Sunspot Oscillations Observed by DKIST

Sarah Riley[1], Junwei Zhao[2], Jiong Qiu[1], Gianna Cauzzi[3]

[1]Physics Department, Montana State University [2]HEPL, Stanford University [3]National Solar Observatory

MONTANA STATE UNIVERSITY

Introduction

Many kinds of waves are generated in the magnetized solar atmosphere inside and above sunspots. Observations of the abundant wave signatures provide opportunities to determine the physical properties, such as the temperature, density, and magnetic field structure of the solar atmosphere. Magneto-acoustic waves have been widely studied along the coronal loops above sunspot regions (Zhao et al. 2025). However, detailed studies on the behaviors of this type of waves propagating between the upper photosphere and lower chromosphere in umbrae and penumbrae are still scarce, due to lack of high-quality high-cadence spectroscopic observations (Sych et al. 2014). Using a set of observations obtained by DKIST (Rimmele et al. 2020) with high spectral resolution and high temporal cadence, **we study the power spectra of the waves above a sunspot umbra and penumbra, as well as how the waves' phases vary with the atmospheric height.**

Observations

DKIST/ViSP observed an active region with the **sit-and-stare mode at 25 ms cadence for a duration of 80 minutes** in excellent seeings ($r_0 \geq 10$ cm). The spectra of three lines, Hα, Na I, and Ca IR were obtained. DKIST/DL-NIRSP also observed the active region with Fe 1.5μm line.

