Probing temperature of the sunspot atmosphere by propagating slow MHD waves

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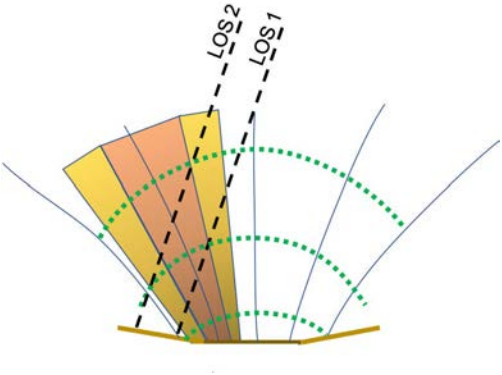
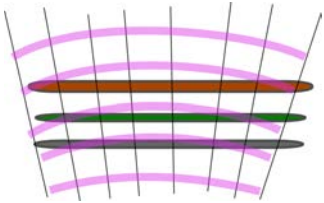
Upward propagating wave in a sunspot atmosphere

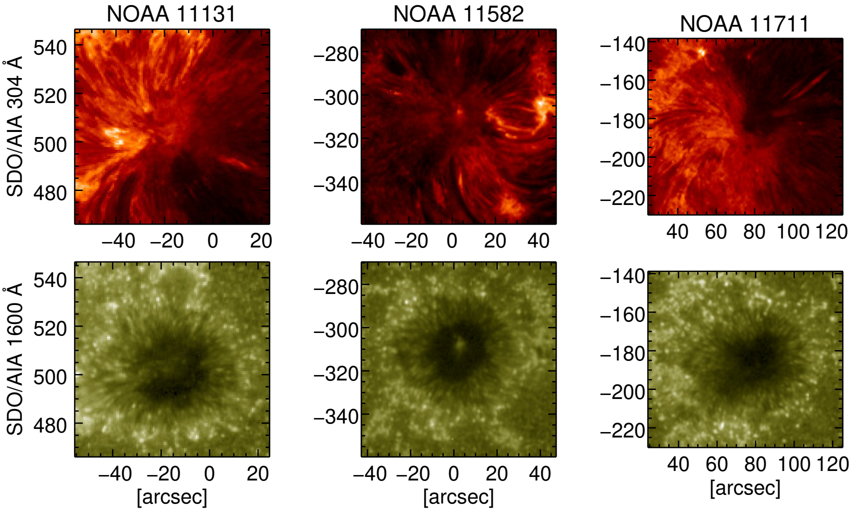
Lower atmosphere vs corona





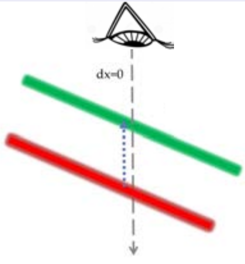
Lower atmosphere

Observations



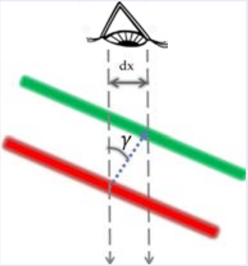
Dependence of the wave displacement upon the magnetic field inclination

Parallel to LOS



Wave arrives in the same point on the picture plane.

