Probing the quiet Sun structure and dynamics with ground and space based instruments

I.Kontogiannis[1], C.Gontikakis[2], G.Tsiropoula[1], S.-H.Park[1] & K.Tziotziou[1]

[1]Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens
[2]Research Center for Astronomy and Applied Mathematics, Academy of Athens

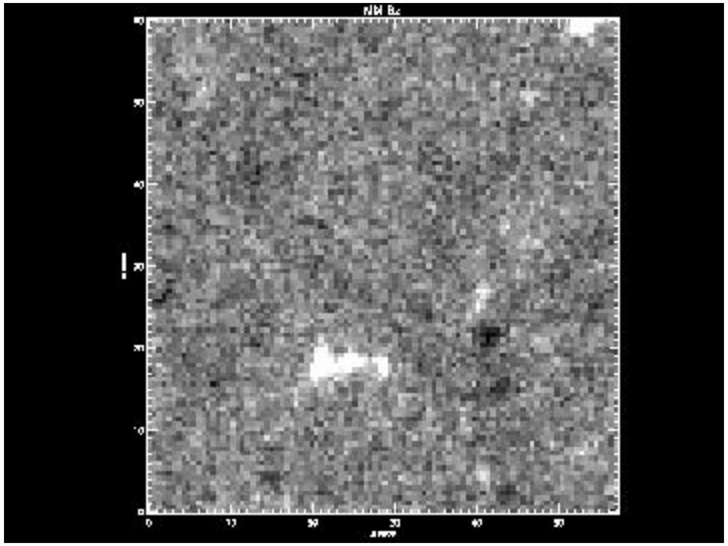
Outline

1. Observations
2. Magnetic configuration
3. Morphology - Structure
4. Chromospheric fine structure and transition region response
5. Wave propagation and interaction with the network magnetic field (2-D case)

Observations

<u>Dutch Open Telescope (DOT):</u>
Hα speckle reconstructed, 5 positions along the profile
G-band, CaII H filtergrams

October 15, 2007



<u>Hinode SOT</u>
G-band – CaII H filtergrams (2 min cadence)
SOT/SP: High resolution vector magnetogram

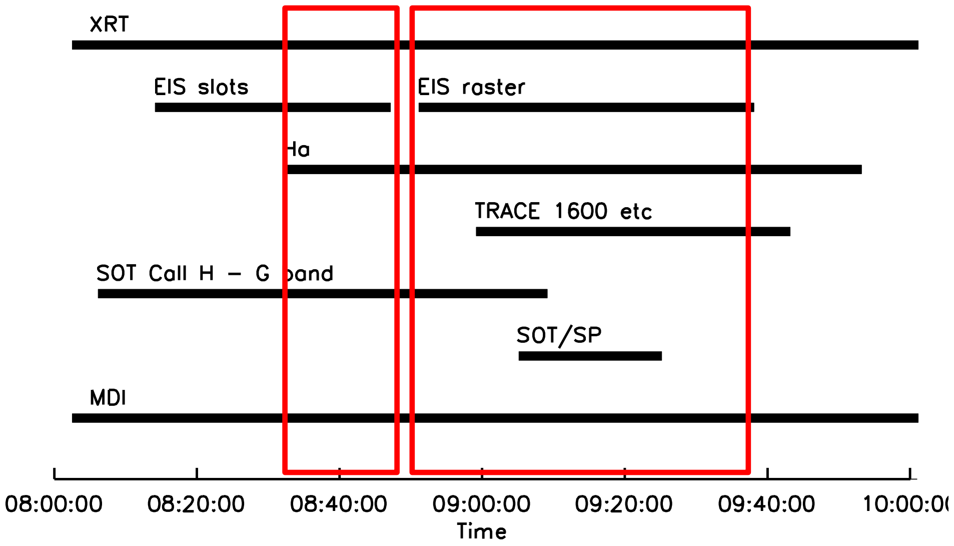
<u>Hinode EIS</u> 40’’ slots (65 s cadence)
2’’ slit raster

<u>Hinode XRT:</u> ‘C_Poly’ filtergrams (24 s cadence)

<u>SoHO/MDI:</u> High resolution LOS magnetograms (60 s cadence)

<u>TRACE:</u> 1550, 1600, 1700 Å images (30 s cadence)

Observations



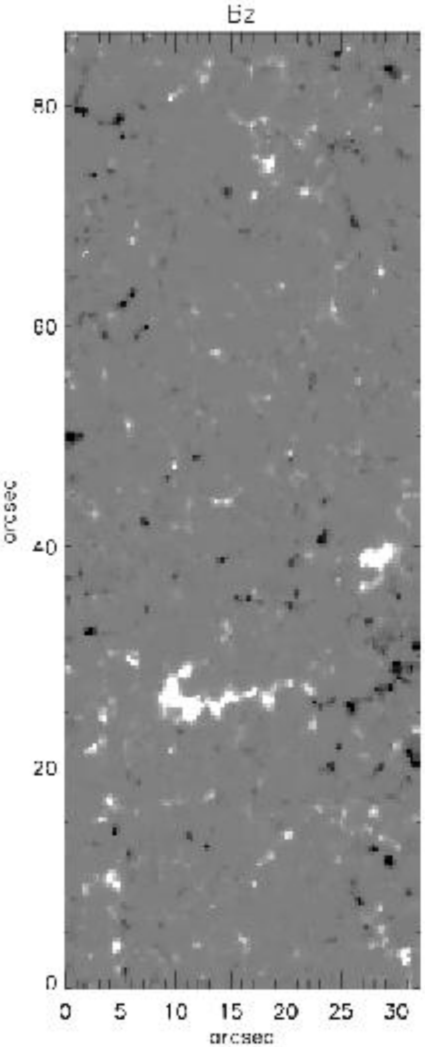
Spectral region/filter	*logT*
He II* 256 Å	4.7
Ca XVII+* 192 Å	5.4, 6.7
Fe VIII+ 185 Å	5.6, 6.0
Mg VI 269 Å	5.6
Mg VI* 270 Å	5.7, 6.25
Mg VII* 278 Å	5.8
Mg VII 280 Å	5.8
Si VII 275 Å	5.8
Fe XII 195 Å	6.15
'C_poly'	6.2

(∗) blendend
(+) another line in the window

Advantages
Coverage from photosphere to the corona
High resolution magnetic field (MDI + SOT/SP)
Hα spectral/temporal information

Drawbacks
Low resolution (EIS,MDI)
Low cadence (30 s – 2 min)
Fragmented mutual coverage
Blended TR and coronal lines

Analysis / tools



Magnetic field extrapolation up to 10000 km from the photosphere (*Alissandrakis 1981*)

Co-alignment between all instruments.

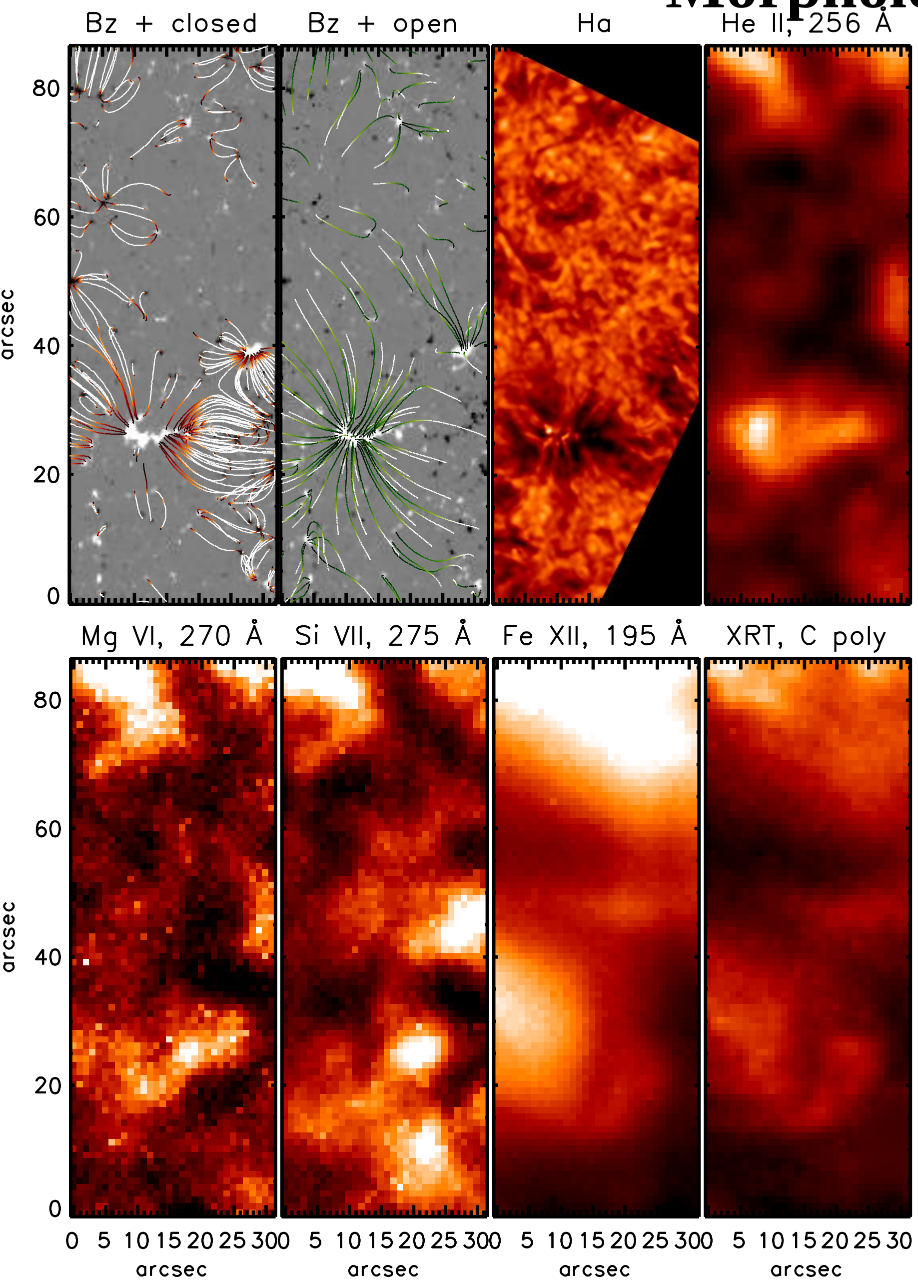
Common time axis

Gaussian fitting of the EIS spectral lines

Construction of "synthetic rasters" in *Hα* to compare with EIS rasters

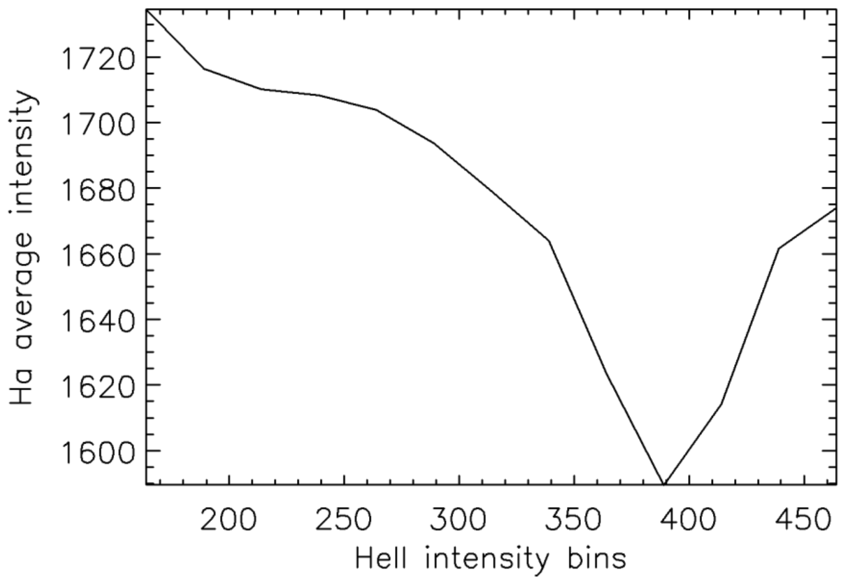
EIS 40´´ slot time series + Hα to infer connections between phenomena at different heights

