



Multiline Wave Signatures in a Sunspot from Near-ultraviolet SUNRISE III/SUSI Observations

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Abstract

Magnetohydrodynamic waves redistribute energy in magnetic structures of the lower solar atmosphere, yet constraints on how wave power and dominant frequencies are organized above sunspots remain limited, because most studies use only a few well-separated diagnostics. Here, we present multiline wave signatures in a sunspot from near-ultraviolet (near-UV) spectroscopy with the SUNRISE-III UV Spectropolarimeter and Imager (SUSI). We analyse a 2 hr time series of repeated raster scans of a sunspot near disc center in the 327–329 nm spectral window (>100 lines). From these, we select 44 lines that radiative-transfer calculations suggest sample effective formation heights within the umbral core, from the deep photosphere toward the low chromosphere. For each line, we extract line-core intensity and line-of-sight velocity time series using a dedicated multiline fitting routine and compute Morlet wavelet power spectra. The refined global wavelet spectra show that most lines (in both intensity and velocity) are genuinely multifrequency, with a dominant peak and substantial statistically significant power up to 12 mHz. Unsupervised clustering of the normalized spectra groups lines into families with similar spectral shapes and reveals a progression of dominant frequencies from ~ 2 to ~ 10 mHz across the ensemble, for both intensity and velocity (not necessarily in the same lines). This behavior is not reproduced by a simple formation-height ranking, suggesting that uncertainties in the formation-height estimates and line-dependent diagnostic response together shape the ordering. These SUNRISE-III/SUSI observations open a new regime for near-UV multiline wave studies and provide the first systematic characterization of frequency-structured sunspot wave behaviour in this spectral region.

Unified Astronomy Thesaurus concepts: The Sun (1693); Sunspots (1653); Solar oscillations (1515); Magnetohydrodynamics (1964); Solar photosphere (1518); Solar chromosphere (1479)

1. Introduction

Energy transport and heating in the solar atmosphere are believed to be strongly influenced by magnetohydrodynamic (MHD) waves, especially in magnetized regions such as



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networks, plages, pores, and sunspots (e.g., V. M. Nakariakov & E. Verwichte 2005; D. B. Jess et al. 2015, 2023a; C. A. Gilchrist-Millar et al. 2021). In the lower atmosphere, waves are guided by structured magnetic fields and partially converted between different MHD modes when they encounter layers where the Alfvén and sound speeds are comparable (P. S. Cally et al. 1994; P. S. Cally & M. M. Gómez-Míguez 2023). Observationally, this gives rise to a rich spectrum of intensity and line-of-sight (LOS) velocity oscillations whose properties vary with height, position, and magnetic topology (e.g., S. D. T. Grant et al. 2022). Disentangling the roles of atmospheric stratification, magnetic geometry, and mode conversion in shaping the observed oscillatory spectra requires spatially and spectrally well-resolved, multiheight observations spanning the photosphere and chromosphere.

Sunspots provide a natural laboratory for such studies. Their strong coherent magnetic fields form large-scale waveguides, while the sharp contrasts between the umbra, penumbra, and surrounding quiet Sun give rise to a variety of wave phenomena throughout the atmosphere, including umbral flashes, running penumbral waves, and global eigenmodes (T. J. Bogdan 2000; T. J. Bogdan & P. G. Judge 2006; E. Khomenko & M. Collados 2015; S. D. T. Grant et al. 2018). Previous works have used photospheric and chromospheric diagnostics—such as Fe I, Ca II, H α , He I, and molecular CO lines—to explore wave propagation along sunspot magnetic fields, to identify dominant frequencies and eigenmodes, and to infer the presence of resonance cavities (e.g., S. K. Solanki et al. 1996; R. Centeno et al. 2006; D. S. Bloomfield et al. 2007; T. Felipe et al. 2010; S. Krishna Prasad et al. 2015; D. B. Jess et al. 2020; M. Stangalini et al. 2021). However, most of these studies rely on a relatively small set of spectral lines, often separated by several hundred kilometers in formation depth/height, limiting the ability to track how wave properties can reorganize over relatively short height ranges in response to strong stratification and changing magnetic geometry (e.g., rapid variations in density/temperature scale heights, field inclinations, and the local cutoff and transmission conditions).