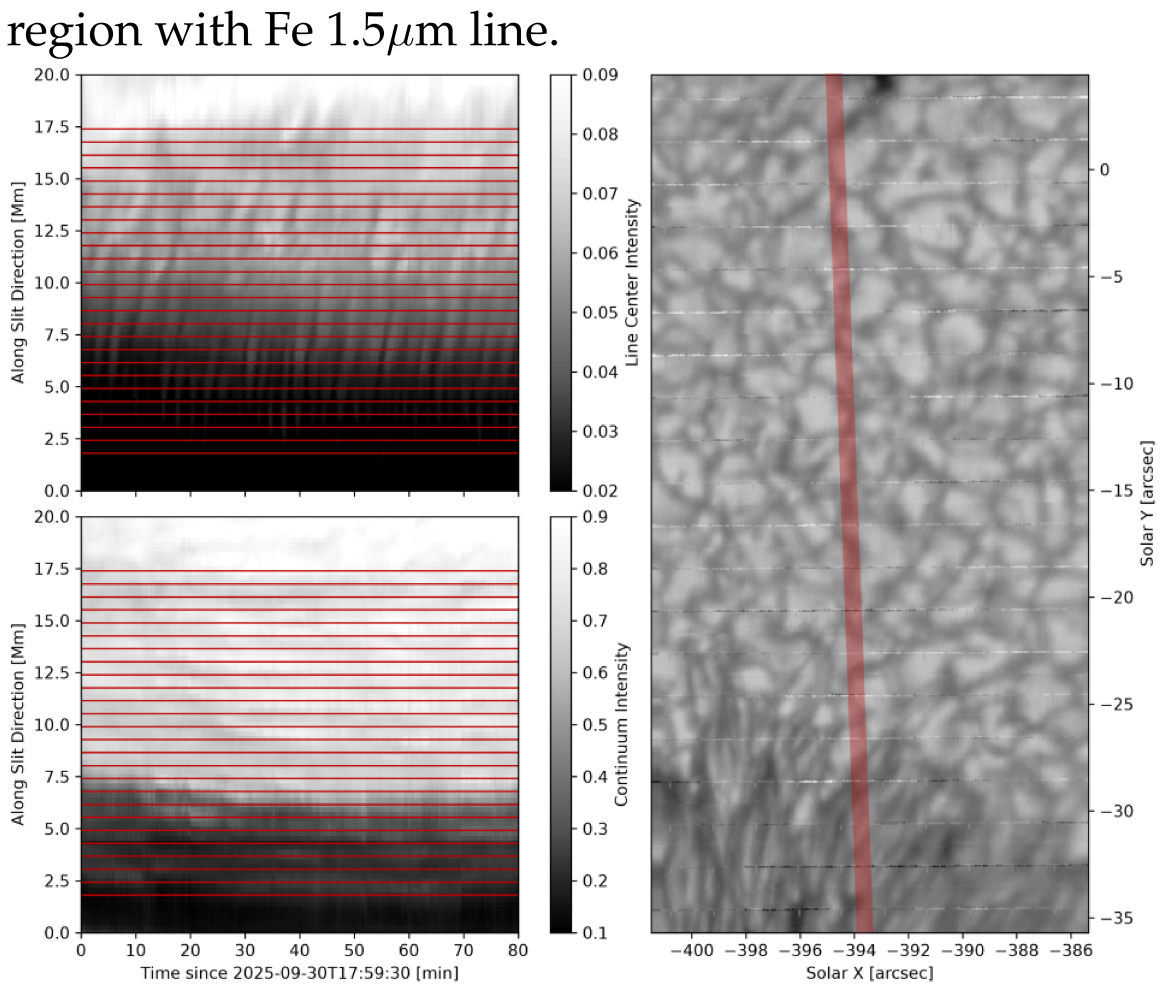

Figure 1: Left: the intensity at the line center (top) and at the continuum (bottom) of Na I line along the ViSP slit over 80 minutes, showing the umbra and penumbra of a sunspot. Right: a snapshot of the Fe 1.5μm Stokes I image by DL-NIRSP in the same active region, capturing the sunspot penumbra.

Analysis

From the Na I spectra, we derive velocity signatures at 5 wavelengths: $F(t, \lambda, s) = F_+ - F_-$, where $F_\pm$ are line intensities at $\pm\lambda$ from the line center, and $\lambda = 0.05, 0.10, 0.15, 0.20, 0.25$ Å (Fig. 2).

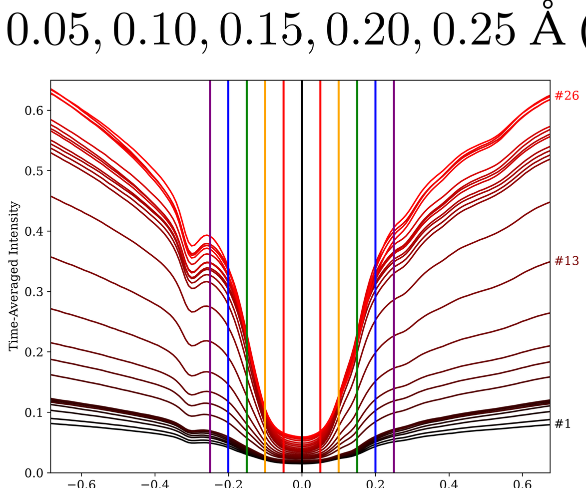

Figure 2: Na I spectrum along the slit, at the distance from 1 to 13 Mm, as shown in Fig. 1. Each spectrum displayed is averaged over 80 min and 0.5″. The black bar indicates the line center, and the color bars indicate the center wavelengths of the 5 passbands where $F_\pm$ is computed.

- At each λ, signals are integrated over a spectral range $\Delta\lambda = 0.05$Å.
- At each slit position s, signals are averaged over $\Delta s = 0.5''$.
- We then apply the FFT analysis to $F(t, \lambda, s)$ at 10 s cadence of the entire duration of 4800 s, and also to high-cadence (25 ms) short duration (150 s) time series.

The analysis is performed for each wavelength (λ) at each slit position (s) to obtain **dominant frequencies $f(\lambda, s)$ and the phase $\psi(\lambda, s)$**, which is the power-weighted average about each dominant frequency.

Results: 10 s time series

The FFT analysis applied to the 10 s cadence time series shows oscillations with periods 120 - 250 s (4-8 mHz).