Morphology - Structure

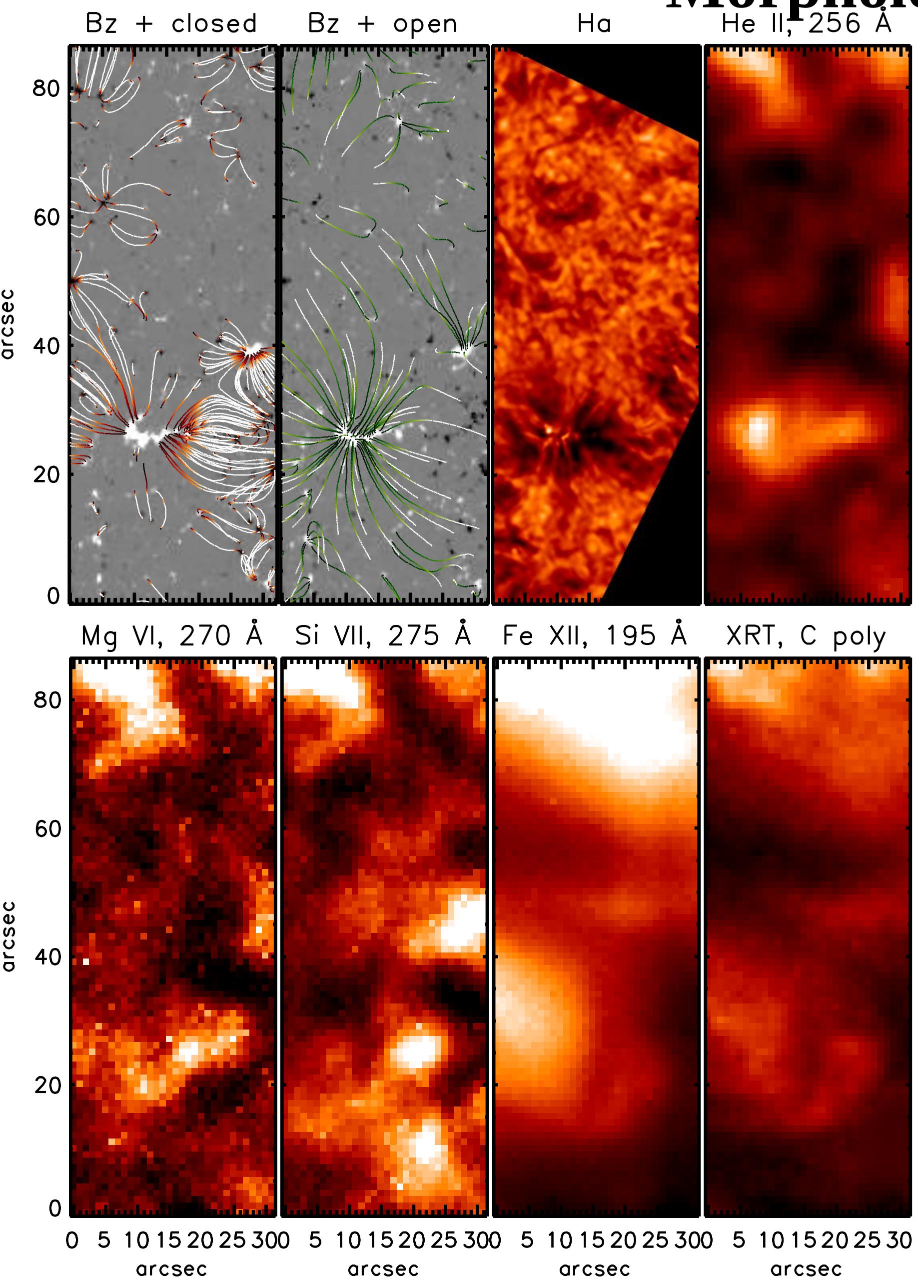


Hα mottles follow magnetic field orientation (*Kontogiannis et al. 2010a, Leenaarts et al. 2012*)

Hα absorption correlates with *He II* emission



Morphology - Structure



<u>Upper transition region lines</u>
(*Mg VI-VII, Si VII, Fe VIII*)

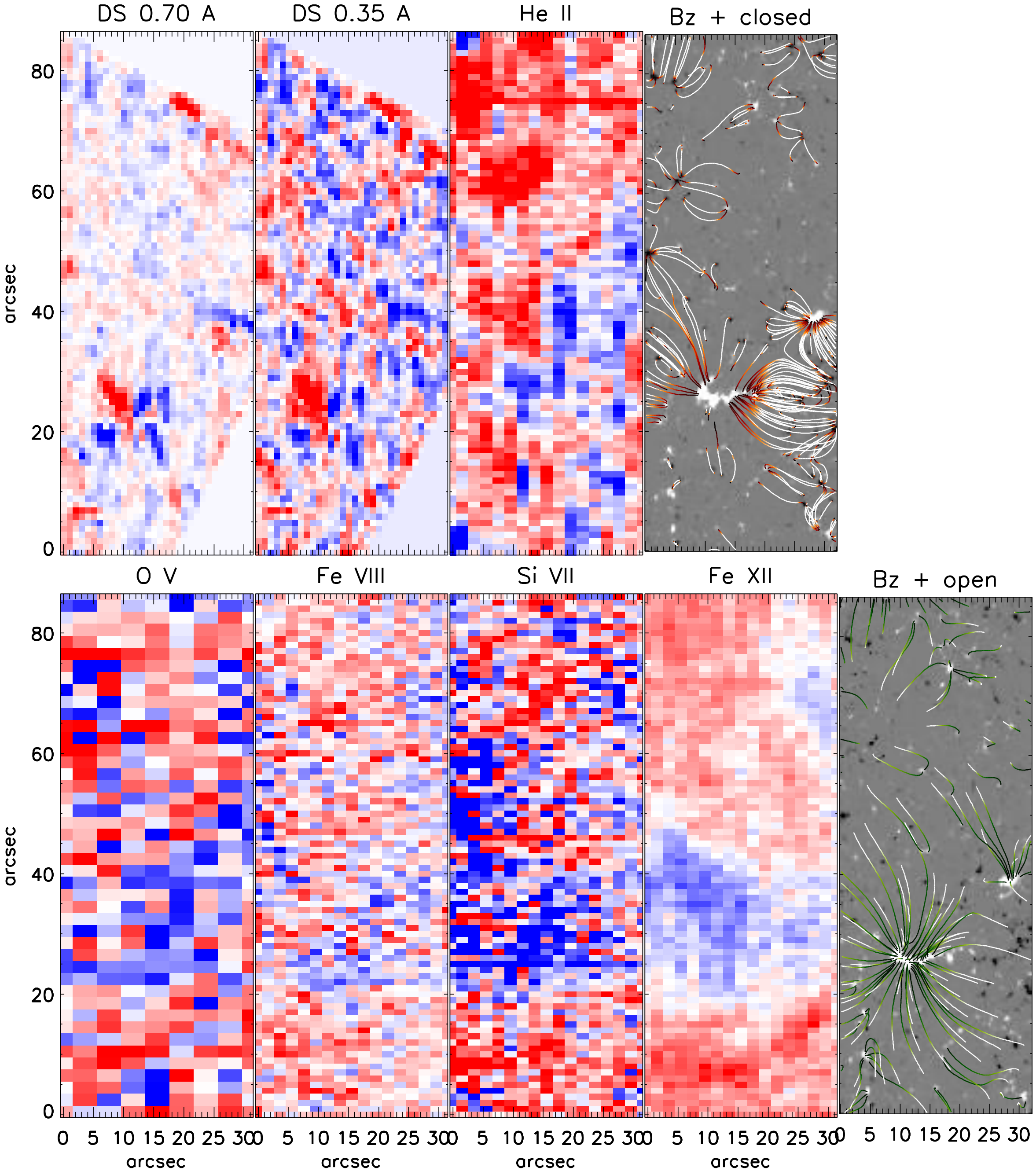
Associated with smaller scale loops and areas with large filling factor

