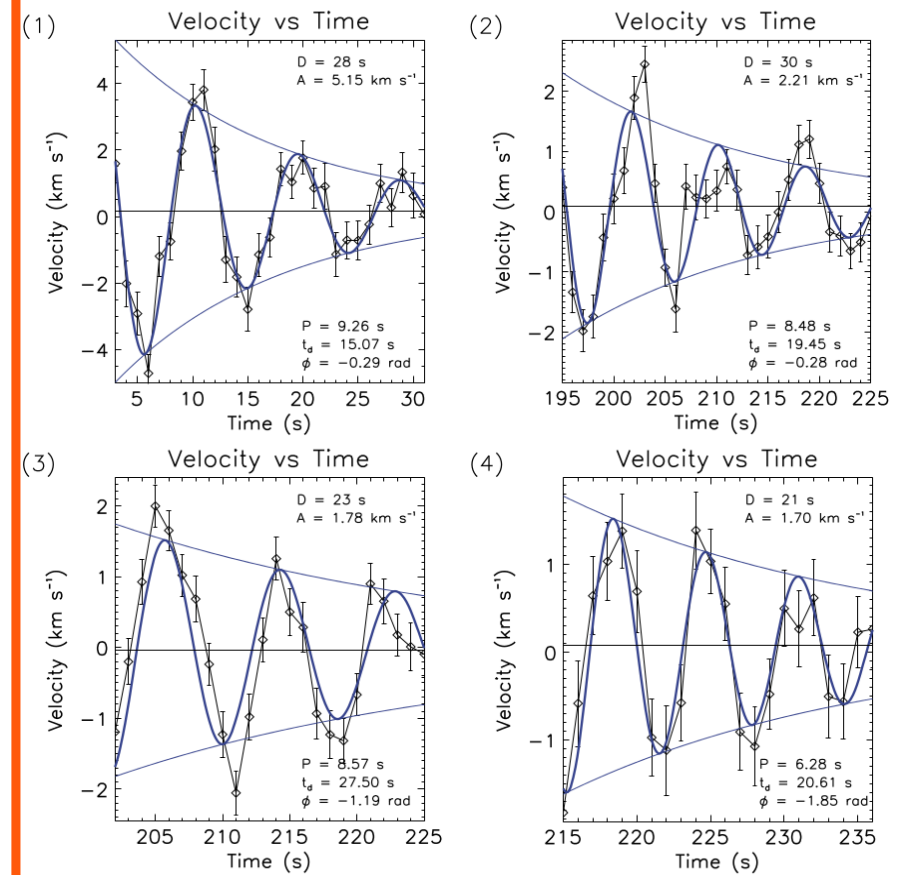
Samanta et al., SoPh, 2015

Damping of Oscillations

Intensity



Doppler



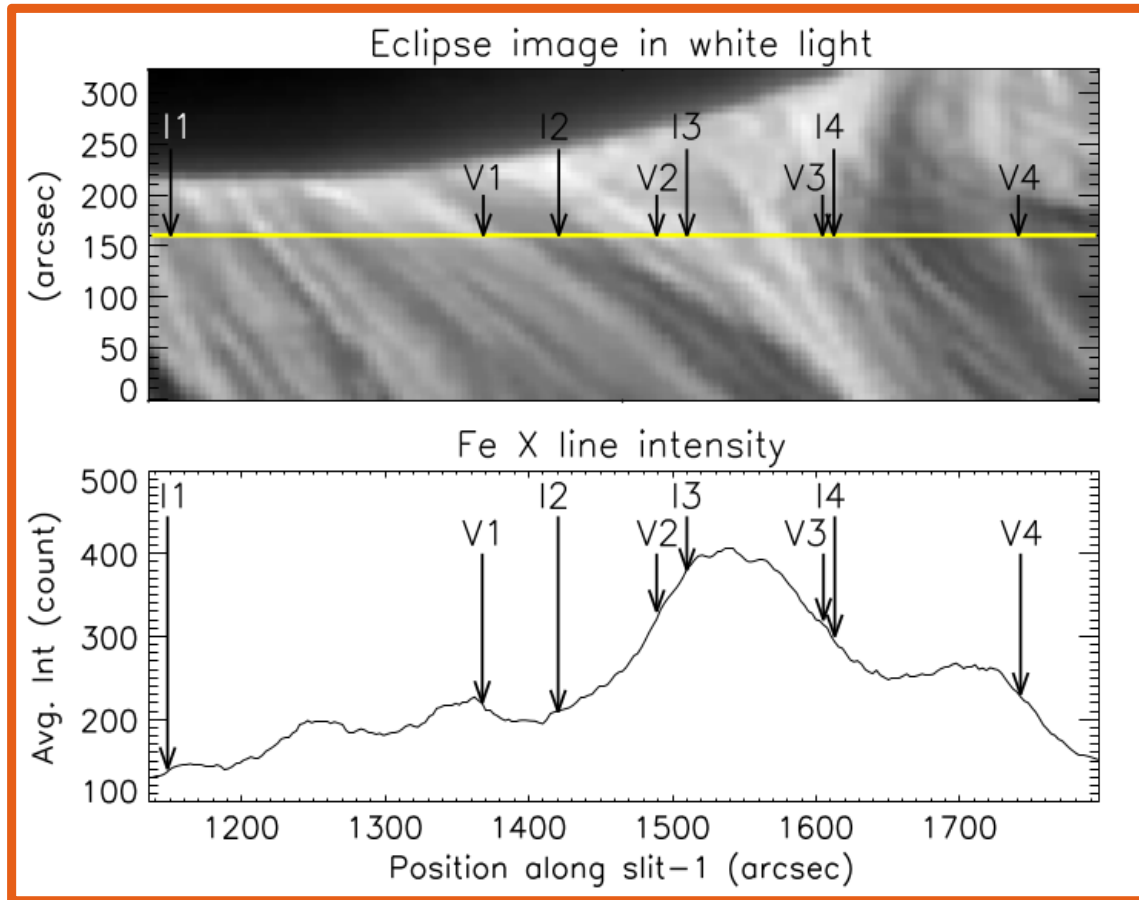
Important Results

- First time detection of the damping of the “high-frequency oscillations” with periods around 10 s at few locations within our ROI. The quality factor, the ratio of damping time over the oscillation period, ranges from 1.7 to 3.5
- “High-frequency wave” damping might make a significant energy contribution for coronal heating as predicted by Porter et al. 1994 and Laing et al. 1995.

Samanta et al., SoPh, 2015

Damping of Oscillations

Locations of the events



Generally occur at locations with high intensity gradients

Samanta et al., SoPh, 2015

Summary:

- What are the sources of these oscillation at high-corona?
- What are these wave modes and what is the damping mechanism?
- Are they significant/contribute to coronal heating?
- Can we use them for coronal seismology?