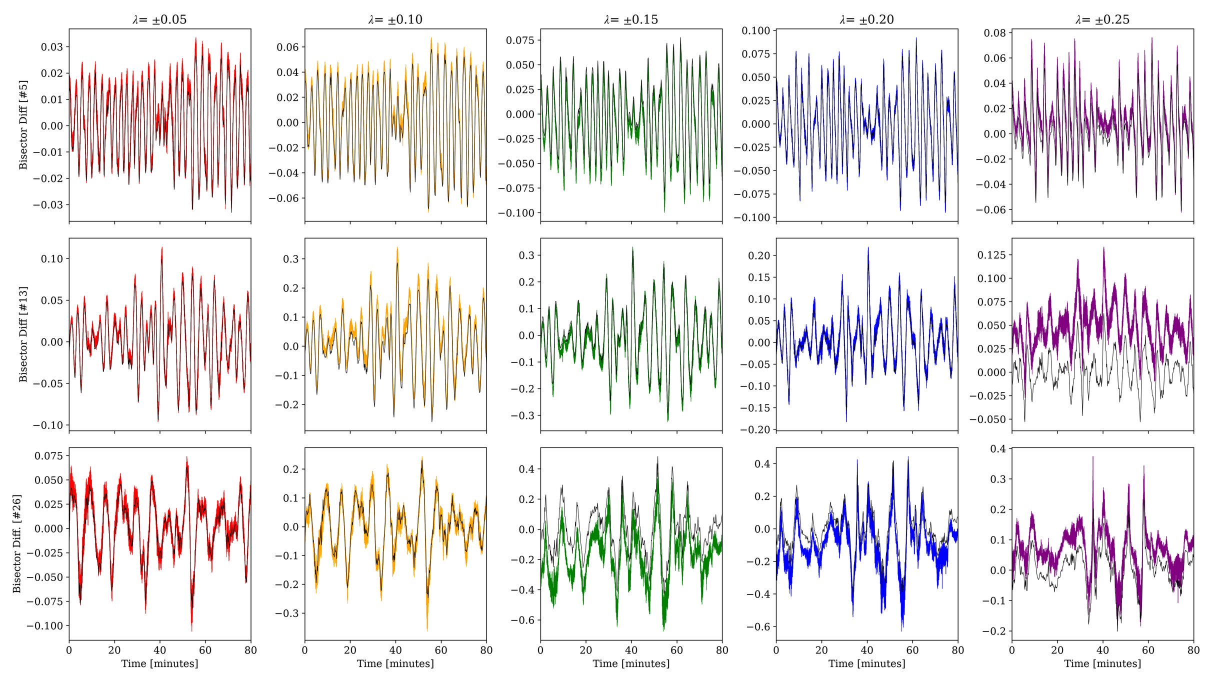

Figure 3: Time series $F(t)$ for 80 minutes, at 5 wavelengths (indicated by colors) and 3 slit positions (top to bottom). The black thin curve in each panel shows the detrended $F(t)$ by subtracting the 1-min smoothed signals.

