Hi-C & AIA observations of transverse waves in active region structures

Coronal Loops VI - 2013

R. J. Morton

and J. A. McLaughlin
Mathematical Modelling Lab, Northumbria University

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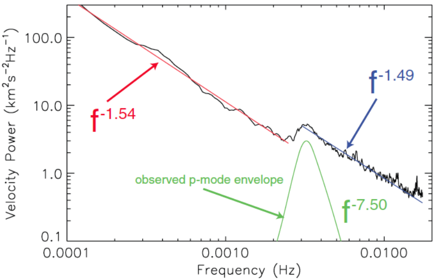
Propagating waves in CoMP

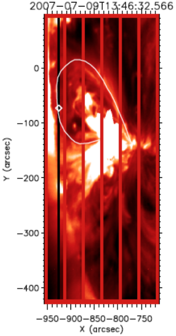


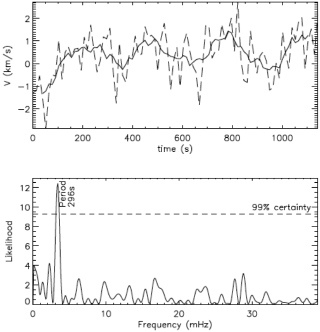
Propagating kink waves in the corona inferred from Doppler shift oscillations in Fe XIII (10747 Å) (*Tomcyzk et al., 2007; Threlfall et al., 2013*).

Tomczyk & McIntosh (2009) were able to derive phase speed estimates in the corona and power spectra for oscillations. Typical velocity amplitudes of < 0.3 km/s.

De Moortel & Pascoe (2012) suggest that large spatial resolution of CoMP (~ 4 Mm) would lead to LOS integration effects. Inability to resolve multiple threads leads to a reduction in measured velocity amplitude.

Hinode/EIS

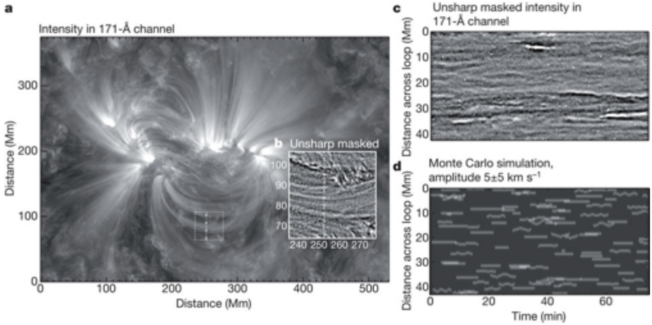




Hinode EIS measurements in Fe XII (195 Å) reveal periodic ($\sim$ 300 s) Doppler shifts ($<$ 2 km/s) with no obvious intensity variations.

Interpreted as the signature of MHD kink modes (*Erdélyi & Taroyan, 2008; Van Doorsselaere et al., 2008; Tian et al., 2012*)

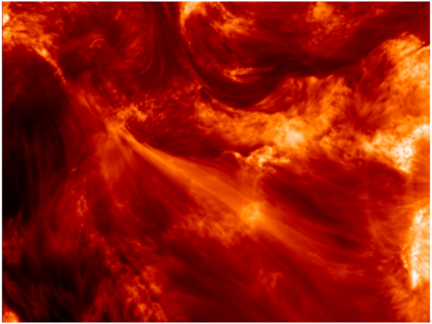
...and AIA/SDO



Improved S/N of AIA allowed for small amplitude (v=5$\pm$5 km/s) waves to be observed in active regions (*McIntosh et al., 2011*) - estimated wave energy $\sim$ 200 W/m^{-2}.

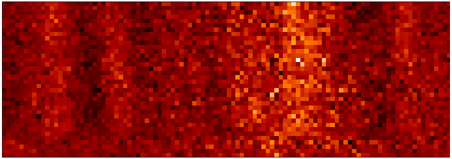
Monte Carlo technique limits cannot detect wave amplitudes $v < 2700/P$, e.g., for P=250 s then the minimum measurable velocity $v_{min} \approx$ 10 km/s.

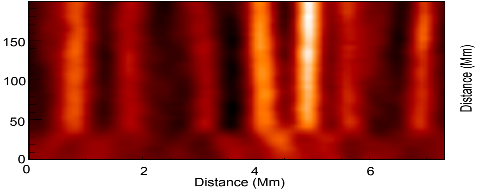
Hi-C



- The launch of Hi-C provide a spatial resolution a factor of 5 better than AIA (0''.103-0.6'' per pixel).
- Images obtained in 193 Å with cadence of 5.4 s.
- Used data processed by Hi-C science team, which was dark-subtracted, flat-fielded, cropped, dust hidden and co-aligned.
- Data still had an apparent shift between frames so additional alignment using cross-correlation was performed.