<u>Coronal lines - Soft X-rays</u>

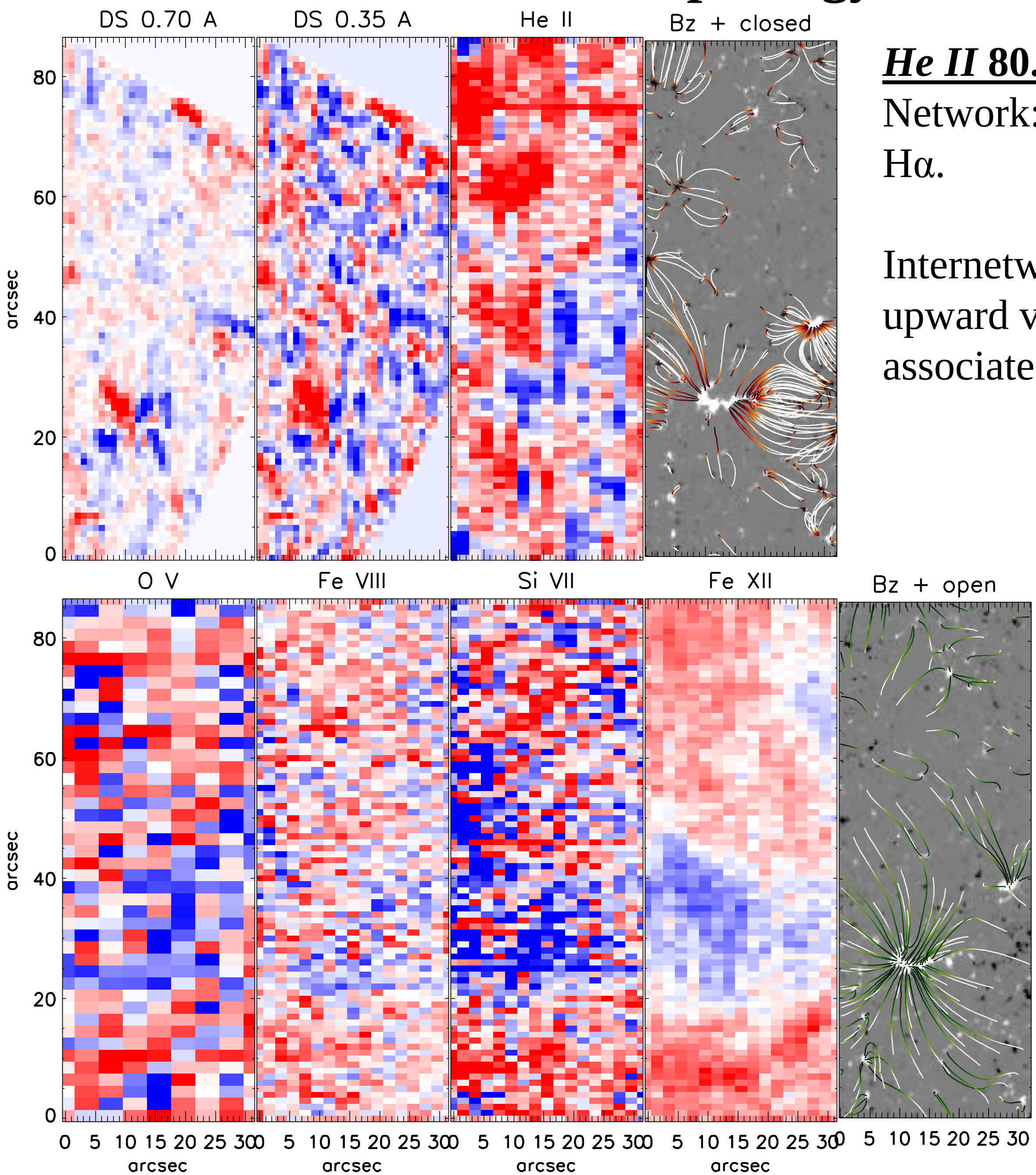
associated with open field lines and longer loops.

In general, magnetic loops with different T (Dowdy et al. 1986)

Morphology - Structure



Morphology - Structure



***He II* 80.000 K:**

Network: similar velocity structures with Hα.

Internetwork structures exhibit some upward velocities,
associated with IN features in Hα.

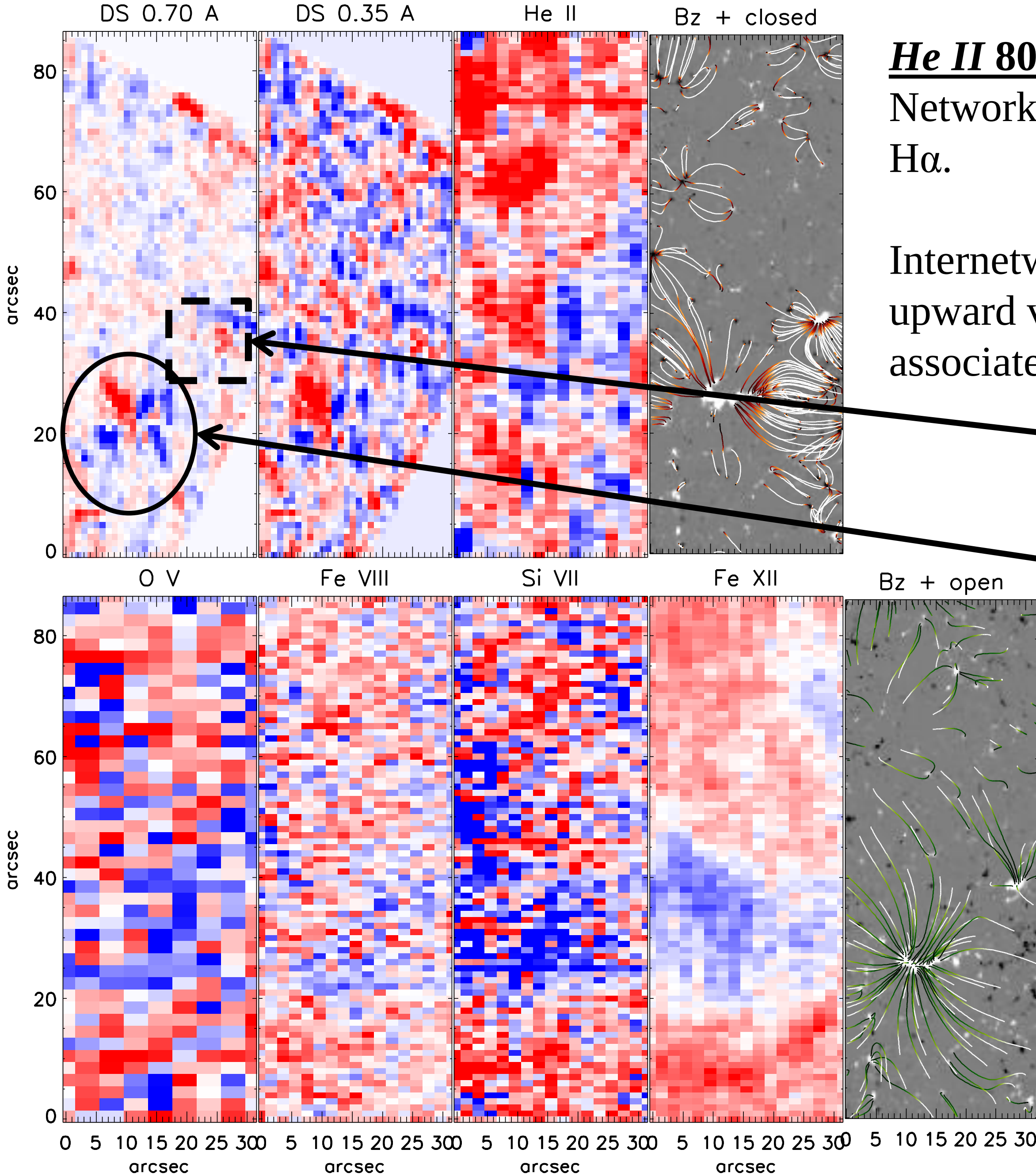
250.000 – 630.000 K:

Network, a mixture of upward and downward velocities,

upward dominant over the boundary

1.6 MK: Upward velocities

Morphology - Structure



***He II* 80.000 K:**

Network: similar velocity structures with Hα.

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associated with IN features in Hα.

Emerging flux

Well established network boundary with an Hα rosette.

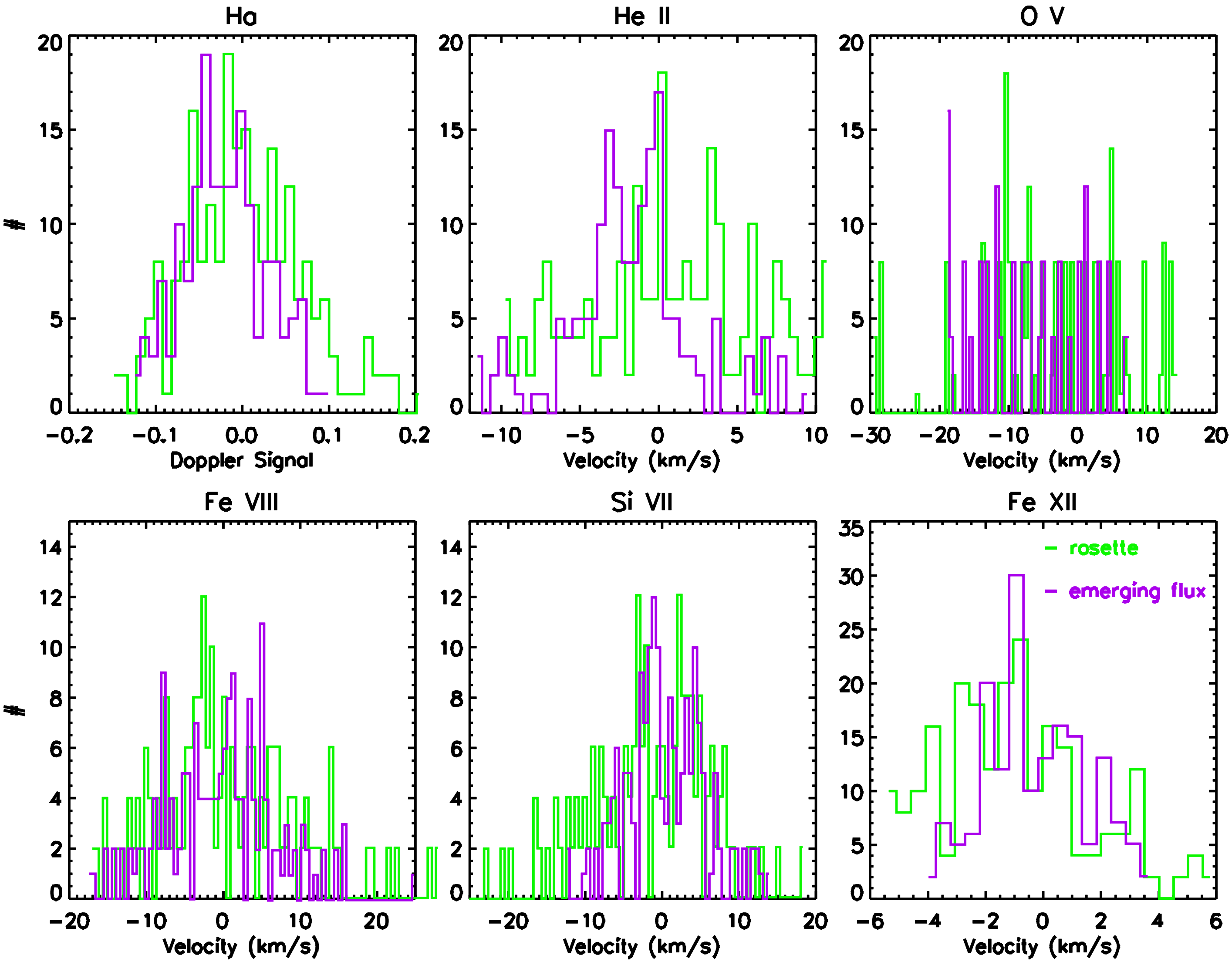
250.000 – 630.000 K:

Network, a mixture of upward and downward velocities,

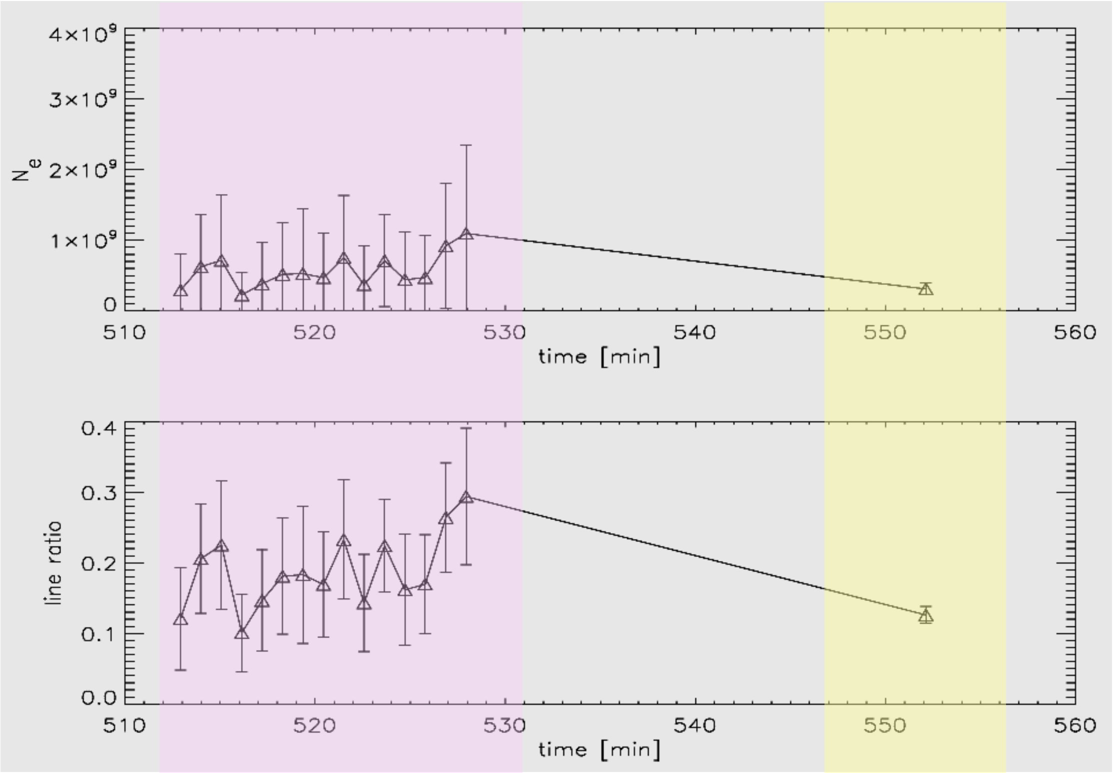
upward dominant over the boundary

1.6 MK: Upward velocities

Morphology - Structure



Morphology - Structure



Density diagnostic:

Mg VII λ278.39/λ280.75 Å line pair (Young et al. 2007)

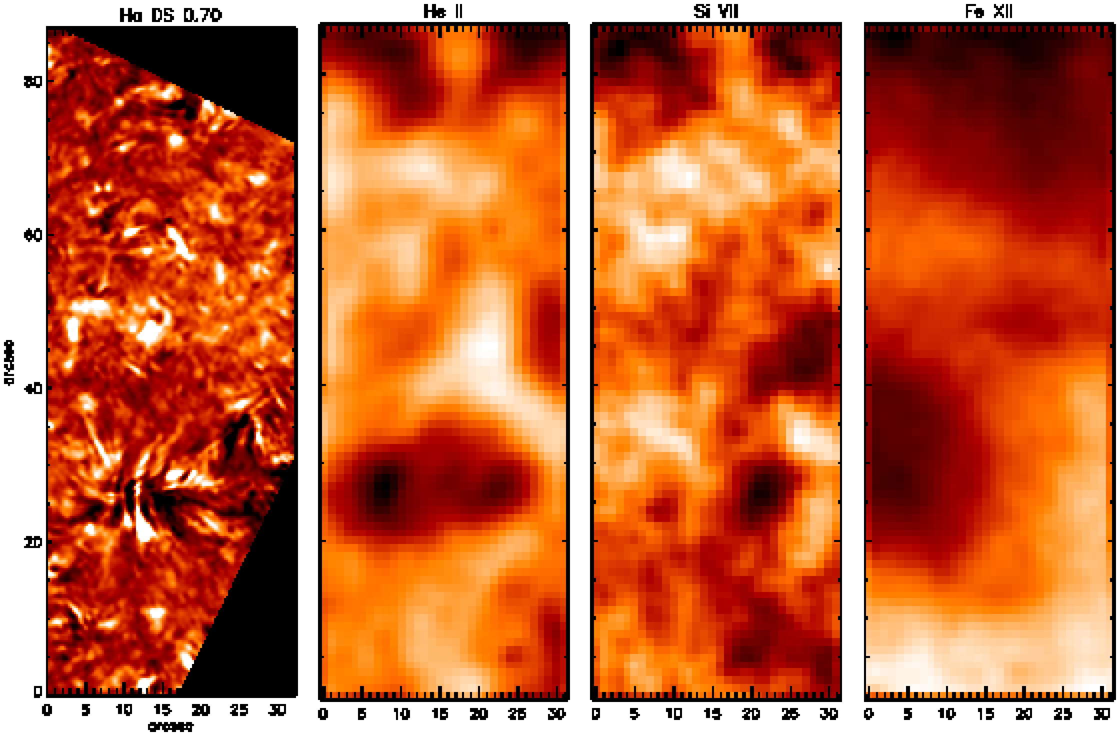
Correction for the *Si VII λ278.44* using the *Si VII λ275.35* Å line

Method applied on both slots and raster data with consistent results

Consistent with previous measurements (e.g. *Fludra et al. 1999, Warren & Brooks 2010*)

Derivation of temperatures is underway!

Temporal variations

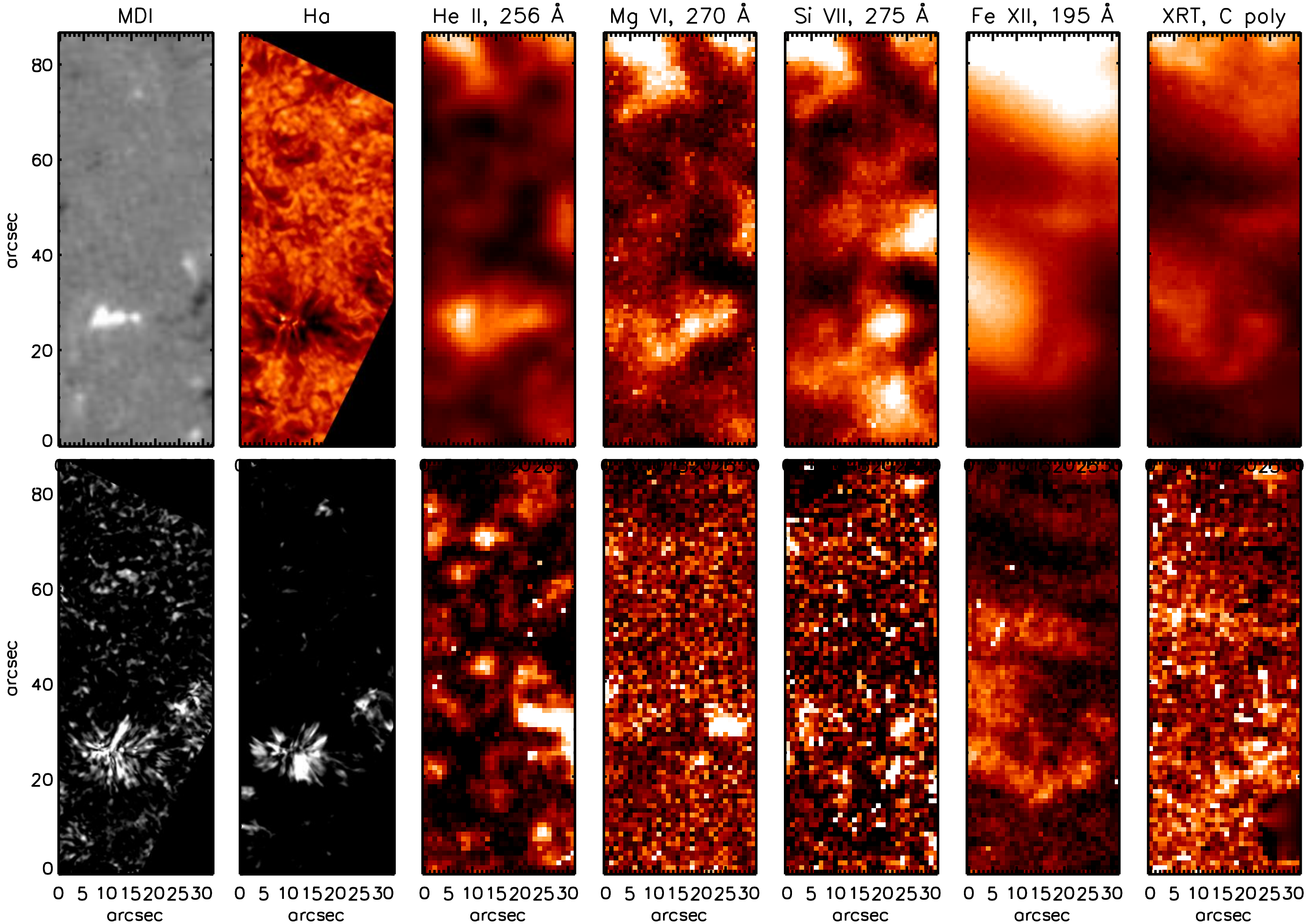


Temporal variations from frame to frame betraying fast temporal variations (*Peter, 2013*)