From a theoretical perspective, the dominant frequencies and wave power are expected to change with height for several reasons. The effective acoustic cutoff frequency depends on temperature and field inclination, so slow magnetoacoustic waves guided along increasingly inclined fields can leak low-frequency wave power into higher layers, while more vertical fields tend to favor higher-frequency propagation (e.g., T. Felipe et al. 2018; S. M. Jefferies et al. 2019). Sharp gradients in atmospheric parameters can form resonance cavities between, for example, the temperature minimum and the transition region, selecting particular frequencies and enhancing their power at specific heights (e.g., T. Felipe 2019; D. B. Jess et al. 2020). Mode conversion near equipartition layers can further redistribute energy between various MHD modes, modifying the observed power spectra with height (H. Schunker & P. S. Cally 2006; P. S. Cally 2007).

An additional complication is that the observed oscillatory signal is filtered not only by the atmospheric structure, but also by the diagnostic properties of the spectral lines used. Different lines respond to different combinations of perturbations—temperature, density, velocity, and magnetic field—through their contribution functions (CFs) and source-function behavior (B. Ruiz Cobo & J. C. del Toro Iniesta 1992;

H. N. Smitha et al. 2023). Lines with strong temperature sensitivity may preferentially highlight thermal oscillations, while lines affected by scattering or non-local thermodynamic equilibrium (NLTE) effects can add complexity due to the MHD signatures being weighted (or filtered) by the radiative properties of the spectral line, even if multiple lines have similar nominal formation heights (G. Cauzzi et al. 2008; J. Leenaarts et al. 2012). Exploiting a large set of diagnostic spectral lines with diverse sensitivities is thus essential for building a more complete picture of wave behavior.

Recent high-resolution studies in the lower solar photosphere have revealed that multiple narrowband frequency components can coexist within the same magnetic structures, and that these are consistent with distinct MHD eigenmodes supported by the local topology (M. Stangalini et al. 2022; D. Calchetti et al. 2023; S. Jafarzadeh et al. 2024). Such results highlight the need for densely sampled, multiheight observations capable of tracking how these multimode wave fields evolve with height and how their relative power is redistributed between photospheric and chromospheric layers. Extending this type of analysis into previously unexplored spectral regimes offers the prospect of identifying additional wave modes and constraining their coupling across heights.

The near-ultraviolet (near-UV) part of the spectrum offers an attractive but historically underinvestigated window for such wave studies. In this spectral region, the solar spectrum is crowded with photospheric and low-chromospheric lines from a range of neutral and ionized species (L. Delbouille et al. 1973). Many of these lines have not previously been exploited, particularly for detailed oscillation diagnostics, largely because of the observational challenges associated with ground-based near-UV spectroscopy. At the same time, the dense distribution of lines in this region provides the potential for a finely sampled height stratification of diagnostics, provided that representative formation heights (or depths relative to a reference atmosphere) can be estimated and that the line profiles can be measured with sufficient spectral and temporal resolution.

Following the two successful earlier flights of the SUNRISE balloon-borne solar observatory in 2009 and 2013 (S. K. Solanki et al. 2010, 2017; P. Barthol et al. 2011), the third flight in 2024 July opened this regime for the first time with high spatial, spectral, and temporal resolution. SUNRISE III carries a 1 m aperture telescope and three polarimetric instruments designed to probe the lower solar atmosphere in seeing-free conditions (A. Korpi-Lagg et al. 2025; S. K. Solanki et al. 2026). The SUNRISE UV Spectropolarimeter and Imager (SUSI) is a slit-based spectropolarimeter operating in the 309–417 nm range, optimized for simultaneous measurements of many near-UV lines with full-Stokes polarimetry and high cadence (A. Feller et al. 2025; F. A. Iglesias et al. 2025).

Here, focus is placed on a single SUSI dataset: a 2 hr time series of a large sunspot near the disk center, observed in the 327–329 nm spectral window. This window contains more than 100 identifiable lines with model-estimated formation heights (referenced to quiet-Sun $\tau_{500\text{ nm}} = 1$), spanning from the deep photosphere to the low chromosphere. For a carefully selected subset of 44 relatively clean lines, the line-core intensity and LOS velocity are extracted as a function of time and position along the slit, enabling a systematic investigation of how wave signatures vary across a dense set of diagnostics and their inferred formation heights inside the sunspot. In this

Letter, only the SUSI Stokes I spectra are used; the polarimetric information will be exploited in future work, once full-Stokes products become available.