Noise suppression





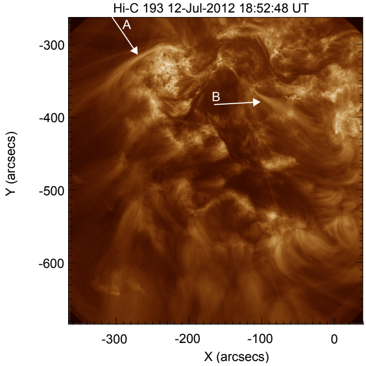
Hi-C suffers from a relatively low S/N ratio - combination of high readout noise and dark current plus low gain.

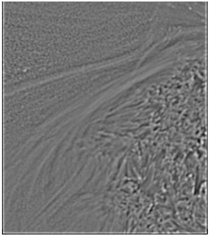
Leads to problems when using un-sharp masking technique.

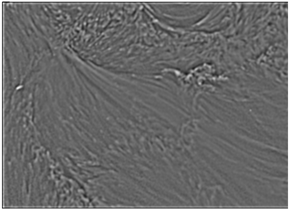
Hard noise suppression - apply Atrous algorithm to each frame and set highest frequency spatial variations equal to zero.

Some loss of signal but significantly improved S/N.

Suitable structures







Two suitable distinct structures in emission in 193 Å - coronal loops.
Hi-C reveals these two structures are made from fine-structure not-resolvable with AIA.
Typical loop widths measured from FWHM of Gaussian fit 150-310 km (see also, *Brooks et al., 2013*).

Observing waves

- Smooth images with 5 by 5 boxcar function to further suppress noise and then USM.
- For each time-slice fit a Gaussian profile to individual loops.
- Errors on returned Gaussian fits are obtained by supplying data noise to the fits.

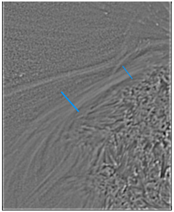
$$\sigma_N = \sqrt{\sigma_p(F)^2 + \sigma_d^2 + \sigma_r^2 + \sigma_{sd}^2} = \sqrt{0.23F + 588.4}.$$

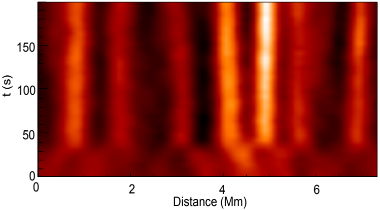
  where $\sigma_p(F) = \sqrt{(F/4.3)}$ is the uncertainty in photon noise, $\sigma_d = 13.7$ DN dark current, $\sigma_r = 20$ DN readout and σ_{sd} digitisation.
- Total error $\sigma_N(F)/5.$ after averaging data.
- Add error estimate on position from alignment (0.05 pix) to error associated with position of the peak of the Gaussian.
- Fit a sinusoidal function of the form:

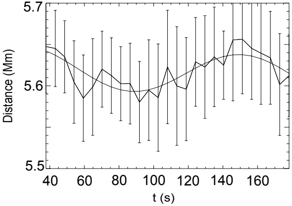
$$F(t) = A\sin(\frac{2\pi}{P}t - \phi) + g(t),$$

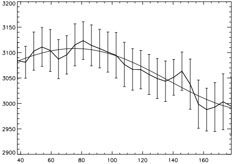
  where A, P and ϕ are the displacement amplitude, period and phase, respectively, of the wave. The parameter $g(t)$ is a linear function.

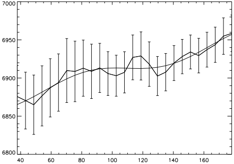
Loop A (apex) and loop B

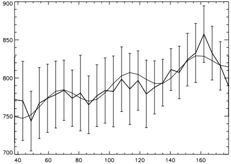










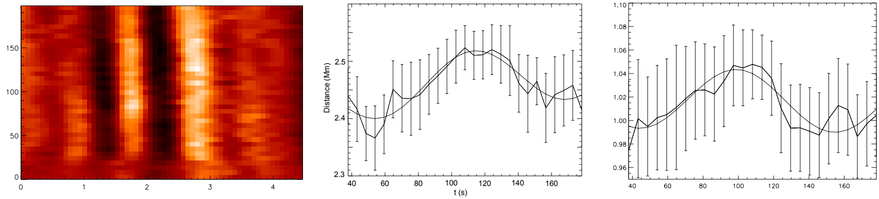


Limited signatures of oscillations above error estimates - typical error is ±30 km. (P=126±80 s, A=25±22 km and v=1.2±1.3 km/s).