Oscillations in Chromospheric Mottles

SST/CRISP H α Core



Samanta et al., Under Prep., 2016



40 Mm

Chromospheric Transverse Waves

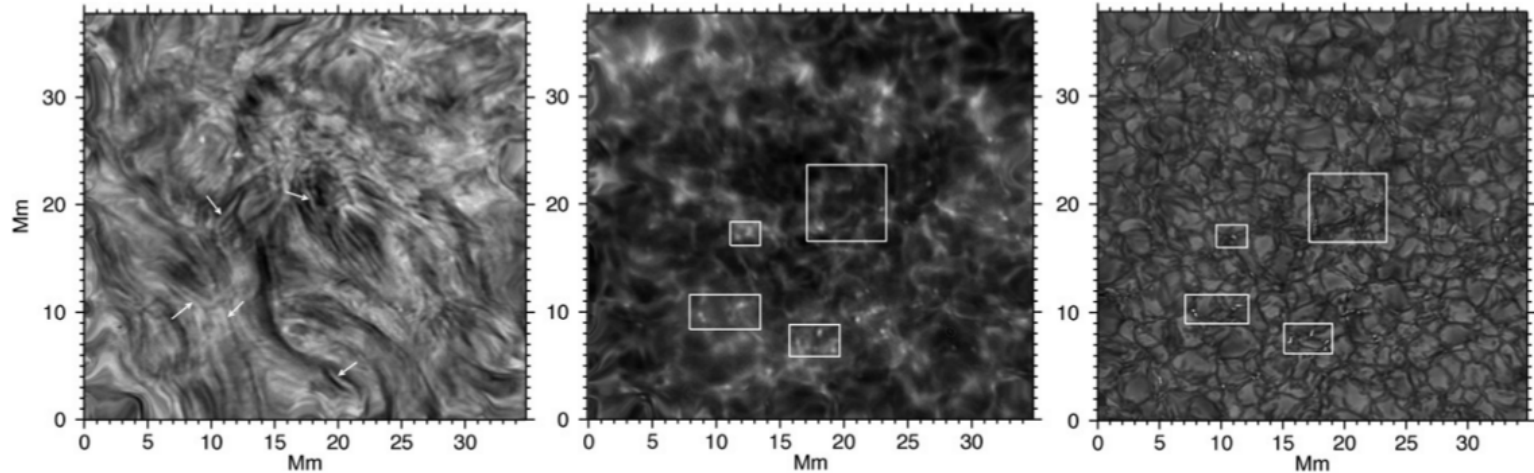


Figure 1. Simultaneous ROSA images in $H\alpha$ core (left), Ca II K core (middle), and G band (right). Arrows indicate typical bright and dark mottles in $H\alpha$. White boxes indicate areas in which long-lived mottles have been detected in $H\alpha$.

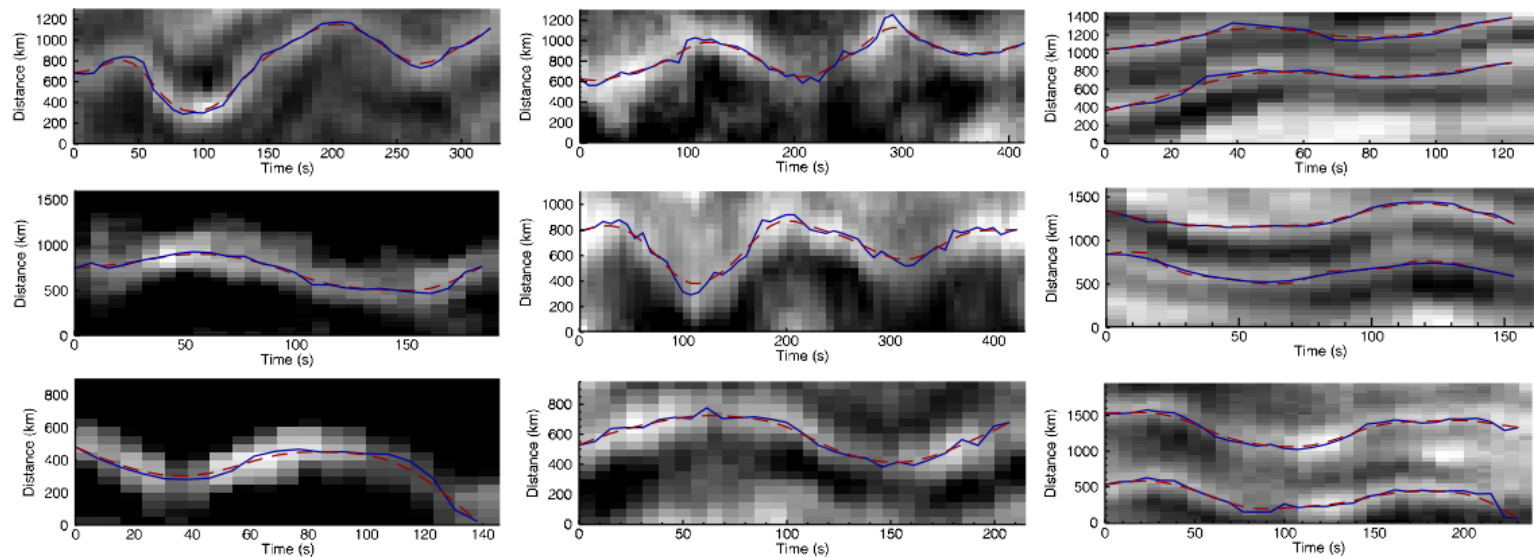


Figure 2. Time–distance diagrams of the mottle intensity in $H\alpha$. The blue line is the centroid of a Gaussian fit to the cross-sectional flux profile of the mottle at each time step smoothed by a ~ 50 km width (red line).