The main aim of this Letter is to provide a first observational characterization of multiline wave signatures in a sunspot using the near-UV spectral lines. The analysis concentrates on power spectra of the intensity and LOS velocity in the umbra's central region, where the magnetic field is expected to be relatively vertical and height comparisons are therefore most straightforward.

2. Observations

The data analyzed in this study were obtained during the main science phase of the SUNRISE III flight on 2024 July 14 between 21:40 and 23:39 UTC. SUSI was operated in a small-raster mode on the 327–329 nm spectral window, targeting a large sunspot (NOAA AR 13744) located close to the disk center ($\mu \approx 0.96$). The SUSI spatial sampling is 0.03 px^{-1} , with spectral sampling in this wavelength range of $\sim 8.3 \text{ mÅ px}^{-1}$ (A. Feller et al. 2025). The SUSI slit was positioned such that the raster crossed the center of the umbra, extended across the penumbra, and reached into the surrounding plage and a quieter region, while also crossing a nearby pore. Each raster step covered a field of view of approximately $46''$ along the slit and $\sim 3.5''$ in the scan direction after processing, producing a narrow but spatially resolved strip across the active region. A full raster cycle in the 327–329 nm spectral window was completed in about 39 s, yielding a nearly 2 hr time series with 180 scans. A short gap of 156 s occurs after the first 57 minutes of observations (due to calibrations), but this does not affect the analysis of wave power in the 1–12 mHz range. The gap is linearly interpolated prior to wave analysis.

In this observing program, SUSI recorded full-Stokes spectra in the selected near-UV window, but the present work only makes use of Stokes I . Standard reduction procedures within the SUSI pipeline were applied to the data, including dark and flat-field corrections, wavelength calibration, and correction for instrumental effects. The slit-jaw images, obtained through the SUSI slit-jaw bandpass filter centered at 325.0 nm with an FWHM of 0.9 nm, have been phase-diversity-reconstructed, while the spectral scans have not. In a subsequent postprocessing step, we constructed time-series raster images from the individual slit positions and applied additional corrections for solar rotation, instrumental image/slit rotation (field derotation), and residual image jitter. The reduced dataset can be represented as a 4D cube with axes corresponding to time, position along the slit, scan position across the raster, and wavelength.

The 327–329 nm window contains more than 100 identifiable absorption lines from multiple neutral and ionized species. For the present umbral study, formation heights were estimated at each spatial pixel of a 3D radiative-MHD MURaM sunspot simulation (A. Vögler et al. 2005; M. Rempel 2012; see also H. N. Smith et al. 2023) using two complementary radiative-transfer approaches. First, we computed an Eddington–Barbier (EB; R. J. Rutten 2021) height-of-formation proxy as the geometric height where $\tau_\lambda = 1$ for each wavelength sample. Second, for a smaller set of selected lines, we computed CFs to the emergent intensity. Because CF calculations are computationally expensive, they were performed only for a subset of lines, whereas the EB

estimate is available for every wavelength sample across the window. While the two methods generally agree, modest line-dependent differences are expected, because EB is an approximation, whereas CF heights incorporate the full opacity and source-function weighting of the line formation. All radiative-transfer calculations in this work were performed assuming LTE using the RH code (H. Uitenbroek 2001; T. M. D. Pereira & H. Uitenbroek 2015), with atomic line parameters taken from the Kurucz line list (R. L. Kurucz & B. Bell 1995).

To obtain representative umbral core formation heights, we accounted for the SUSI spatial point-spread function (PSF) and averaged over a small umbral core region. For the CF method, the CFs in a 5×5 pixel region around the umbral center were convolved with the SUSI spatial PSF, averaged over the region, and the weighted-mean height of the resulting mean CF was adopted for each line. For the EB method, each wavelength-dependent EB height map was convolved with the same spatial PSF and then averaged over the same 5×5 pixel umbral core region, yielding one representative EB height per wavelength sample. Both height scales are referenced to the quiet-Sun $\tau_{500 \text{ nm}} = 1$ level, so the inferred umbral formation heights are mostly negative, reflecting the Wilson depression of the umbral $\tau \approx 1$ surface by several hundred kilometers (e.g., S. K. Solanki 2003; B. Lötjen et al. 2018, 2020); the diagnostics nevertheless sample a substantial range of layers within the umbral photosphere and toward the low chromosphere. In the wave analysis below, we use the CF-based heights, while the EB heights are included for completeness over the full wavelength range.