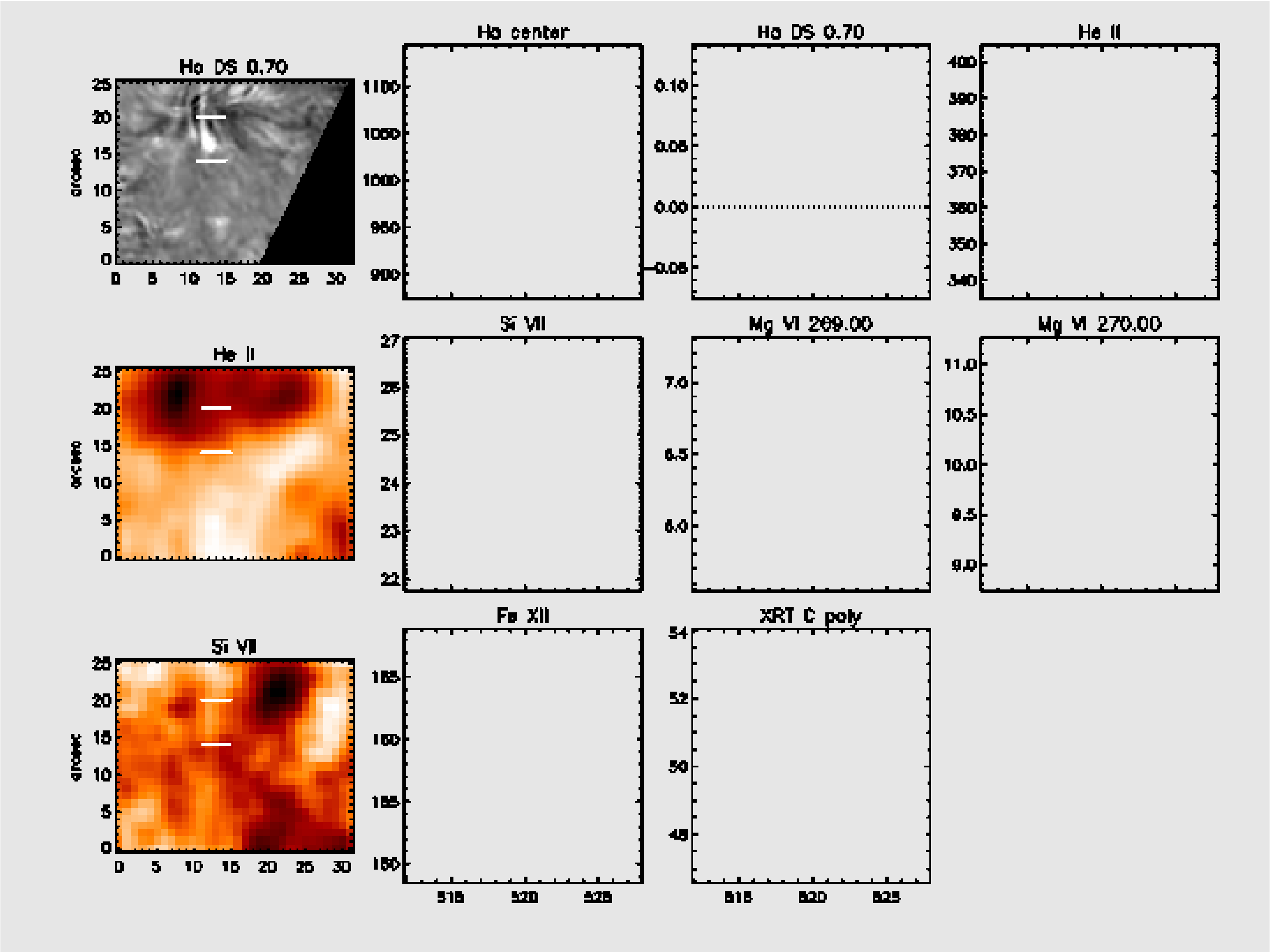
Correspondence with Hα Doppler-shifted features

Significant variations at the IN

Temporal variations - *σ*/<*I*> maps



Chromospheric jet with TR and coronal response 1



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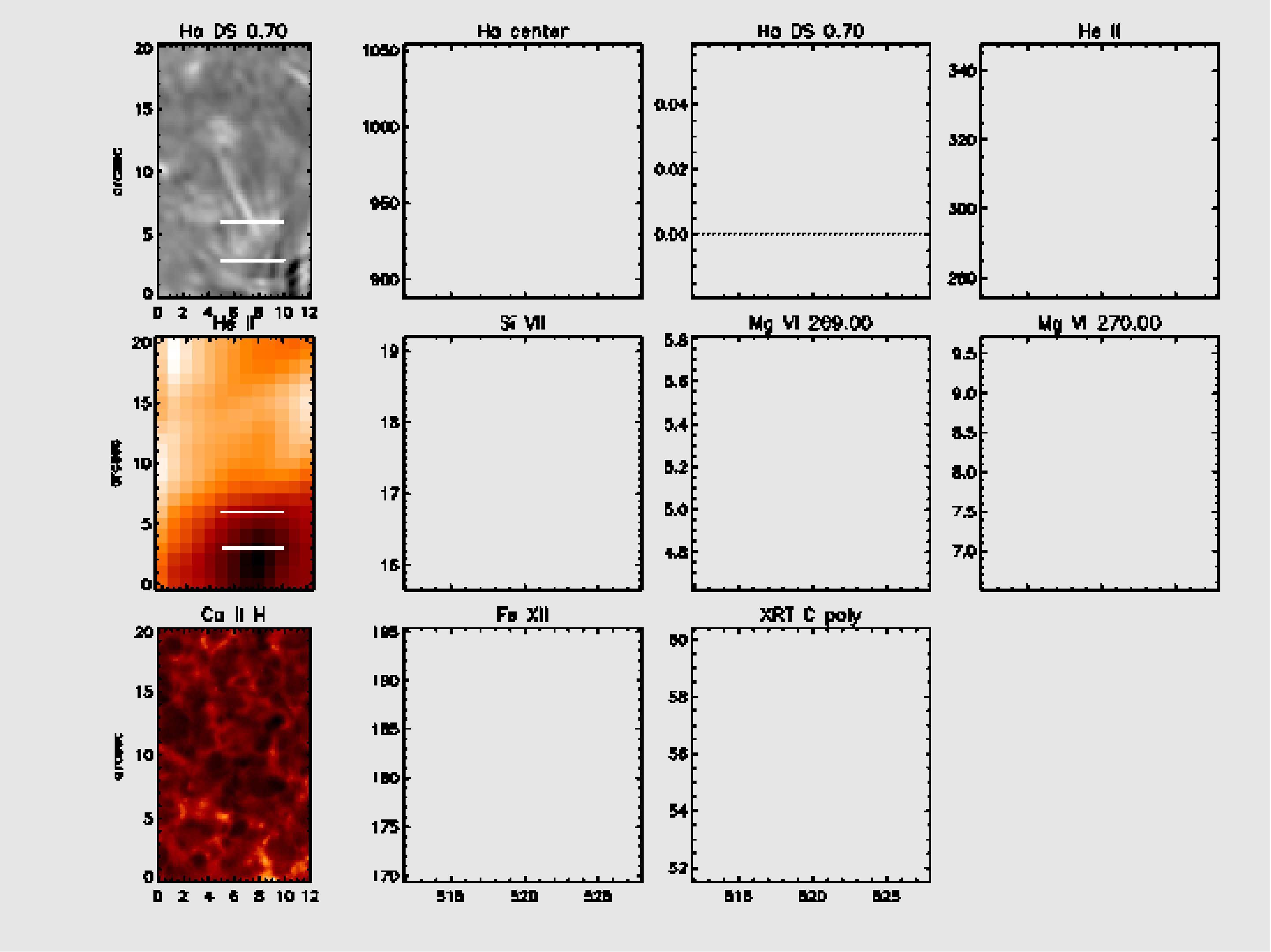


Summary

A mixture of magnetic loops with various lengths constitute the low-β atmosphere.

Some of them do not reach coronal temperatures

HeII emission correlates very well with *Hα* absorption and shows similar velocity structure at the network.

Transition region and coronal variations are related to *Hα* structures.

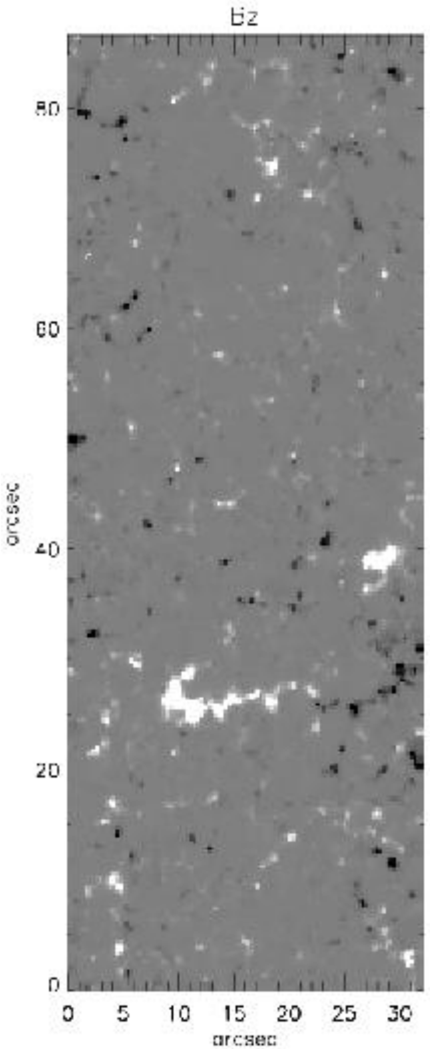
The generating mechanism produces high temperatures (signal at MK temperatures and soft X-rays). Increased TR emission may be associated with chromospheric downflows.

Merging of photospheric bright points associated with chromospheric/TR jets.

Impulsive heating a viable mechanism in quiet Sun (e.g. reviews by *Klimchuk 2006*, *Reale 2010*)

Waves and network magnetic field

High resolution magnetic field provides the opportunity to calculate parameters crucial for wave propagation!



$$\beta = P_g/(B^2/2\mu_0)$$

Pg from *Vernazza et al. 1981*

Magnetic canopy: $\beta = 1$ surface (*Gabriel 1978*)

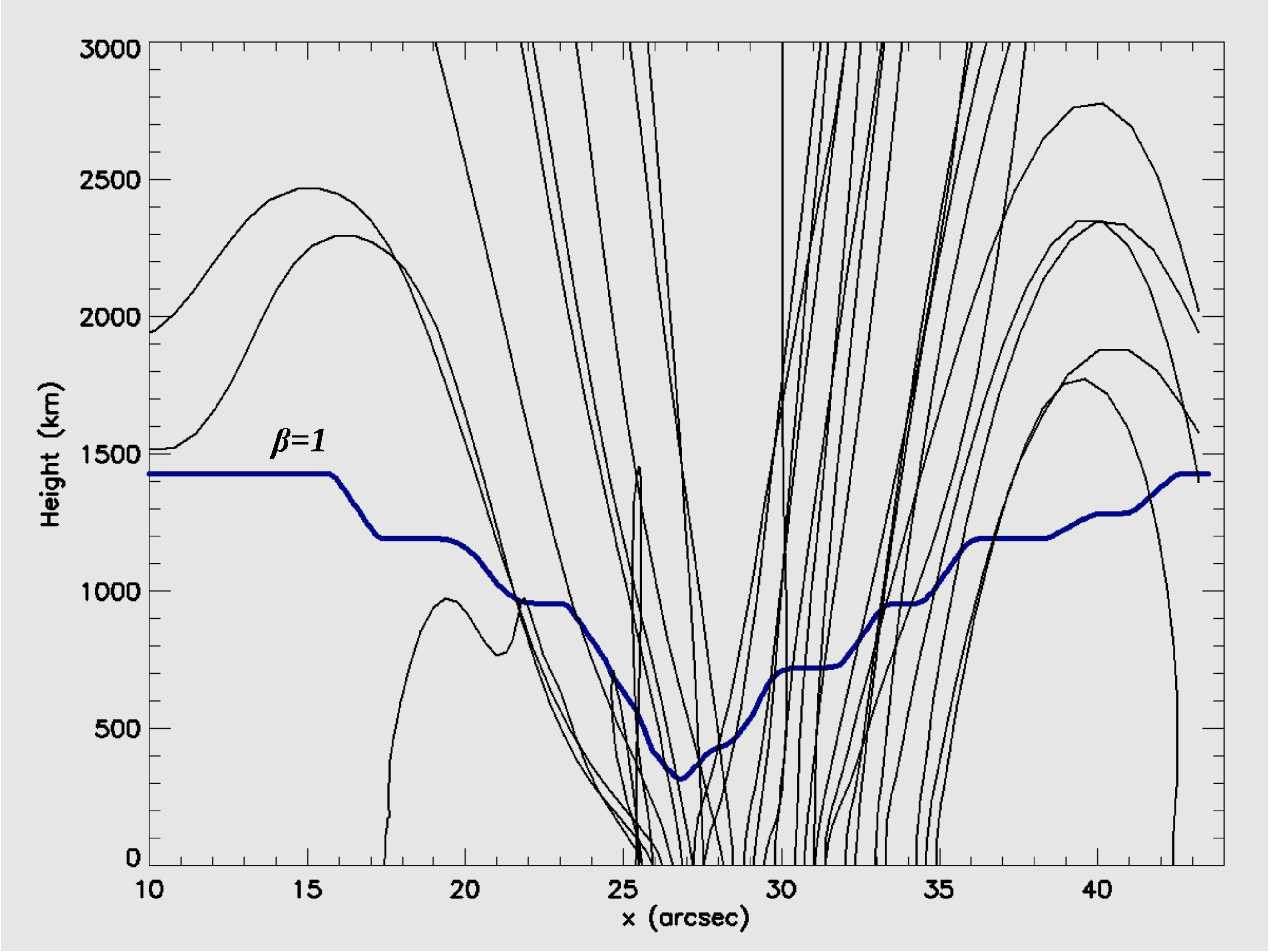
$$\upsilon_A = \frac{B}{\sqrt{\mu\rho}}$$