Chromospheric Transverse Waves

Damping of the Oscillations

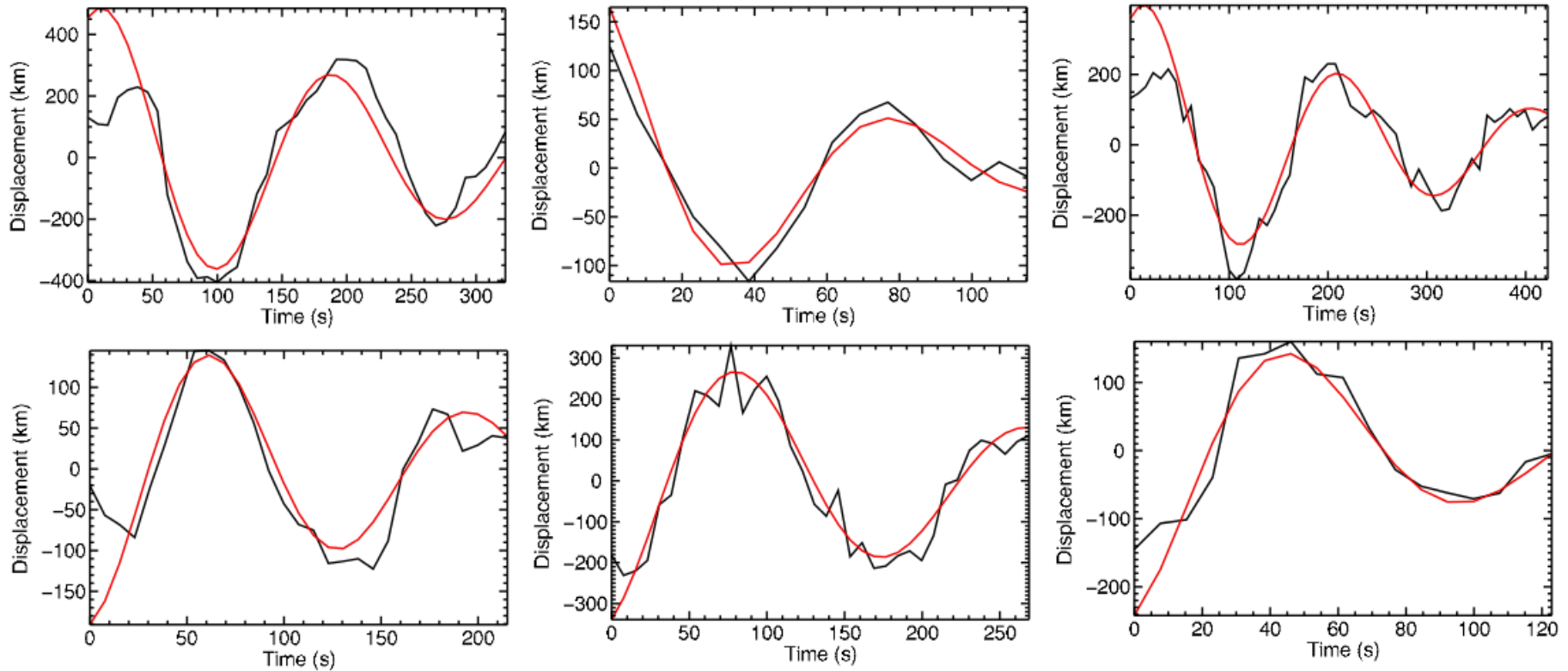
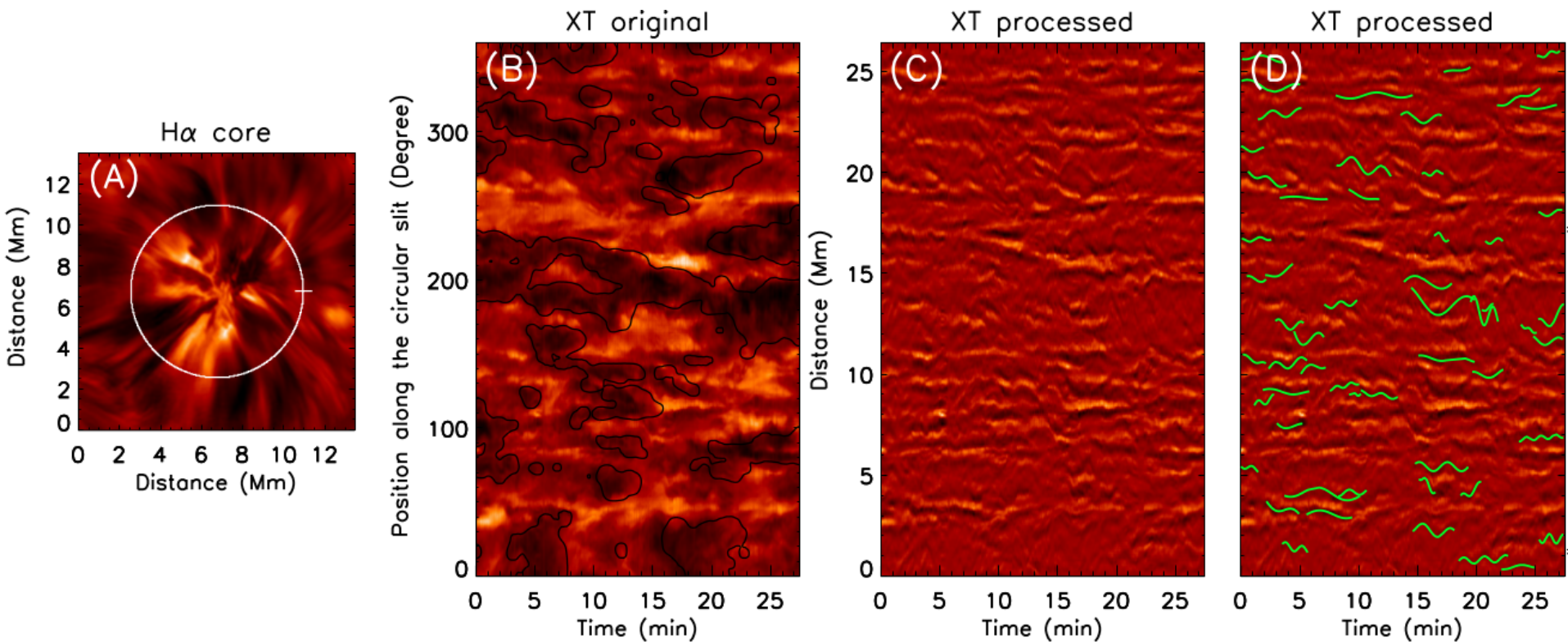
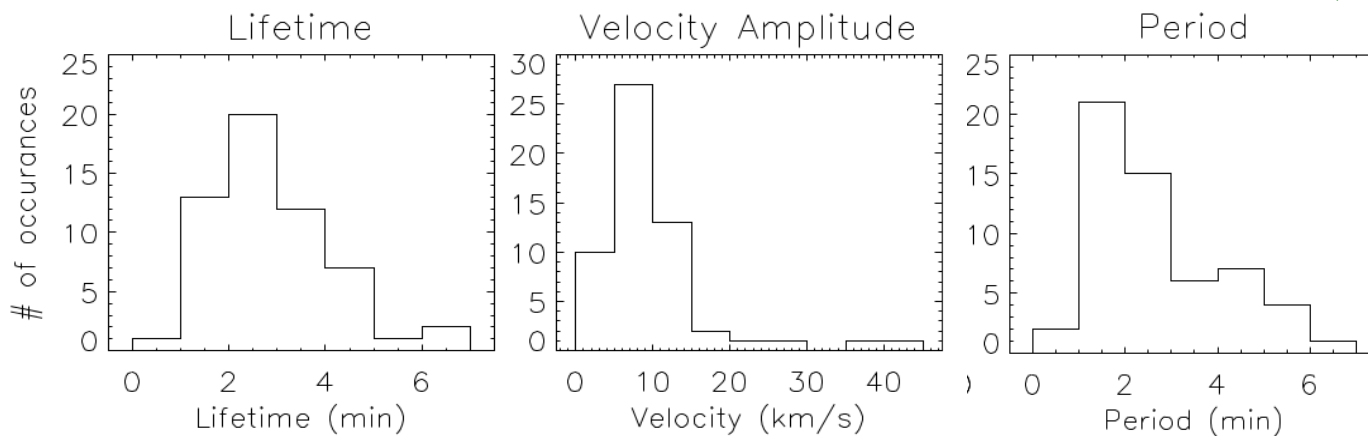


Figure 4. Observed mottle displacements (black line) fitted with an exponentially damped cosine function (red line).