Low-frequency waves with periods > 200 s have amplitudes < 3 km/s.

Suggestion of high frequency transverse waves...

Loop A - leg

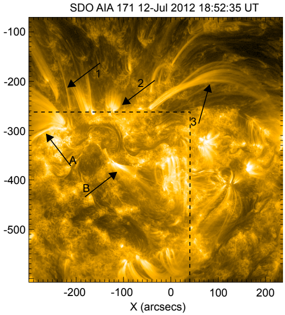


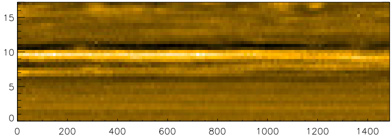
Greater S/N towards loop legs leads to improved errors - small amplitude transverse waves resolvable.

P=109±16 s, A=50±14 km and v=2.9±0.9 km/s.
P=65±10 s, A=22±12 km and v=2.1±1.2 km/s.

Velocity amplitudes in agreement with Hinode/EIS values. Estimated propagation speed is 400 ± 300 km/s - calculated from cross-correlation of fitted signals.

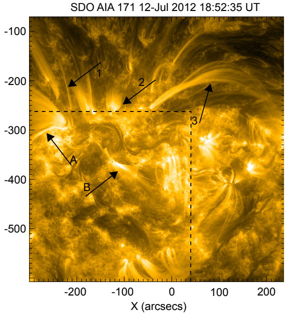
Unusually quiet?

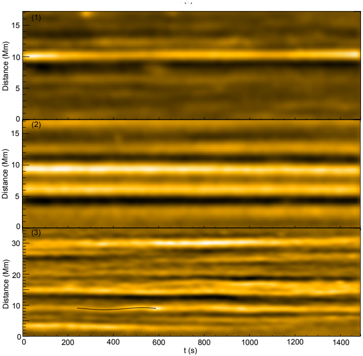




AIA observations cover a period 25 minute period around Hi-C observations (660-870 s). Although AIA cannot resolve the individual threads, time-distance diagrams do not appear to show evidence for energetic waves.

Unusually quiet?





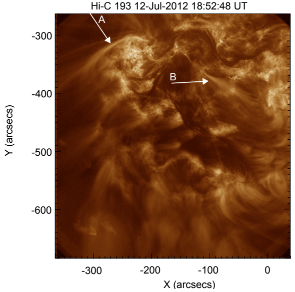
Certain loops in AIA data have widths on the order of the PSF, probably single loop threads.

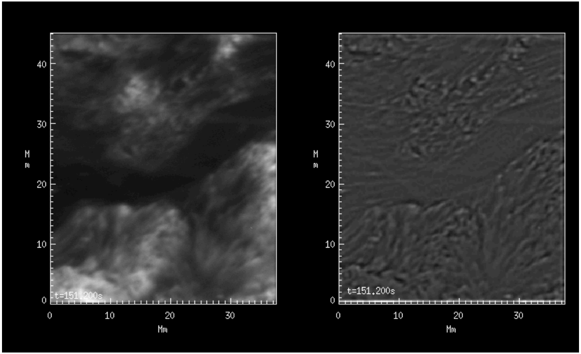
Wave tracking typically finds waves with periods > 300 s, and small displacement amplitudes, < 100 km, hence v$<$ 3 km/s.

One loop structure shows waves with visible motion in time-distance diagrams -

P=324±2 s, A=331±4 km, v=6.42±0.09 km/s - in line with *McIntosh et al. (2011)*

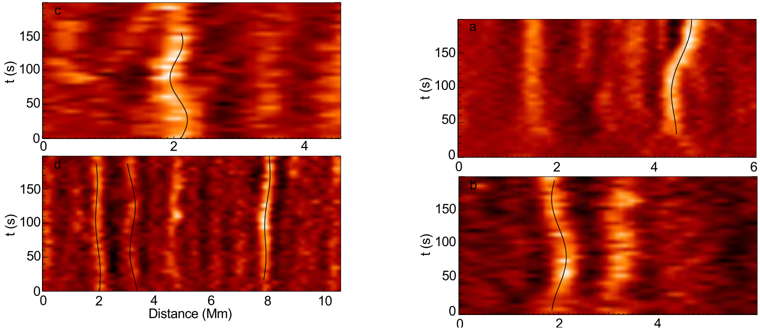
Waves in the moss





Hi-C reveals dark inclusions surrounding moss has fine-structuring. The low emission fine-structure is connected to the enhanced, reticulated emission.
Intensity decrease - signature of cool chromospheric plasma below TR emission.
Spicules? - Features have similar widths to chromospheric structures ($<$ 400 km, e.g., *Morton et al., 2012*).