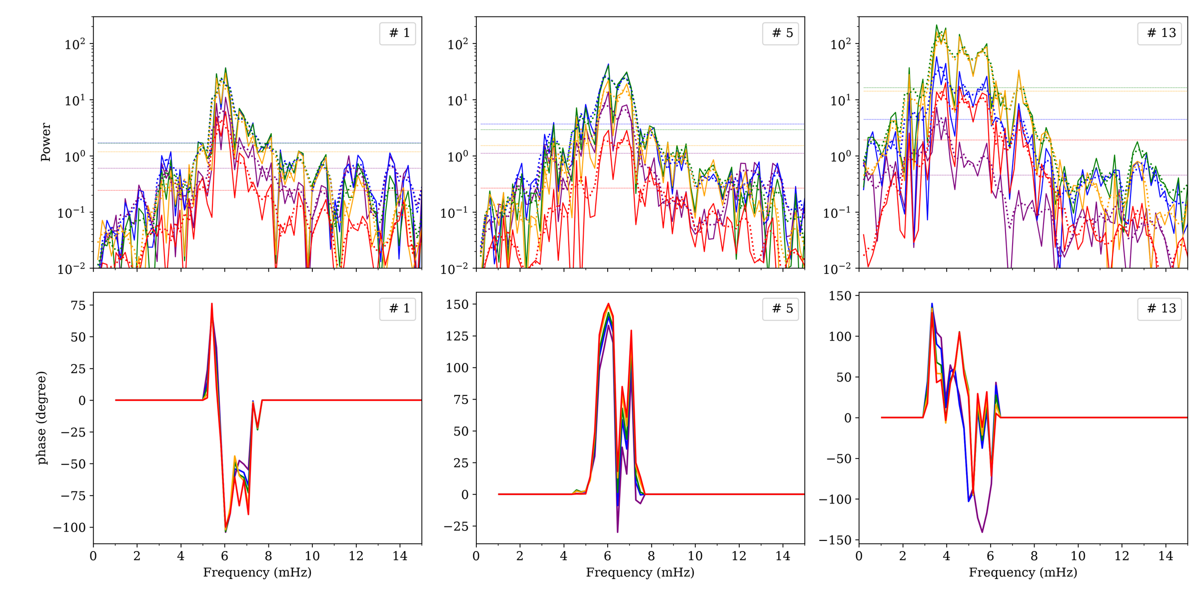

Figure 4: The power (top) and phase (bottom) at 5 wavelengths (colors) and 3 slit positions (left to right). Thin horizontal lines in the top indicate the 95% confidence level. The phase is computed as the power-weighted average across 6 frequencies (i.e., ±0.63mHz), and values are zeroed at frequencies where the power is below the confidence level.