Chromospheric Transverse Waves

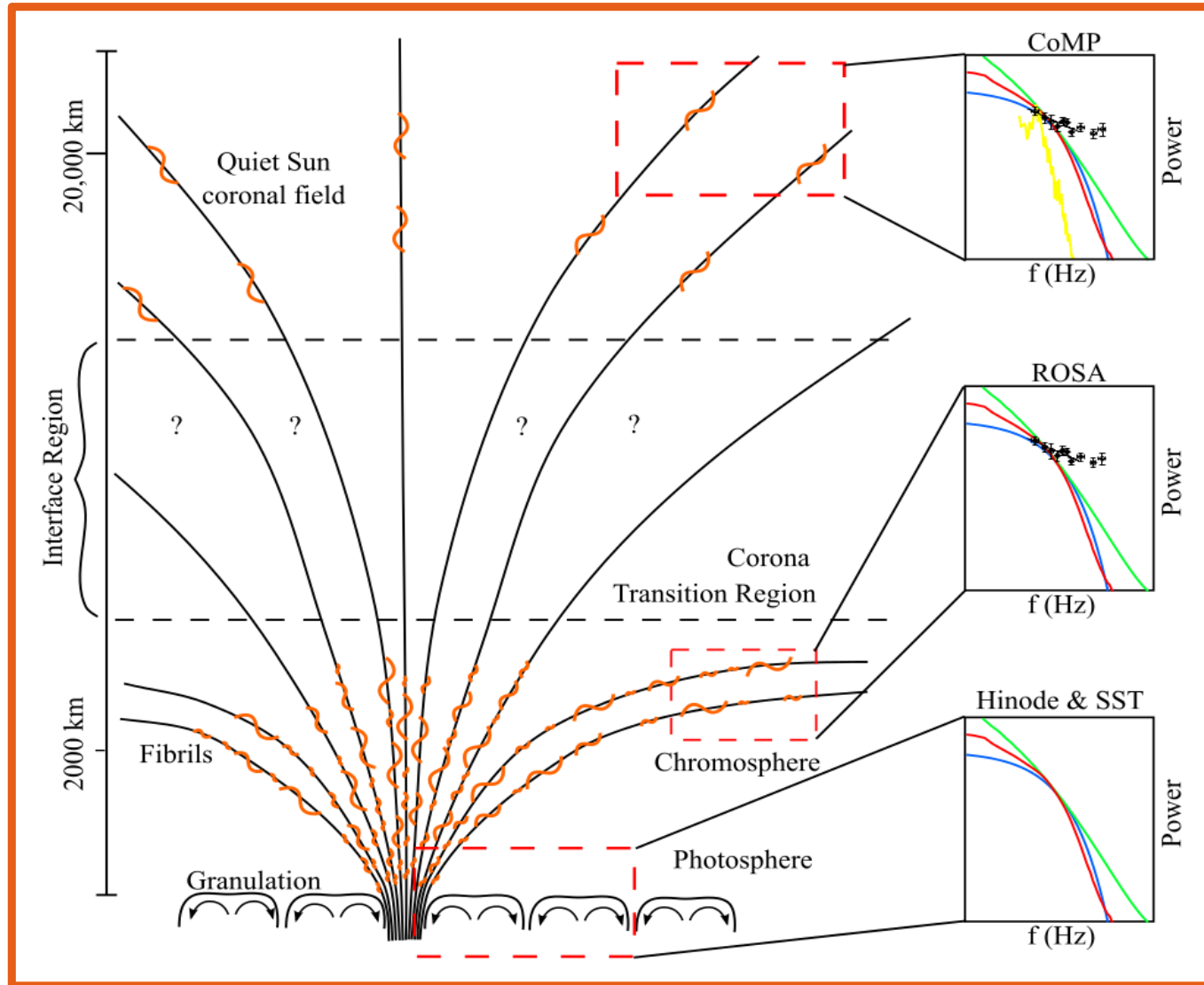


Samanta et al., Under Prep., 2016



Similar to Morton et al., ApJ, 2013,2014

MHD Kink Waves



Morton et al., ApJ, 2014

Schematic diagram depicting the transport of kink MHD wave energy through the solar atmosphere, as implied by observational results.

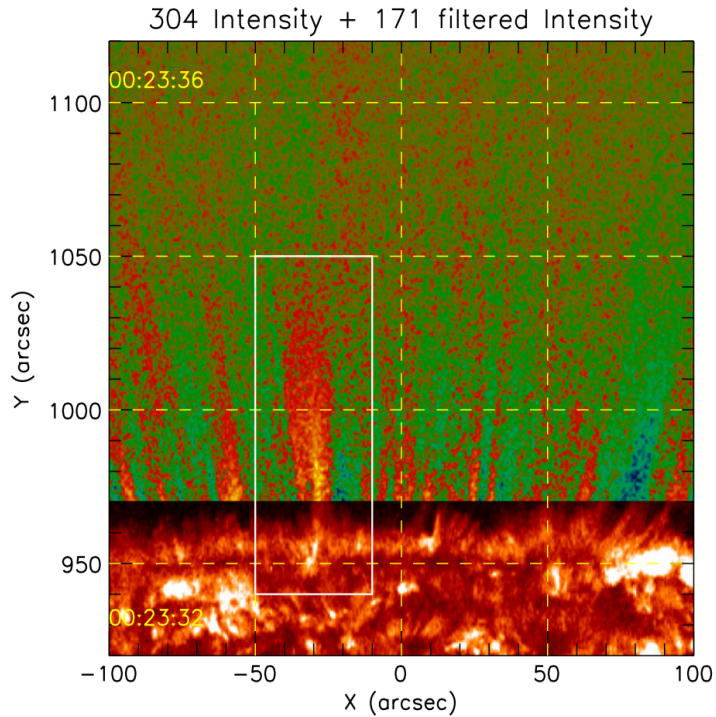
Key Questions?