In this Letter, we adopt the formation-height ranking derived from the 3D sunspot model as a plausible strong-field reference for the umbral conditions studied here, and we use the CF-based heights for the wave analysis. We emphasize, however, that the resulting formation heights remain model-dependent and should be regarded mainly as approximate proxies for relative ordering. A more detailed comparison of the formation-height estimates obtained from quiet-Sun (FALC), plage (FALP), and sunspot model atmospheres, as well as their implications for different magnetic environments (the umbra, pore, and surroundings), are presented in S. Jafarzadeh et al. (2026a).

An overview of the spectral content and the associated diagnostics is shown in Figure 1. The top panel displays a sample SUSI spectrum recorded at the beginning of the time series, highlighting the dense forest of absorption features in the 327–329 nm window. The second panel shows the average spectrum along the slit versus wavelength, illustrating the overall contrast and line depths. The third panel presents a corresponding high-spectral-resolution solar atlas spectrum (C. E. Moore et al. 1966), where individual lines have been identified, labeled, and color-coded: known blended lines are marked in red, the subset of 44 relatively clean lines selected for the wave analysis is shown in green, and the remaining identified lines are plotted in black. The bottom panel shows the EB formation heights across the full spectral window (solid curve), with the CF-based heights overplotted as orange bars at a selected subset of lines for which CFs were computed.

These observational products, together with the line identification and selection indicated in the atlas panel, form the basis for the multiline wave analysis presented in the following section, where the extraction of line-core quantities and the construction of the time-series diagnostics are detailed.