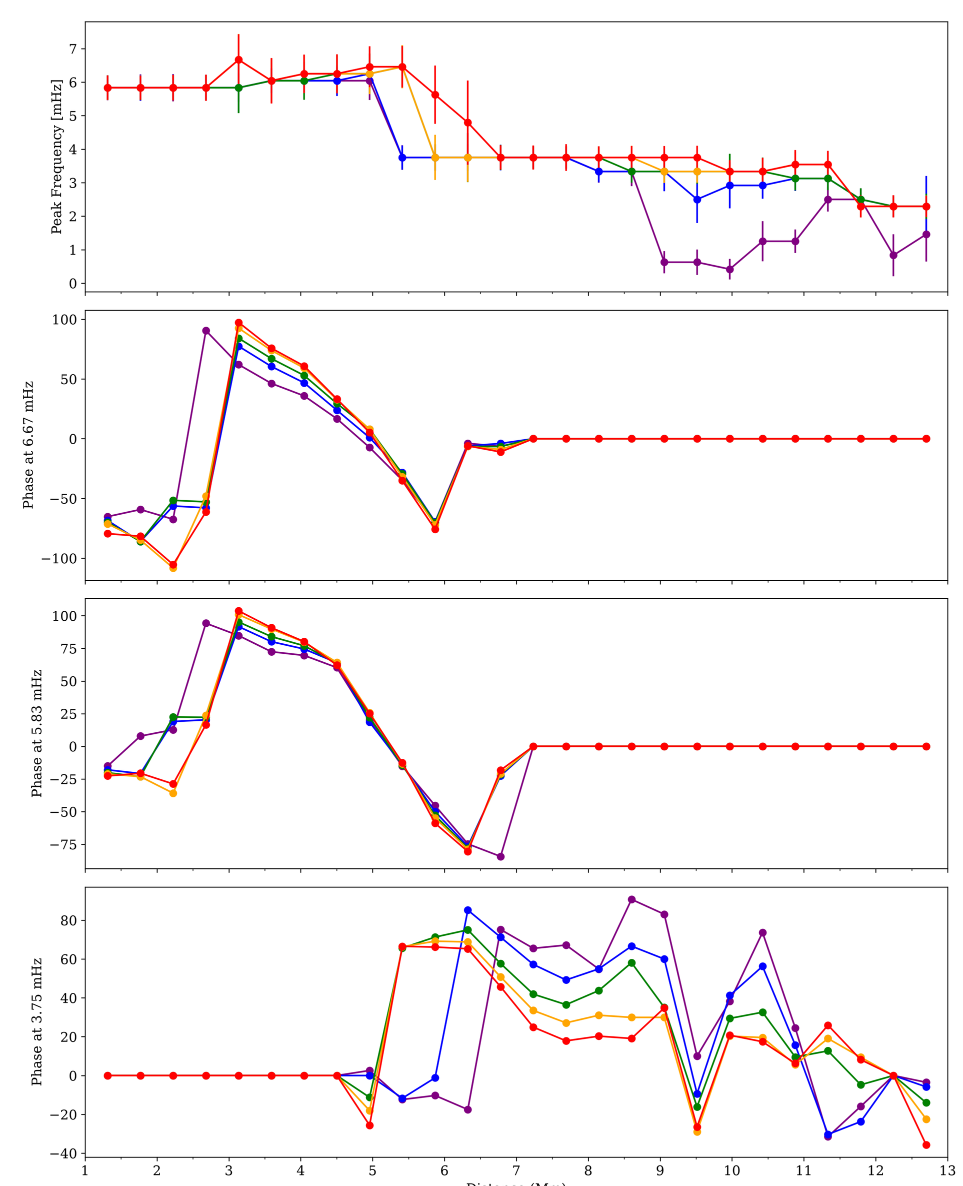

Figure 5: Peak frequencies $f(\lambda, s)$ (top) and phase $\psi(\lambda, s)$ at 3 peak frequencies (bottom) along the slit.

Fig. 5 shows the **shift of dominant frequencies** from the umbra towards the penumbra. In the umbra, the dominant frequency is at 5.8 mHz, and towards the penumbra, the dominant frequency is lower to 3.8 mHz, and with significant powers also at 6.7 mHz. We also find **systematic phase shift** as a function of the wavelength and slit position.

- In the umbra, at 6.7 mHz, the velocity at the line core (0.05 Å; upper chromosphere) is **delayed** with respect to the line wing (0.25 Å lower chromosphere) by $\leq 50°$ at 3 Mm, which is rapidly reduced to zero at 5.5 Mm.
- At 5.8 mHz, the behavior is similar; the velocity at the line core is **delayed** with respect to the line wing by $\leq 25°$ at 3 Mm, reduced to zero at 5.5 Mm.
- At 3.8 mHz, the wavelength & position dependence of the phase shift is observed between 6 Mm and 10 Mm in the penumbra, where the velocity at the line core is **ahead of** the line wing by 25° at 6 Mm, and then increases to 60° at 8 Mm.

These results indicate significant changes of the physical conditions at the position of ∼6 Mm, the edge of the umbra (see Fig. 1).

Results: 25 ms time series

Analysis of the time series of 25 ms cadence & 150 s duration (Fig. 6) shows significant powers at frequency 0.4-0.8 Hz, suggesting 1-2 s oscillations. The dominant frequencies $f(\lambda, s)$ are comparable at different wavelengths, yet exhibit a slight trend of decreasing from the umbra toward the penumbra. We have not found evident wavelength or spatial dependent phase shift at these frequencies. The origin of these variations will be further investigated.

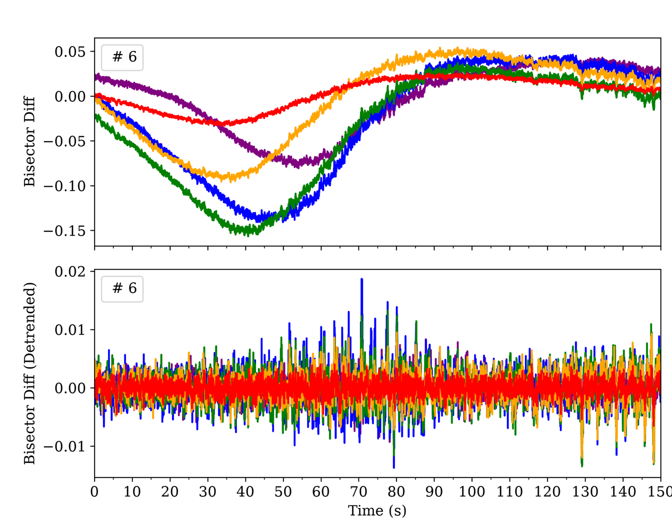

Figure 6: Top: $F(t)$ at 5 wavelengths showing phase-shift of 20 s (or 45° at 6 mHz) over 0.20 Å. Bottom: detrended $F(t)$ by subtracting the 10 s smoothed signals.