c_s (sound speed) *Vernazza et al. 1981*

fast and slow speeds

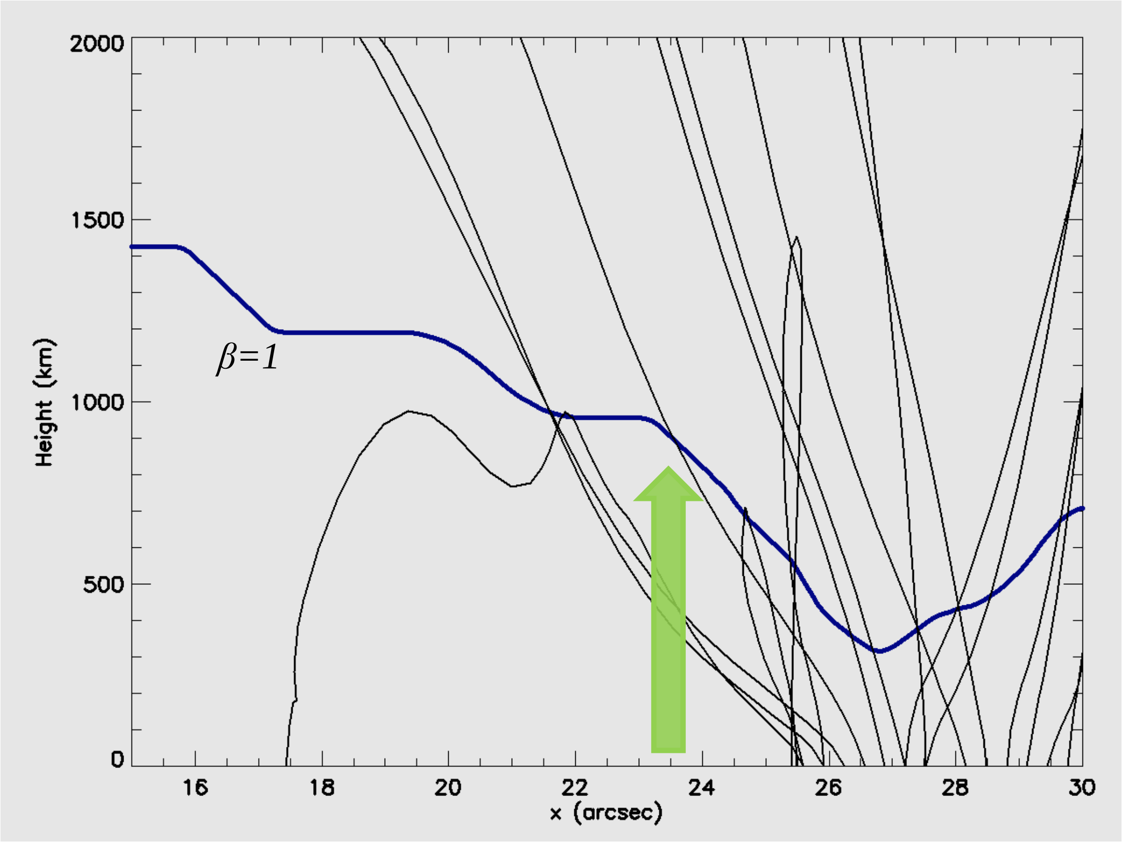
Waves and network magnetic field

Magnetic canopy height



Waves and network magnetic field

What happens when acoustic waves meet the magnetic canopy?



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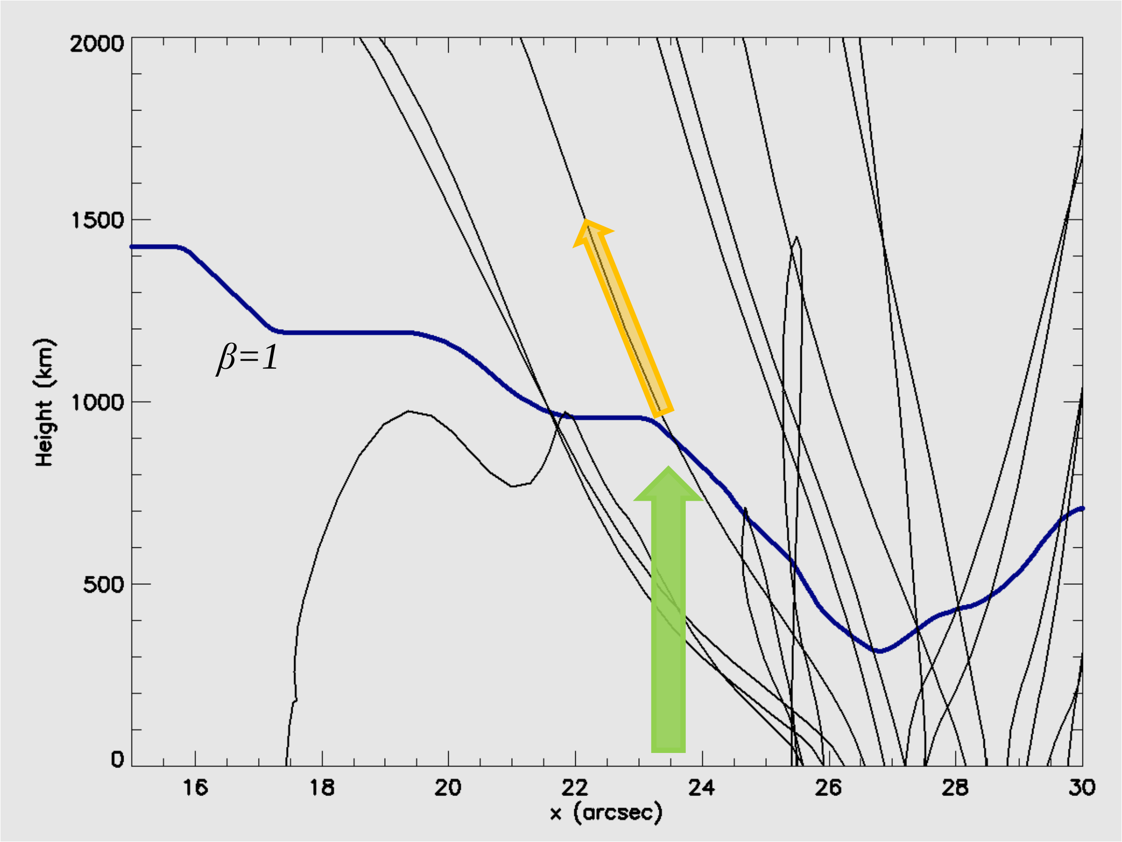
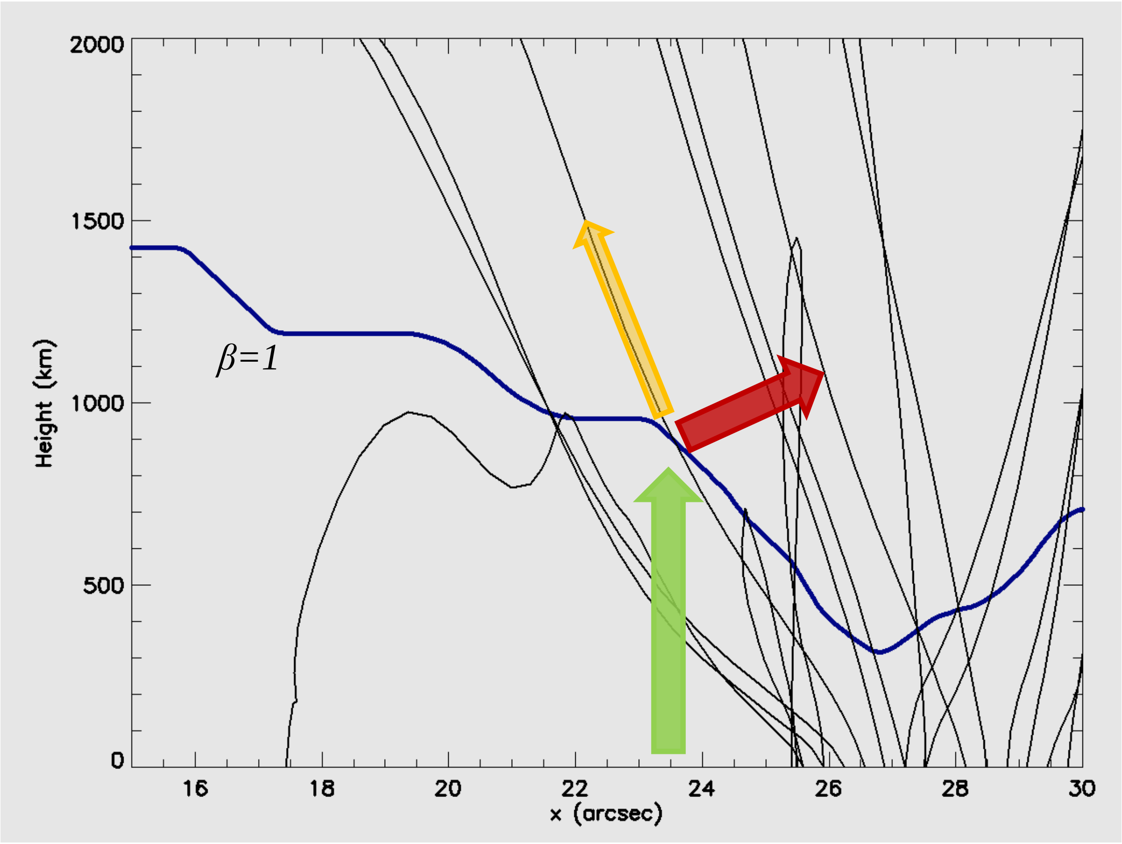


Slow wave along magnetic field (transmission)
U_{slow}

(*Cally 2006, 2007, Schunker & Cally 2006, Stangalini et al. 2011, Nutto et al. 2012a,b*)

Waves and network magnetic field

What happens when acoustic waves meet the magnetic canopy?