- How the lower and upper atmosphere is coupled ?
- What are the sources of these transverse oscillations ?
- How important they are for contributing energy for heating ?
- How these waves can be used for seismology ?
- Etc ... Etc

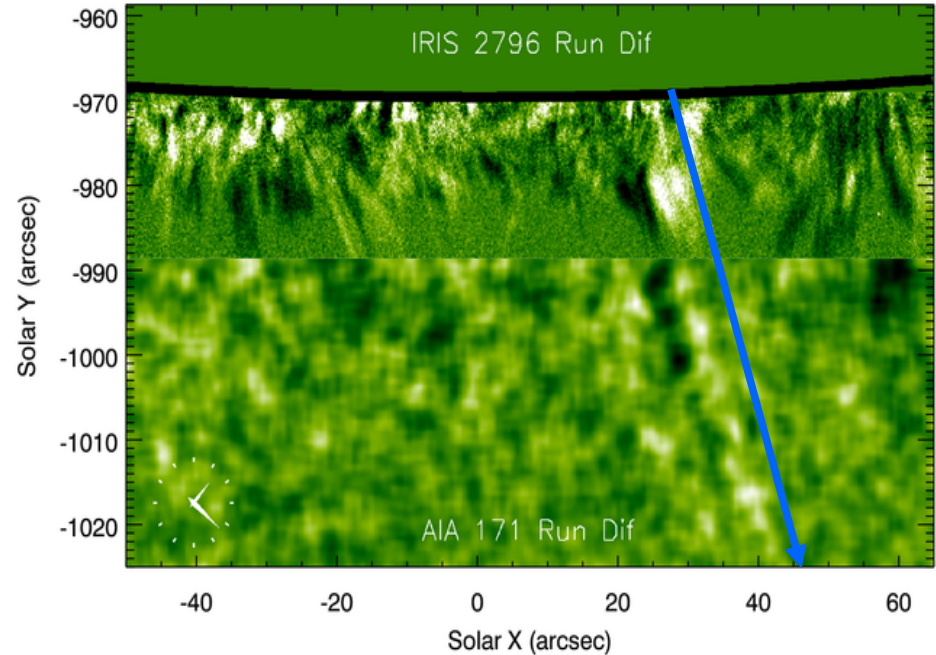
The image features a central black circle containing the word "Thanks" in a light blue, sans-serif font. This central circle is surrounded by a vibrant, glowing blue ring with a jagged, flame-like edge. From this ring, numerous thin, concentric blue lines radiate outwards, creating a ripple effect that fills the dark blue background. A horizontal blue line also passes through the center of the circle, intersecting the radiating lines.

Thanks

Lower & Upper atmosphere coupling



Jiao et al., ApJL, 2015

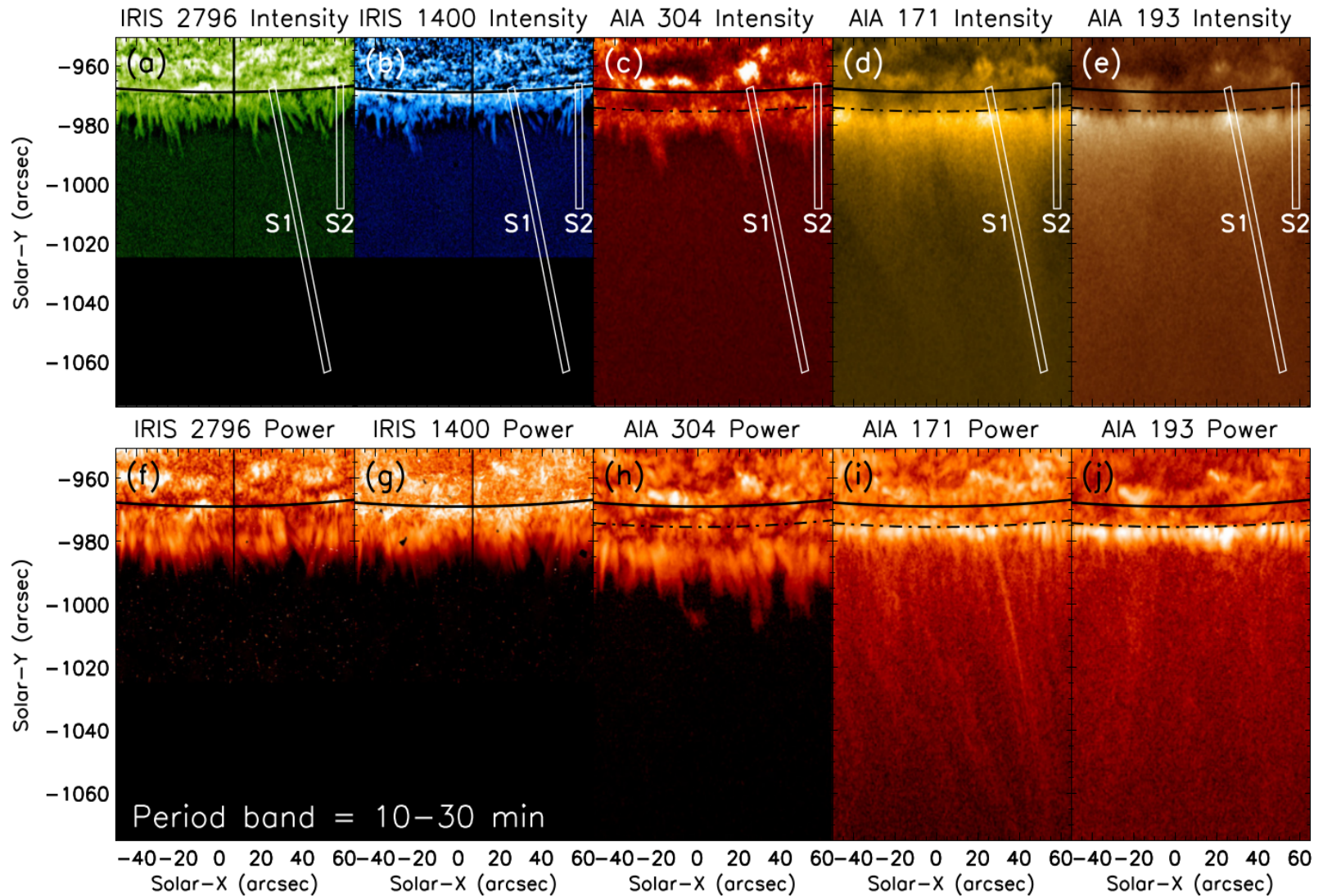


Samanta et al., ApJL, 2015

Spicules are and coronal Pds show some connection.