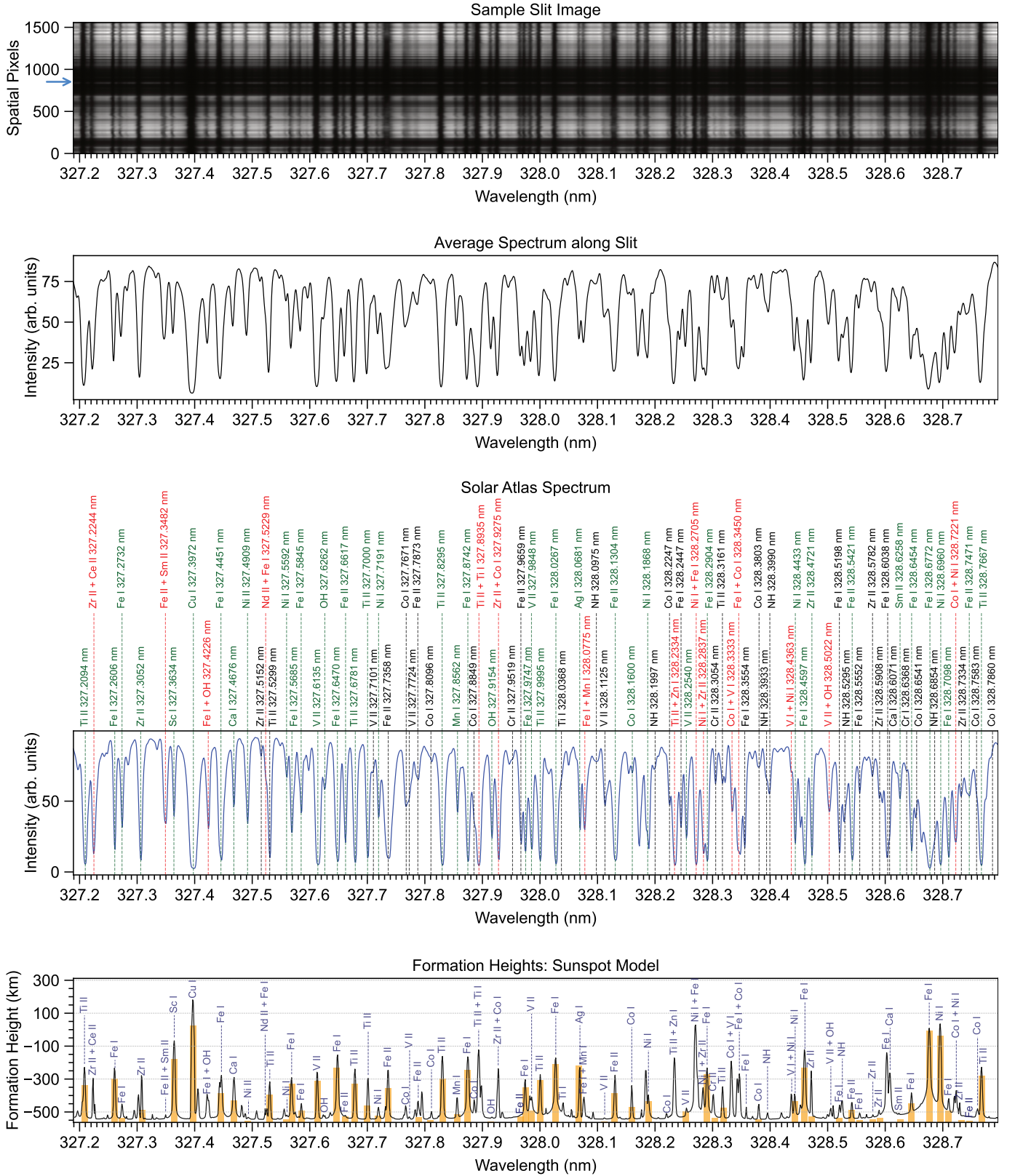


Figure 1. Overview of the near-UV SUSI diagnostics used in this study. Top: sample SUSI spectrum in the 327–329 nm window at the beginning of the time series; the blue arrow to the left of the panel marks the slit position (y-pixel) used for the umbral core analysis. Second panel: the corresponding average spectrum along the slit, displayed as a function of wavelength, to illustrate the overall contrast and line depths. Third panel: high-resolution solar atlas spectrum for the same wavelength range, with individual lines identified and labeled; known blended lines are marked in red, the 44 relatively unblended lines selected for the wave analysis are highlighted in green, and the remaining identified lines are shown in black. Bottom: EB formation heights (solid curve) across the full spectral window, referenced to the quiet-Sun $\tau_{500 \text{ nm}} = 1$ level, with CF heights shown as orange bars for the lines with computed CFs.

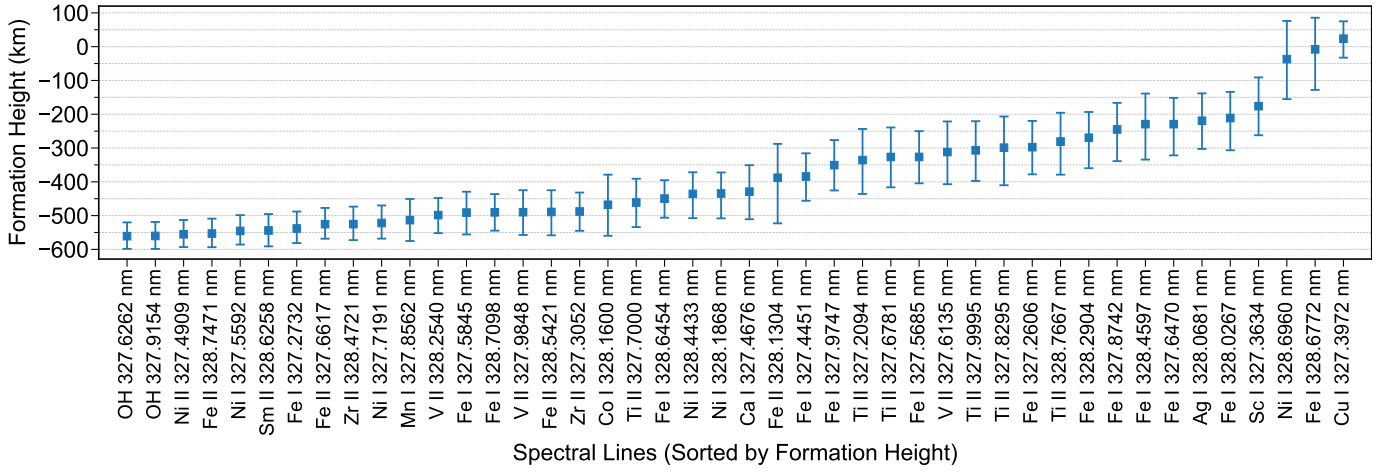


Figure 2. Effective formation-height ranking for the 44 near-UV spectral lines used in this Letter. The plotted symbols correspond to weighted-mean line-core formation heights derived from CFs in a representative 3D radiative-MHD sunspot model, after accounting for the SUSI spatial PSF and averaging over a small umbral core region. The asymmetric vertical bars show the 16th–84th percentile range of each line’s CF, illustrating the finite vertical extent of the diagnostic. Heights are measured relative to the quiet-Sun $\tau_{500\text{ nm}} = 1$ level. As a result, most lines appear at negative geometric heights in the umbra, while the relative ranking still spans from deeper photospheric layers toward diagnostics approaching the low chromosphere.