Slow wave along magnetic field (transmission)
U_{slow}

Fast wave across magnetic field (conversion)
U_{fast}

Reflect when they meet high velocity gradients

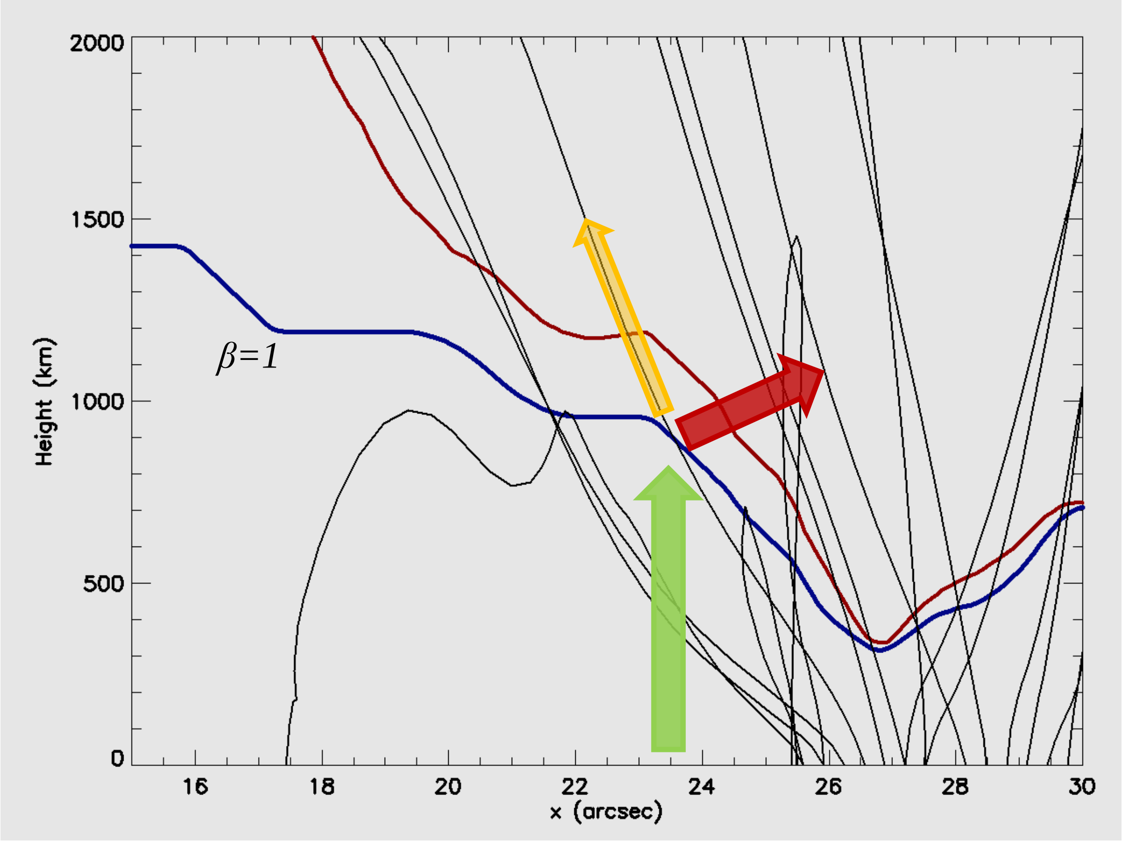
Conversion is favored by large attack angle and high frequency (fast waves – high *f*)

Transmission is favored by small attack angle and low frequency (slow waves – low *f*)

(*Cally 2006, 2007, Schunker & Cally 2006, Stangalini et al. 2011, Nutto et al. 2012a,b*)

Waves and network magnetic field

What happens when acoustic waves meet the magnetic canopy?



Snell's law

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{v_i}{v_r}$$

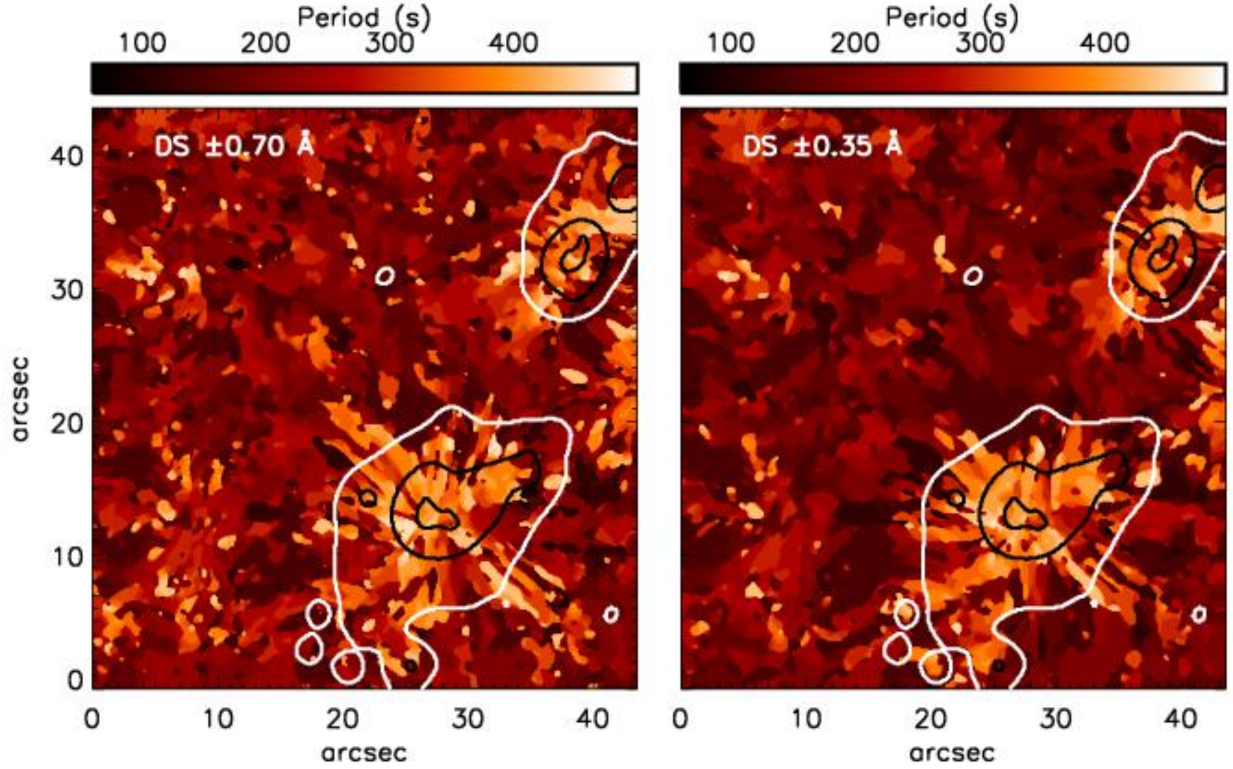
i: *incident acoustic wave*
r: *refracted fast wave*

$$\sin\theta_r = \frac{v_f}{c_s}\sin\theta_i$$

Total internal reflection:

$$\frac{v_f}{c_s}\cos\theta > 1$$

Evidence: Dominant periods and turning height

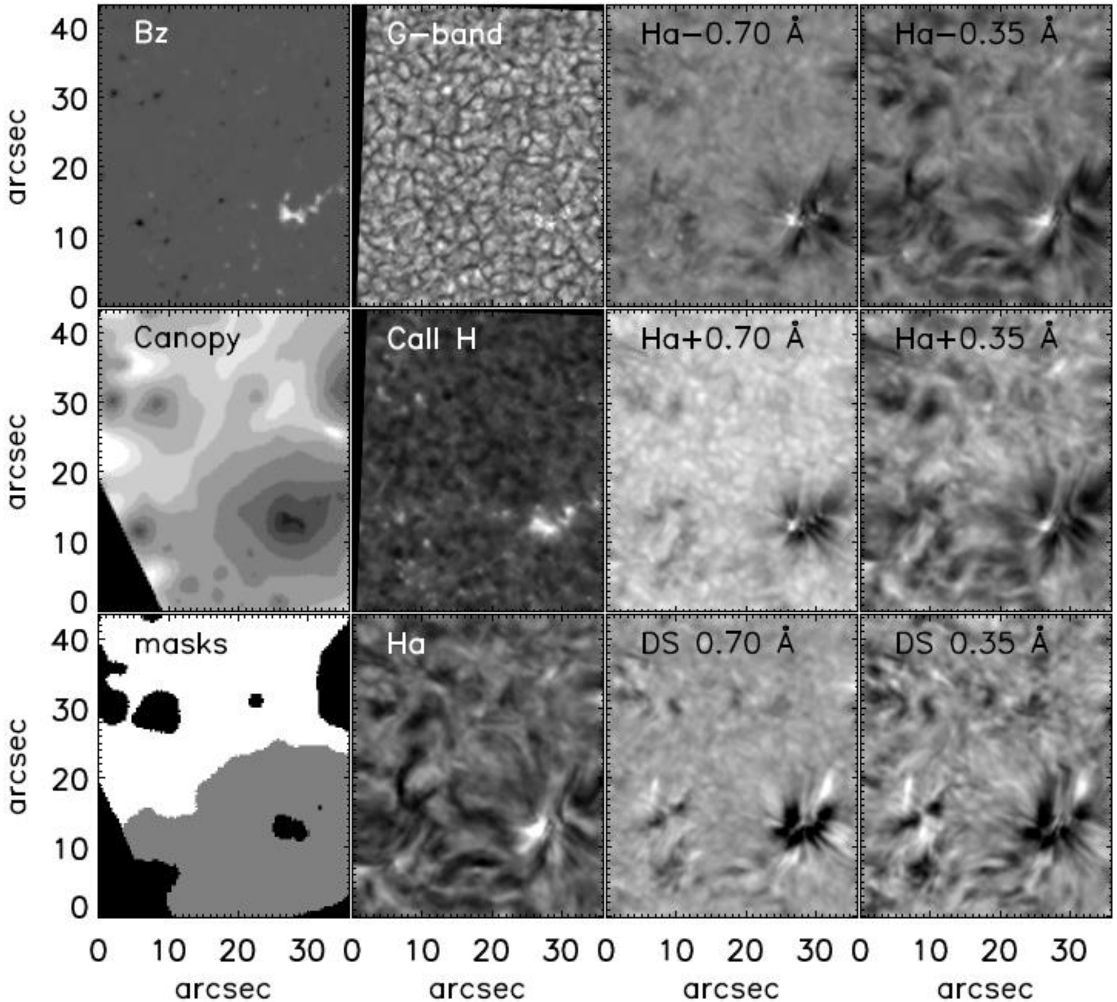


Kontogiannis et al. 2014

Hα formation height: up to *1600 km*

When turning height is lower that 1600 km, long period oscillations (low frequencies) dominate.