Waves in the moss



Parameters of transverse waves measured in low-emission fine structure connected to moss:

Periods: 87-172 s, Displacement: 25-135 km, Velocity: 1-7 km/s.

Measured properties comparable to those obtained in spicules (e.g., *Okamoto & De Pontieu, 2011; Pereira et al., 2012*) and fibrils (*Kuridze et al., 2012; Morton et al., 2012, 2013*).

Summary

- Hi-C was able to resolve the magnetic fine-structure (< 400 km in diameter) in the corona and TR.
- Improved resolution allows for small-amplitude MHD kink waves (Alfvénic) to be measured in coronal loops and active region moss structures.
- The Hi-C and AIA data suggest wave activity is typically small in corona, velocity amplitudes < 3 km/s for waves with periods of (50 to 500 s). In agreement with Hinode/EIS observations.
- Certain loop structures demonstrate waves with larger typical velocity amplitude (similar to those reported in McIntosh et al., 2011).
- Restrictions on maximum amplitude of high-frequency waves in corona, for waves with periods of 20-50 s suggests velocity amplitudes of $3 - 6$ km/s.

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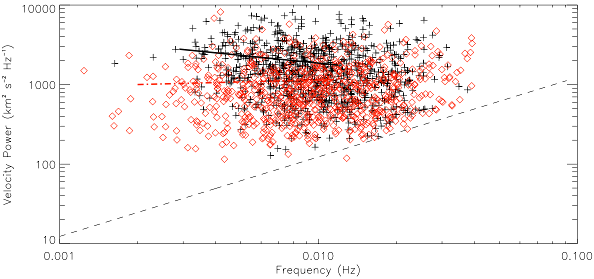
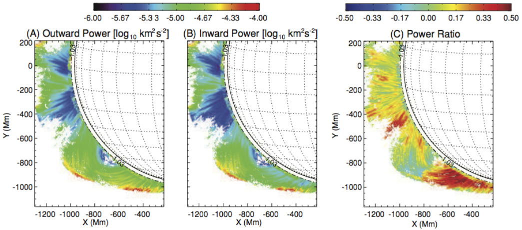
The velocity power

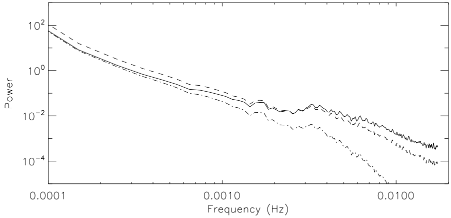


Velocity power as a function of frequency -

Calculated as $< v_{rms} >^2 / f = v^2 P/2$. Error is $\Delta(\log(P/f)) = \frac{1}{P}\sqrt{(2vp\Delta v)^2 + (v^2\Delta p)^2}$.

Observed waves - propagating kink waves





Images courtesy of Tomcyzk & McIntosh (2009).

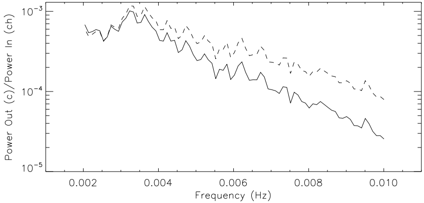
Propagating kink waves in the corona inferred from Doppler shift oscillations of coronal loops (Tomcyzk et al., 2007).

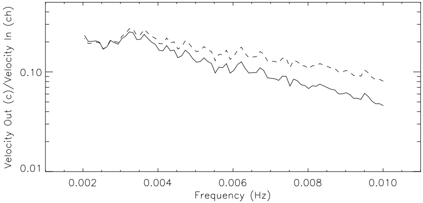
The power input, $P(f)_{in}$ at the loop base can be calculated from spatially averaged total power, $< P(f) >_{total}$,

$$P_{in} = \frac{\frac{2L}{L_D} < P(f) >_{total}}{1 - \exp\left(-\frac{4L}{L_D}\right)},$$

where $L_D = v_{ph}\xi_E/f$ and $v_{ph} = 0.6$ Mm/s, $\xi_E = 2.69$, L=250 Mm.

The velocity power II - evidence for dissipation?





Ratio of the **coronal** velocity power spectra to the **chromospheric** power spectra.
CoMP has a well known problem with under-resolving Doppler velocities due to line-of-sight integration (De Moortel & Pascoe, 2012). Transmission profiles between chromosphere and corona.
The comparison suggests enhanced frequency dependent transverse wave dissipation in the lower corona - somewhere between 3 Mm and 15-20 Mm, i.e. Transition Region and low Corona.