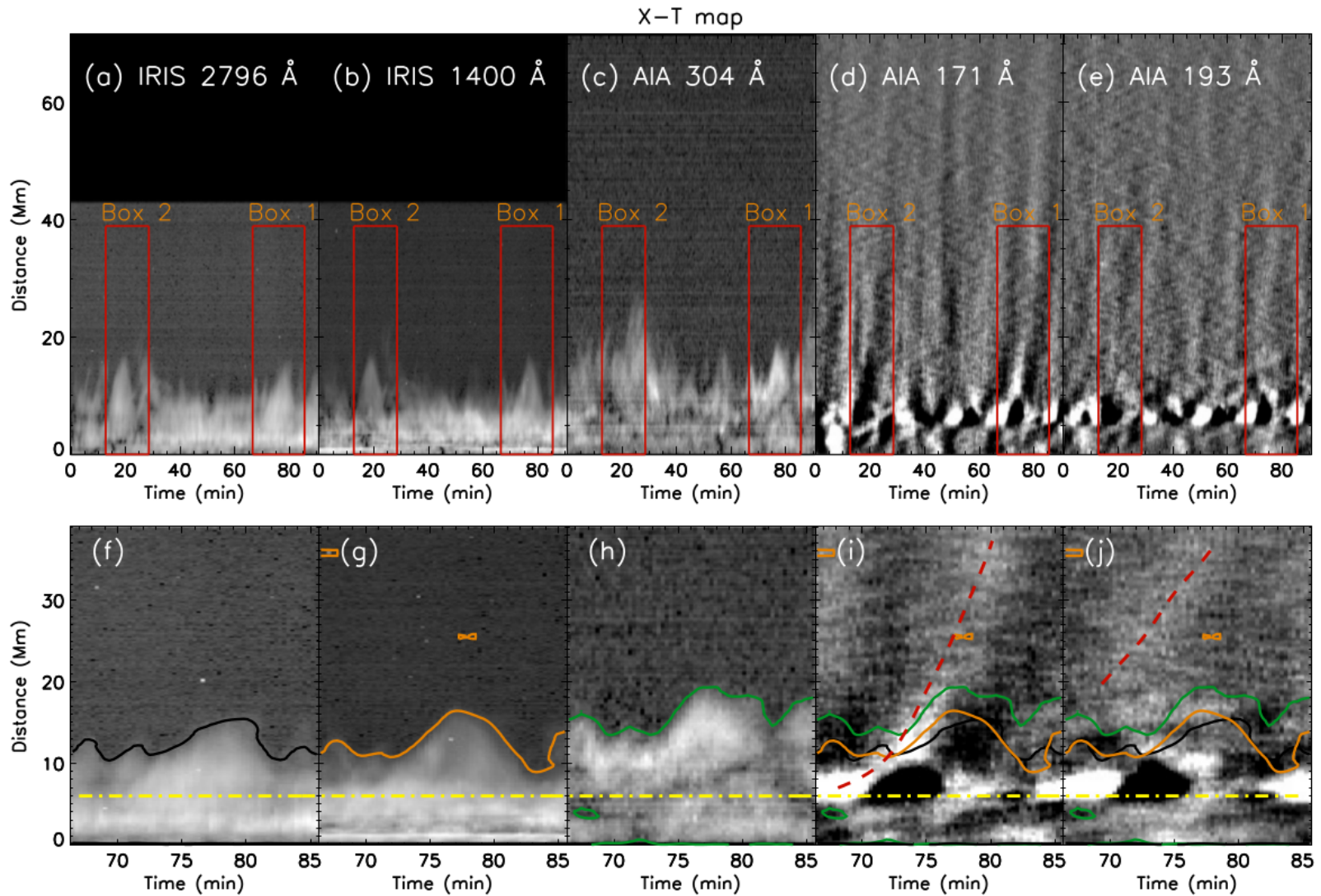
**How they are connected?
What are the sources of the Coronal Pds ?
Just began to understand**

Lower & Upper atmosphere coupling



Samanta et al., ApJL, 2015

Lower & Upper atmosphere coupling



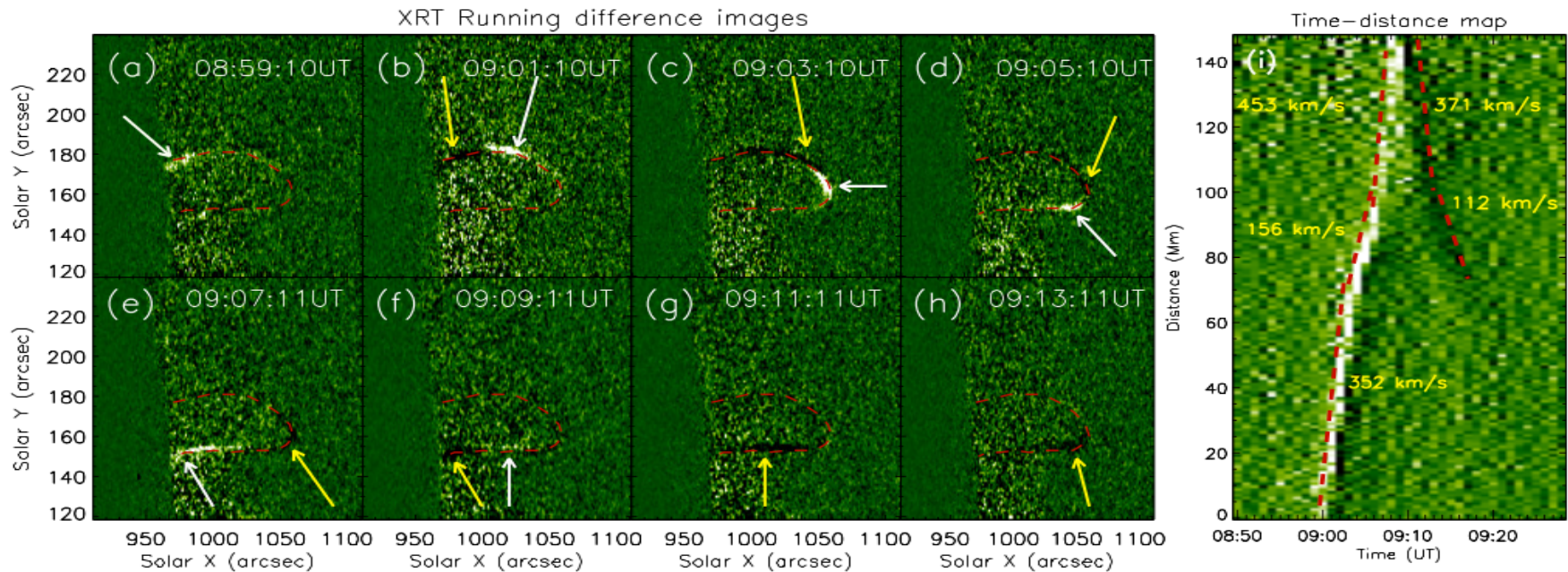
Samanta et al., ApJL, 2015

Spicules and Pds both originates from a common Process.

Reflection of longitudinal wave in hot coronal loops

Slow MHD waves are important tools to probe and understand the coronal structures and dynamics. EUV imaging analysis provides access to the loop diagnostics i.e loop density, temperature, flows. But, slow waves are often subject to damping and thus reflection of a slow wave is an rare event to observe in a coronal loop. We have identified two such events, observed with HINODE/XRT and SDO/AIA where we see clear signature of reflection.