Phase difference analysis



Fast and slow waves are compressible and should be **BOTH** detected as oscillations in velocity and intensity signals.

Wavelet spectral analysis to detect period on every pixel (*Torrence & Compo 1998*)

Phase difference analysis between different filters is used to infer wave propagation between layers of the atmosphere. (*Lites et al. 1979*, *Bloomfield et al. 2006*)

Phase difference analysis: interpretation

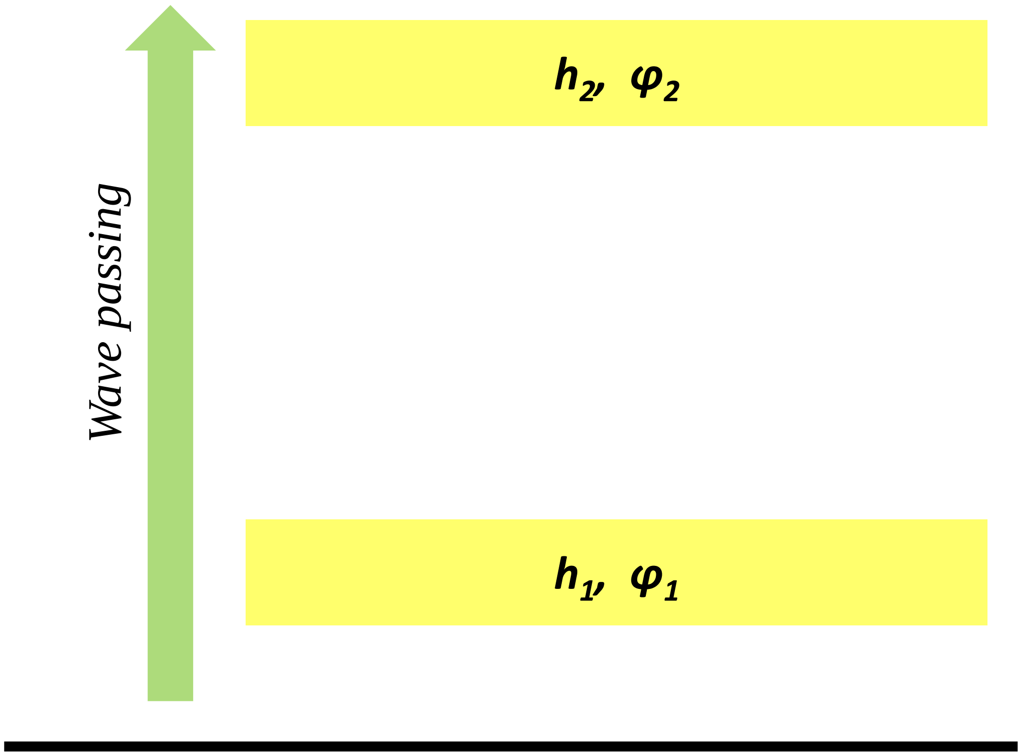
<u>Upward propagation:</u>

$\varphi_2 > \varphi_1$, $\Delta\varphi>0$
$\Delta\varphi$ increasing monotonically with f

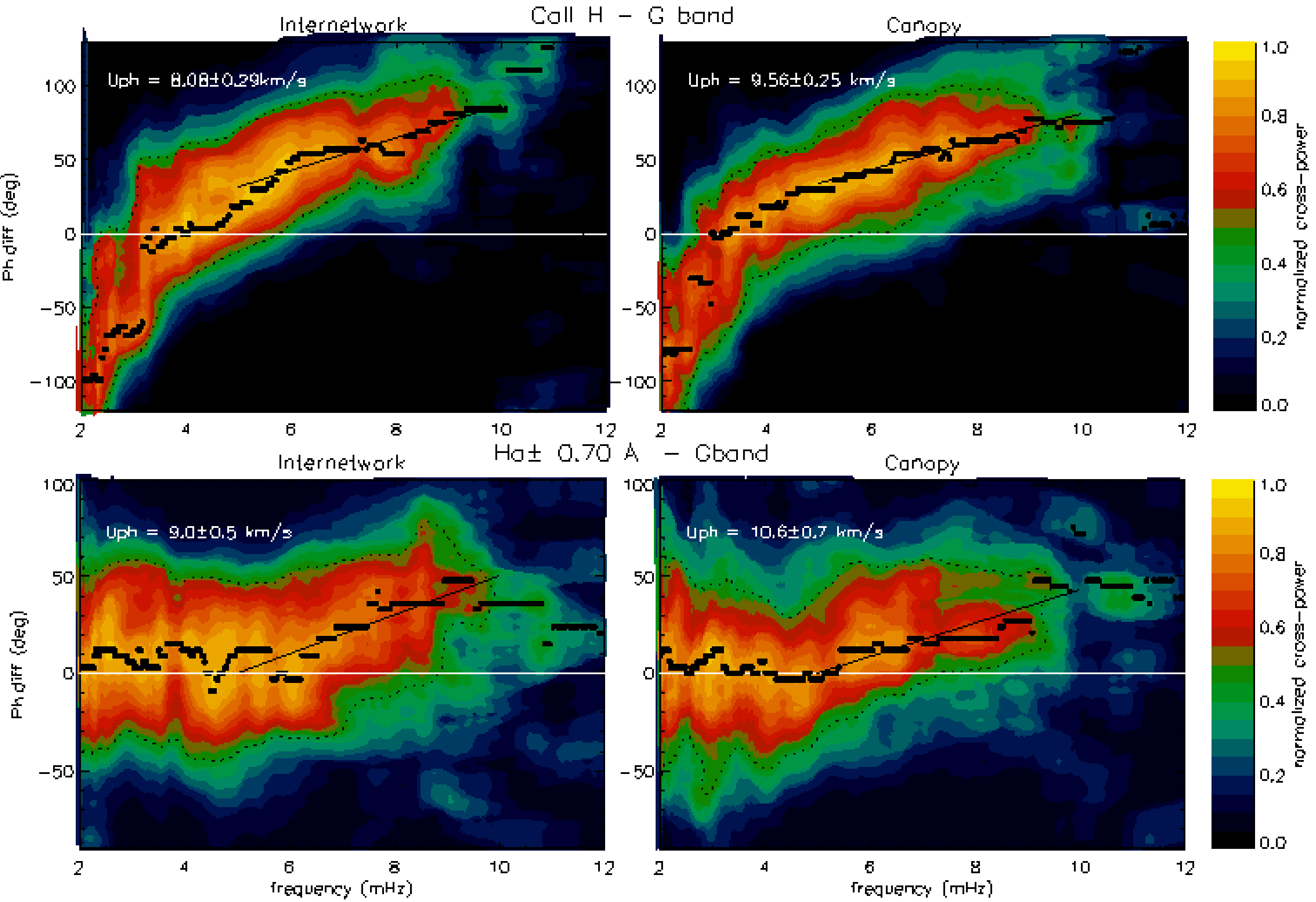
$$\Delta\phi = 2\pi \frac{dh}{\upsilon_{ph}} f$$

$dh=h_2-h_1$, *height difference*
υ_{ph}, *phase speed*

<u>Standing waves:</u> small and constant $\Delta\varphi$

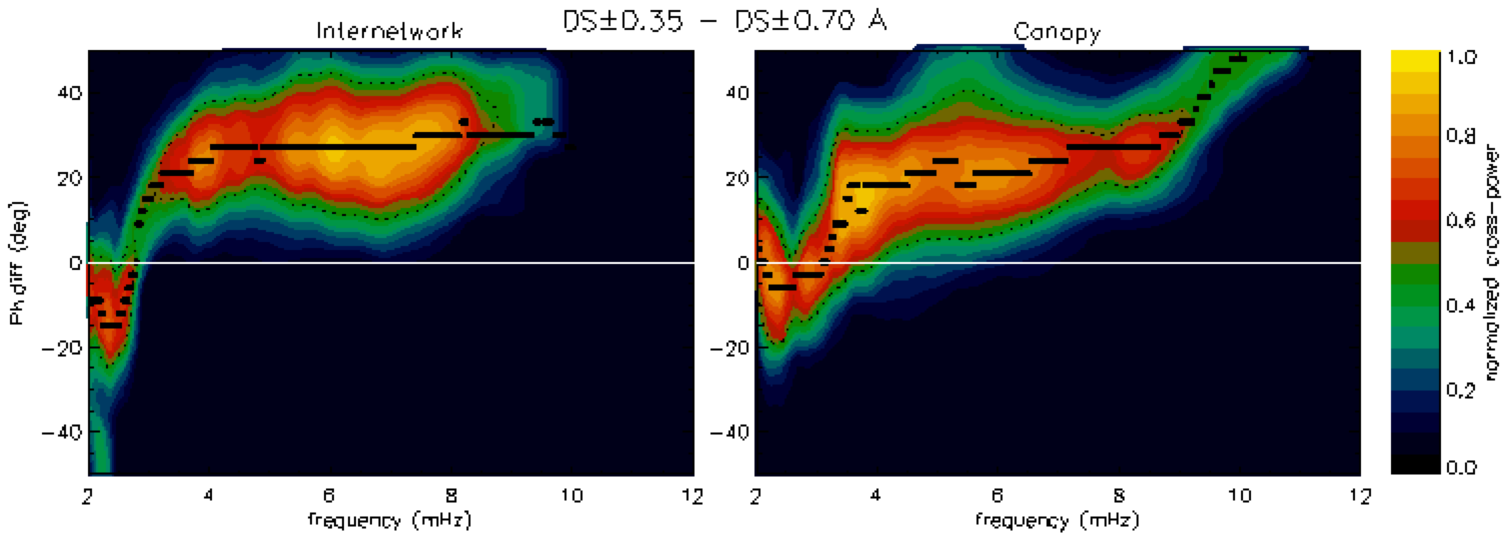


Evidence: Lower phase differences at the magnetic canopy



Rutten et al. 2004, Cadavid & Lawrence 2012

Evidence: Standing wave pattern at the chromosphere



No wave propagation at the chromosphere
(*Mein & Mein 1976*, *Schmieder 1979*, *Fleck1989*)

Lower phase difference: higher phase speed due to conversion to fast waves.
The reflection on the turning height results to atmospheric layers oscillating in phase
(*Nutto etal. 2012,a,b*)

The combination of standing and propagating waves result to a complex wave field.
(*Deubner et al. 1996*)

Concluding remarks

Multi-wavelength studies provide the opportunity to study the dynamics of the quiet Sun in a two-fold way:

a) Wave propagation – interaction of various MHD modes with the magnetic field of the quiet Sun
b) Impulsive phenomena that appear in many temperatures/layers, are generated at the photosphere/chromosphere and affect transition region/corona.

<u>High resolution magnetic field information is necessary</u>

1) to resolve small scale magnetic fields in the quiet Sun
2) to determine the geometry of the chromoshperic/transition region/coronal magnetic field and
3) to accurately calculate parameters, important for wave propagation.

Thank You!