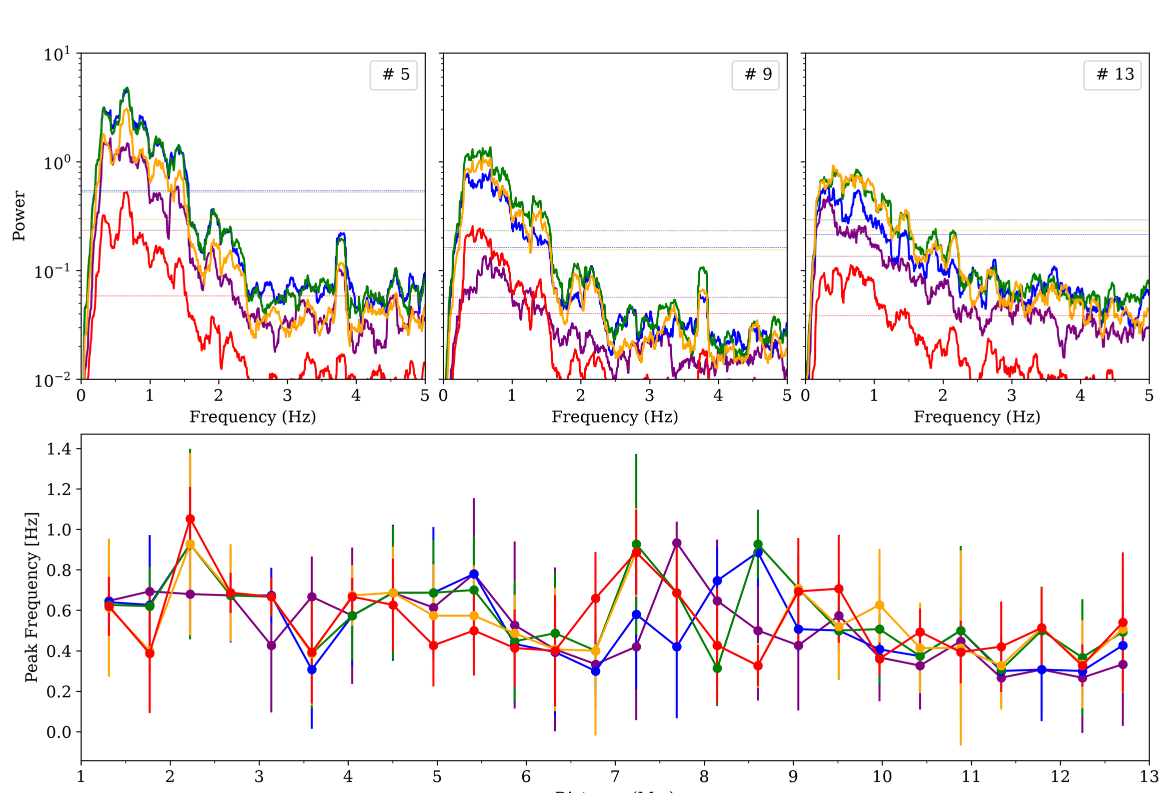

Figure 7: Top: power spectrum at 5 wavelengths and 3 slit positions. Bottom: peak frequency $f(\lambda, s)$ at different wavelengths along the slit.

Conclusion

With DKIST's high-cadence high-resolution spectral observations, **we investigated some properties of magneto-acoustic waves in the low chromosphere of a sunspot**.

Our preliminary analysis reveals **the dominant frequencies (4-8 mHz) and phase shifts at these frequencies, which vary systematically from the lower to upper chromosphere and from the umbra to the penumbra**. These properties reflect the variations of the direction, speed, reflection, and dispersion of waves, and can be used to diagnose the thermodynamic and magnetic structure of the sunspot chromosphere across which waves travel.

The high-cadence (25 ms) observations may also suggest the presence of oscillations at higher frequencies.

References

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