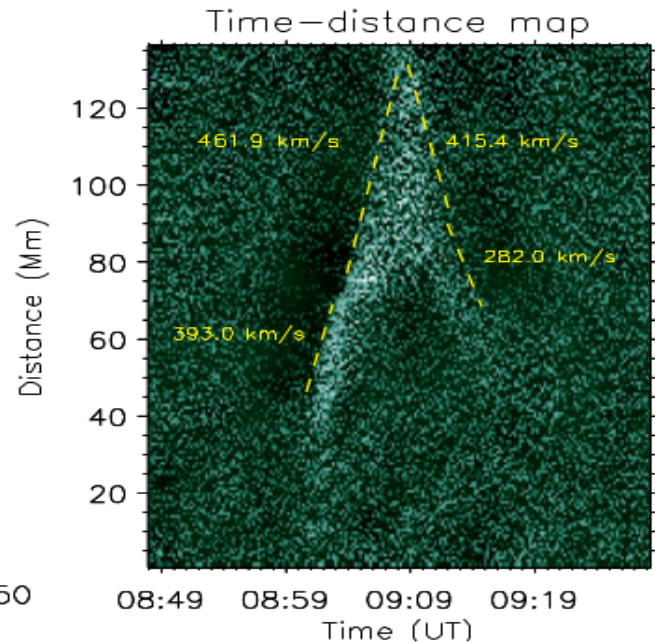
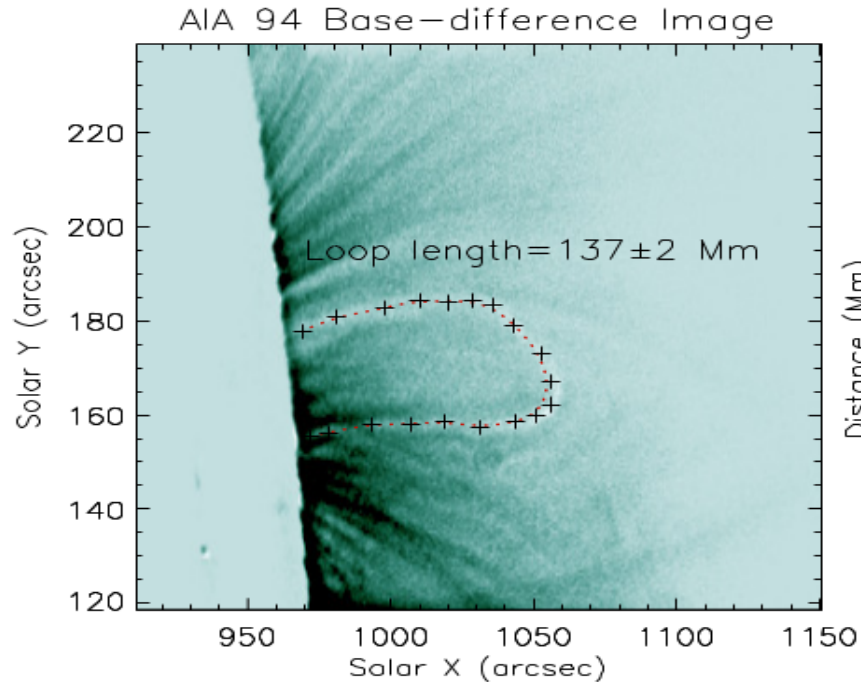
Time-Distance Map (XRT data):



- 1.** The speed changes as the wave propagate through the loops. This indicates the change of loop orientation with the change of LOS.
- 2.** The wave is getting damped as it progress to the other end of the loop and ultimately vanishes after one reflection.
- 3.** The lack of signal after the first reflection makes it harder to get the damping information.

Time-Distance Map (AIA data):

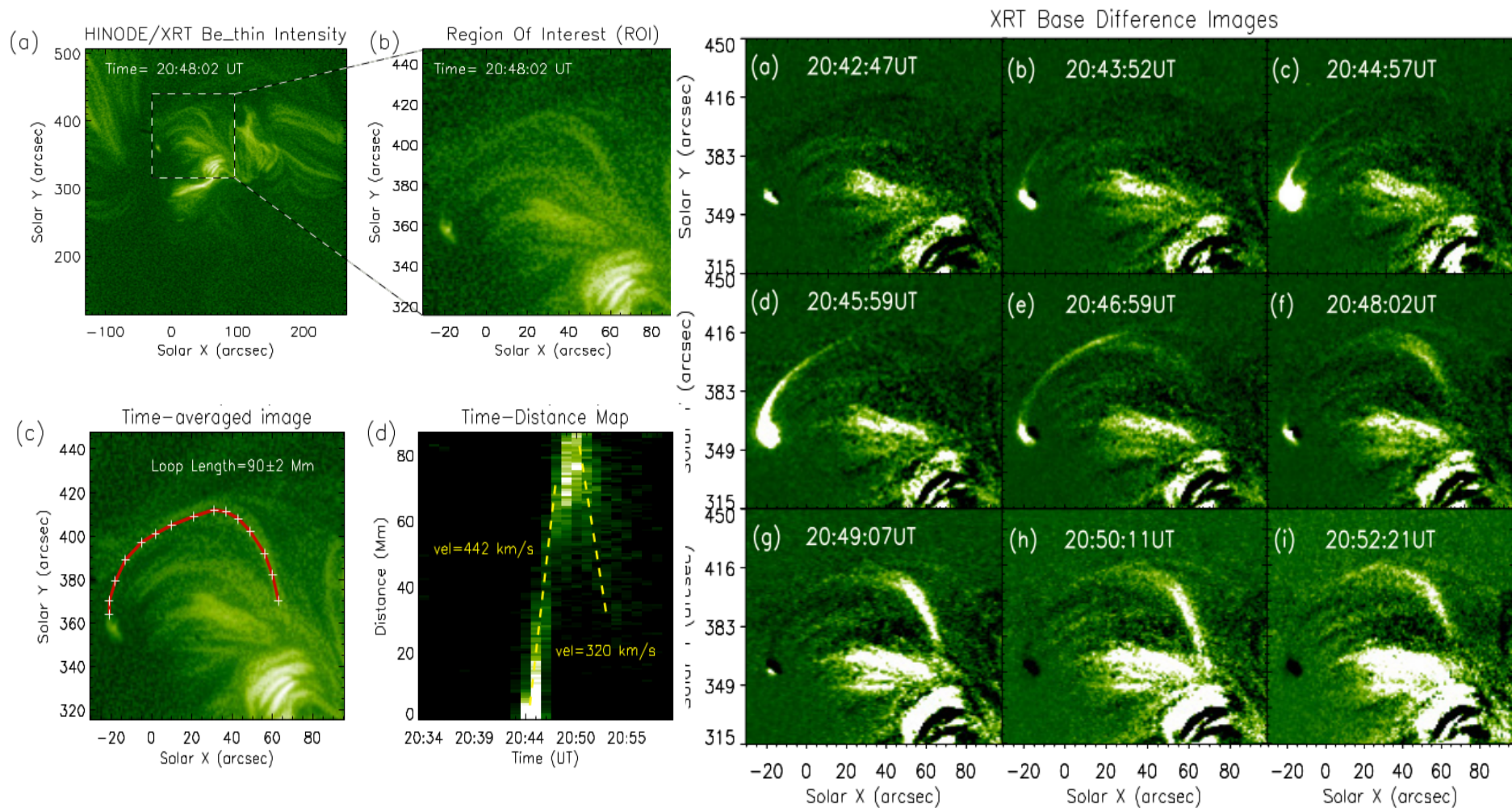
The same loop is also visible in AIA 131 and 94 channel. Though the visibility of the loop in the 131 channel is very poor. In other EUV channels of AIA, we do not see the loop at all. This indicates a presence of high temperature plasma in the loop.



From the AIA image sequence we obtain the temperature and the density of the loop using the automated DEM analysis method by Aschwanden et al. (2013). It shows an average density and temperature to be around $\sim 10^9 \text{ cm}^{-3}$ and $\sim 10 \text{ MK}$.