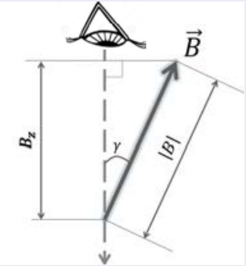
Oblique to LOS



$$\Delta = l \sin\gamma$$

$$\Delta = l \cos(\frac{\pi}{2} - \gamma)$$

Field lines

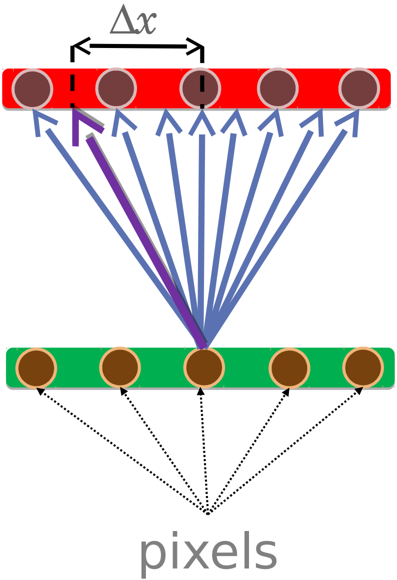


$$\cos\gamma = B_z/B$$

$$\cos(\frac{\pi}{2} - \gamma) = B_\tau/B$$

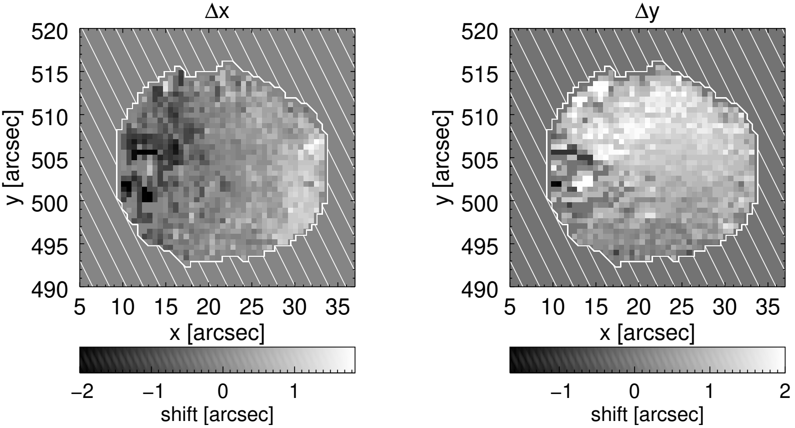
Estimation of delays and displacements

- Calculate cross-correlation for all possible wave paths
- Select the path with maximal correlation coefficient
- Estimate delay using cross-correlation analysis
- Ensure that correlation coefficient is greater than 0.6

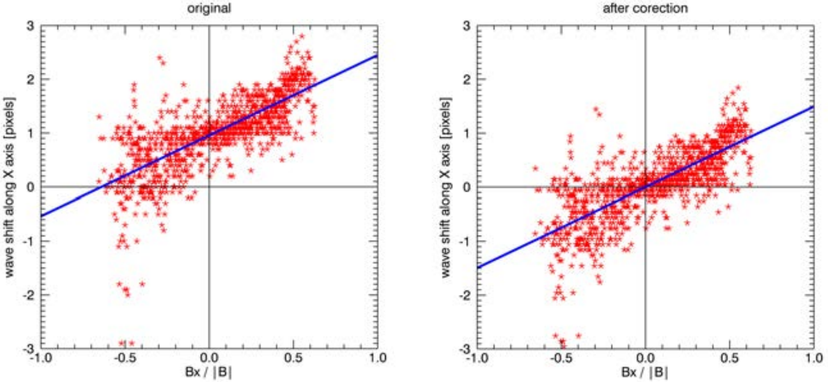


Wave displacements

NOAA 11131



Dependence of the wave displacement upon the magnetic field inclination



$$\Delta x = l \cos\phi_x = l\frac{B_x}{B},$$

l - wave propagation distance, ϕ_x - angle between $\mathbf{B}$ and $\hat{\mathbf{x}}$

Calculation of distance between emission layers

- Take γ from the magnetic field measurements $\gamma = \arccos(B_z/B)$
- Wave propagation distance

$$l = \frac{\sqrt{\Delta x^2 + \Delta y^2}}{\sin\gamma}$$

- Angle φ between the magnetic field $\mathbf{B}$ and the normal $\hat{\mathbf{n}}$ to the solar surface:

$$\cos\varphi = \frac{\mathbf{B}\cdot\hat{\mathbf{n}}}{B}$$

- **Distance between the layers**

$$h = l\cos\varphi$$

- Calculate the **average phase speed** from the measured delay τ

$$v_{\mathrm{p}} = \frac{l}{\tau}$$

Calculation of the phase speed

Dispersion relation for magneto acoustic gravity waves

$$\omega^2 = k^2 c_{\mathrm{s}}^2 + \omega_0^2,$$

where ω_0 is the acoustic cut-off frequency $\omega_0 = \frac{g_0 \gamma}{2 c_{\mathrm{s}}} \cos \alpha$
The phase speed

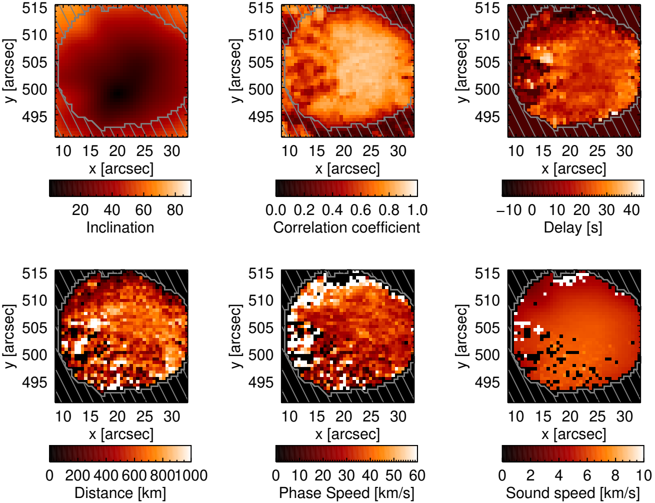
$$v_{\mathrm{p}} \equiv \frac{\omega}{k} = \frac{c_{\mathrm{s}}}{\sqrt{1 - (\omega_0/\omega)^2}}.$$