Another such event:

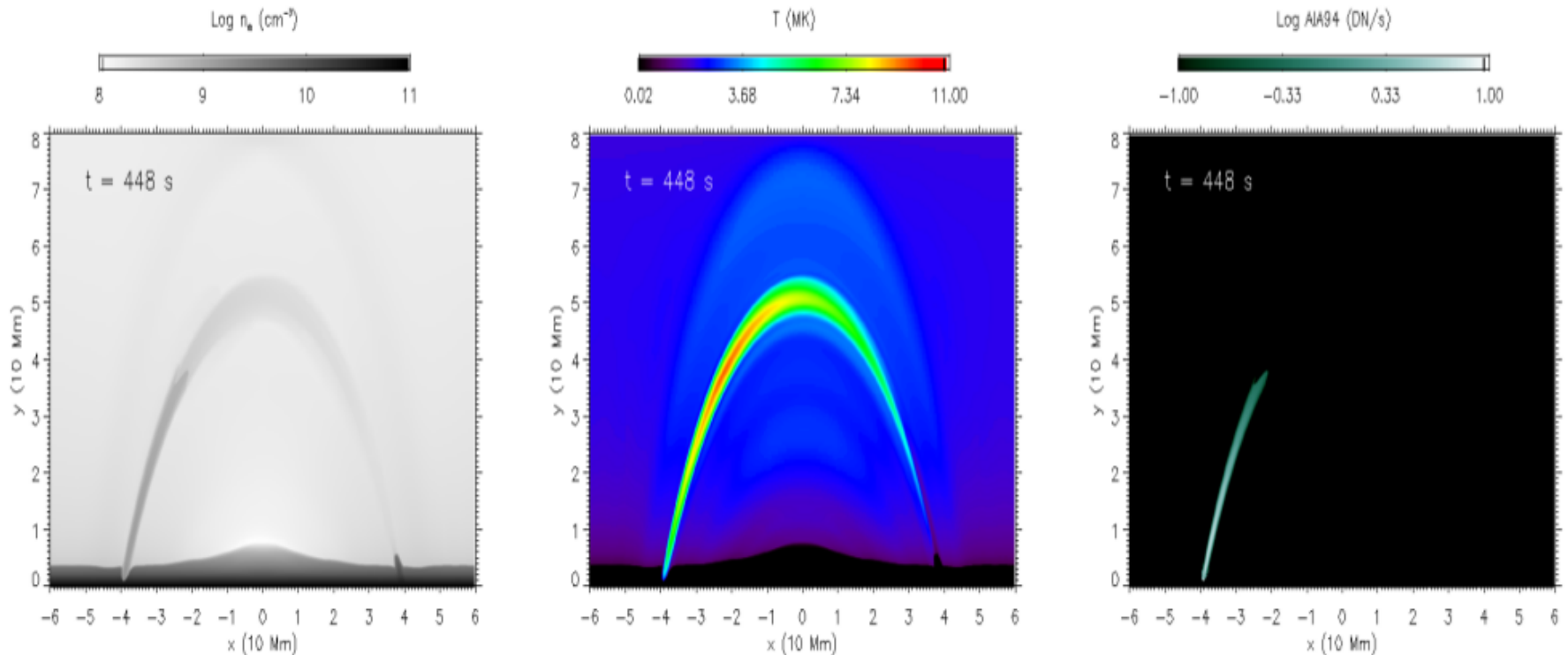
We found another such event observed from XRT but the reflection signature is not as prominent as the previous one.



A Numerical Model:

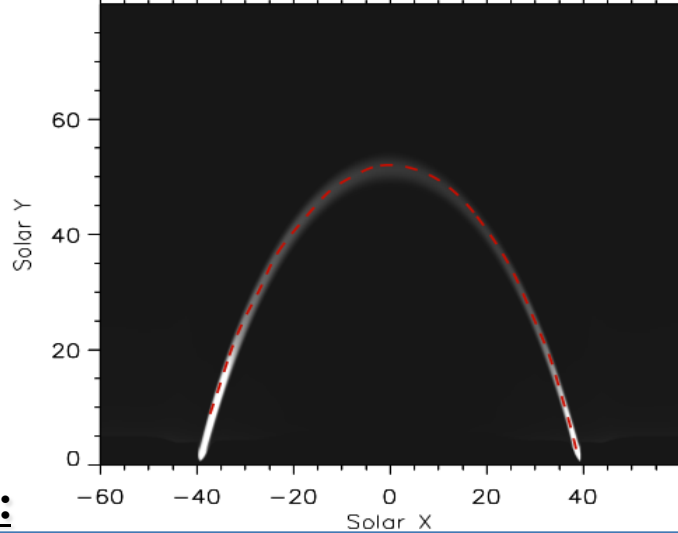
From Event1: We got loop length, speed of propagation, temperature and density
From Event2: We got loop length and speed and information about the generation mechanism.

Our numerical setup includes gravity, anisotropic thermal conduction and radiative cooling and parametrized heating terms, in a domain of $-60 \text{ Mm} \leq x \leq 60 \text{ Mm}$ and $0 \leq y \leq 80 \text{ Mm}$. We inject heat at the one of the loop footpoints to mimic the flare situation. AIA 94 channel emission has been synthesized using FoMo forward modelling code.

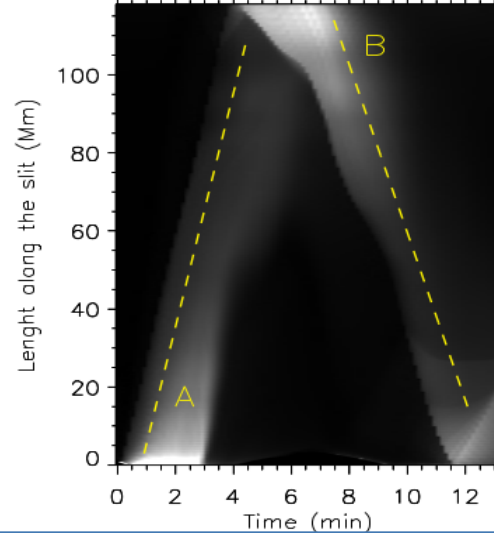


Analysis of the synthetic data:

Synthesized AIA 94 Channel Time Averaged Intensity



Time-distance Map



Conclusions:

1. we report, for the first time, simultaneous observation of an intensity oscillations in a hot coronal loop as seen with HINODE/XRT and SDO/AIA.
2. Observed wave appears after a flare occurs at one of the loop footpoints and propagates with lower than the sound speed.
3. The DEM analysis performed on the AIA data revealed the loop temperature and density to be $\sim 10\text{MK}$ and $\sim 10^9 \text{ cm}^{-3}$ respectively.
4. Analyzing the synthesized data, we have obtained the propagation speeds which matches well with the observed speeds from XRT and AIA.
5. simultaneous imaging and spectroscopic data will greatly improve our understanding about such phenomena