Sound speed

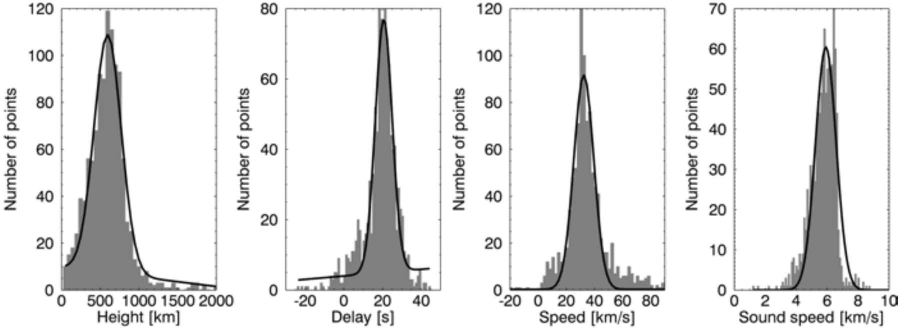
$$c_{\mathrm{s}} = \frac{\sqrt{2}}{2} \sqrt{v_{\mathrm{p}}^2 \pm \frac{v_{\mathrm{p}}}{\omega} \sqrt{-g_0^2 \gamma^2 \cos^2(\alpha) + \omega^2 v_{\mathrm{p}}^2}}$$

Results

Maps of the measured parameters



Results [1]

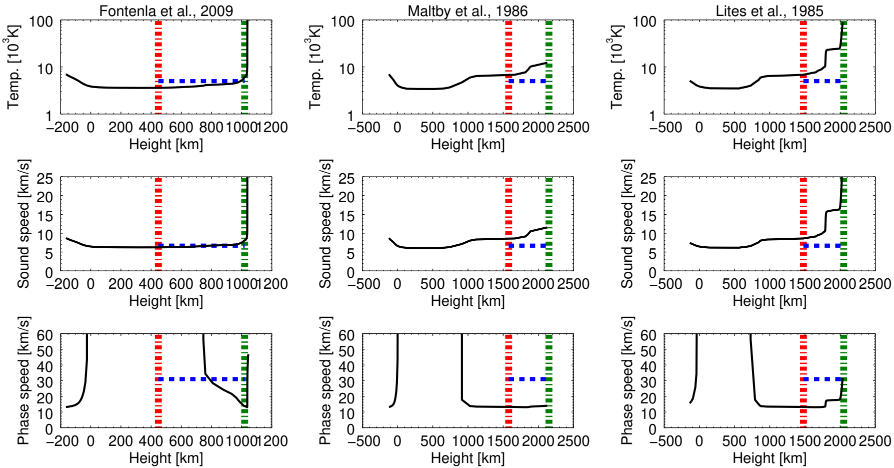


NOAA	Dist. [km]	Delay [s]	Ph. sp. [$\mathrm{km\,s^{-1}}$]	S. sp. [$\mathrm{km\,s^{-1}}$]	Temp. [K]
11131	572 ± 176	20 ± 4	31 ± 7	6 ± 1.0	3300 ± 1000
11582	749 ± 243	25 ± 10	30 ± 10	5 ± 0.7	2300 ± 700
11711	670 ± 320	24 ± 6	29 ± 9	6 ± 0.3	3300 ± 300

[1] [Deres and Anfinogentov, 2018]

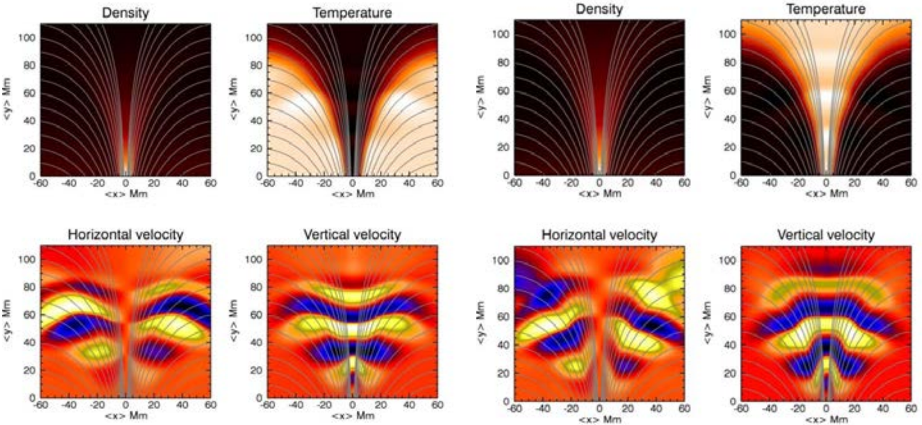
Results

Comparison with the models



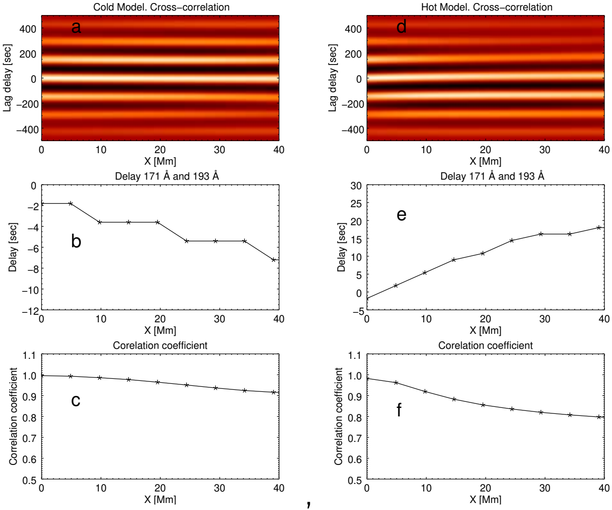
MHD modelling of a slow wave in a coronal fan

"Hot" and "cold" models



MHD modelling of a slow wave in a coronal fan

Apparent delays[2]



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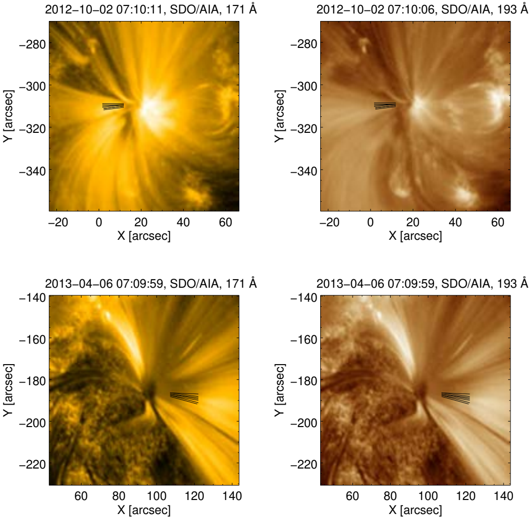
[2]from forward modelling with the FoMo code [Van Doorsselaere et al., 2016]

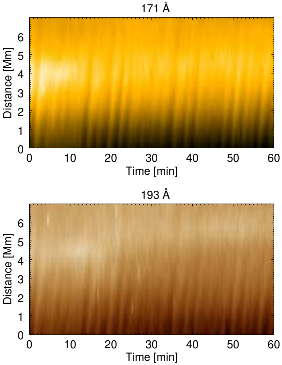
Real observations

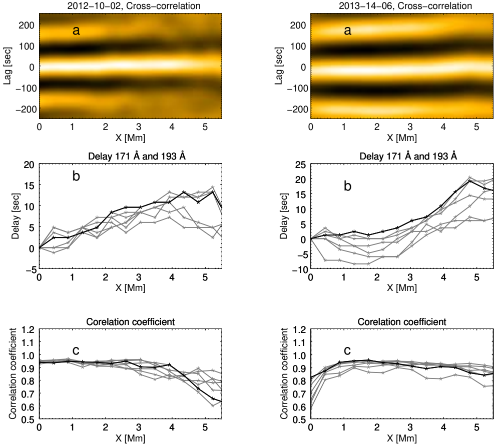
EUV images



Real observations

Correlation analysis





Summary

- Spatially resolved observation of 3 min oscillations allow for seismological estimation of
  - **Average phase speed** (*30 km/s between 1600 and 304 Å*)
  - **Distance between layers** (*500 – 750 km between 1600 and 304 Å*)
  - **“Average” sound speed** (*5-6 km/s between 1600 and 304 Å*)
  - **“Average” temperature** (*2000-4000 K between 1600 and 304 Å*)
- Apparent propagation speed is NOT a projected speed
- Observed propagation speed, amplitude and damping are apparent quantities. Forward modelling should be used for interpretation of these observations.
- We have found a seismological evidence that the coronal fans have a core wormer than the background plasma

Thank you for your attention!

References

Deres, A. and Anfinogentov, S. (2018).
Probing the Sunspot Atmosphere with Three-Minute Oscillations.
Sol. Phys., 293(1):2.

Van Doorsselaere, T., Antolin, P., Yuan, D., Reznikova, V., and Magyar, N. (2016).
Forward modelling of optically thin coronal plasma with the FoMo tool.
Frontiers in Astronomy and Space Sciences, 3:4.