3. Analysis and Results

The aim of this work is to quantify how wave signatures vary across the ensemble of near-UV diagnostics sampling a sunspot atmosphere, by exploiting the dense set of spectral lines in the SUSI 327–329 nm window. From the full set of identified lines, we focus on the subset of 44 relatively unblended lines with clear, well-defined absorption cores (highlighted in green in Figure 1). These lines were selected based on a combination of the line depth, isolation from known blends, and careful inspection of their umbral profiles, excluding lines that show peculiar or highly dynamic behavior at the analysis location or strongly skewed cores suggestive of potential blends. Effective line-core formation heights for this subset, obtained from the CFs in the 3D sunspot model (including the SUSI spatial PSF and a small umbral core average; Section 2), are used primarily to provide a first-order stratification and, most importantly, a relative ranking of the diagnostics in terms of sampled height (see Figure 2). In addition to the weighted-mean height, we also show the finite vertical extent of each line’s CF through its 16th–84th percentile range, to illustrate that the diagnostics sample a nonnegligible height range that can be asymmetric and overlap substantially with neighboring lines, rather than a single geometric layer.

In what follows, we employ this ranking to stack and compare wave diagnostics as a function of inferred formation height (noting that heights are referenced to the quiet-Sun $\tau_{500\text{ nm}} = 1$ level and are therefore mostly negative in the umbra), while recognizing that the absolute height values are model-dependent and subject to uncertainties that will need to be further investigated, and possibly refined, in future modeling work.

3.1. Multiline Adaptive Voigt Fitting and Line-core Quantities

To extract the line-core intensity and LOS velocity for each of the selected lines, we employ our dedicated Python-based multiline fitting routine (LineFit; S. Jafarzadeh et al. 2026b), which models each spectral line with a Voigt profile. The code is designed to work on 1D spectra along the slit, but can be applied to all spatial pixels and time steps in a parallelized manner.

For each spectrum, the code first multiplies the intensity profile by -1 (so absorption minima become peaks) and uses a standard peak-finding algorithm to locate absorption minima in the vicinity of the reference wavelengths for the lines of interest. The detected peaks provide initial estimates of the central wavelength, line depth, and FWHM. Around each candidate line center, the algorithm defines a small local fitting window and performs a nonlinear least-squares fit of a Voigt function to the observed spectrum. The continuum/baseline level is therefore treated locally for each fitted line, rather than as a single value across the full 327–329 nm spectral window, which is essential in this dense near-UV region where neighboring lines and local profile asymmetries are common. The Voigt profile combines Gaussian and Lorentzian functions, allowing us to account, in an effective way, for thermal, instrumental, and pressure broadening (for saturated lines).

A key feature of the code is its adaptive fitting strategy: the initial line depth and FWHM estimates are used to set line-specific parameter bounds and, where needed, to adjust the fitting window and weighting. This allows the same routine to robustly fit many lines simultaneously, despite their differing depths, widths, and profile shapes, and helps to avoid unphysical broadening or spurious shifts for weak or blended lines.

The fitting is performed iteratively. After an initial fit, simultaneously to all selected lines, the resulting line centers and widths are used as updated initial guesses for a second fitting round. This process is repeated until the change in the total residual (summed over all fitted lines) and in the individual line centers falls below a chosen convergence threshold, or until a maximum number of iterations is reached. We also impose moderate bounds on the allowed shifts and widths, to prevent the fits from drifting to unphysical solutions in noisy profiles.

For each line, the final fit provides: (1) the best-fit central wavelength, λ_{core} ; (2) the line-core intensity, I_{core} , taken as the fitted line-core intensity evaluated at λ_{core} ; and (3) an associated LOS velocity, $v_{\text{LOS}} = c \frac{\lambda_{\text{core}} - \lambda_0}{\lambda_0}$, where λ_0 is the reference wavelength and c is the speed of light.

The procedure yields subpixel-accurate line centers and robust line-core intensities and LOS velocities for all 44 lines

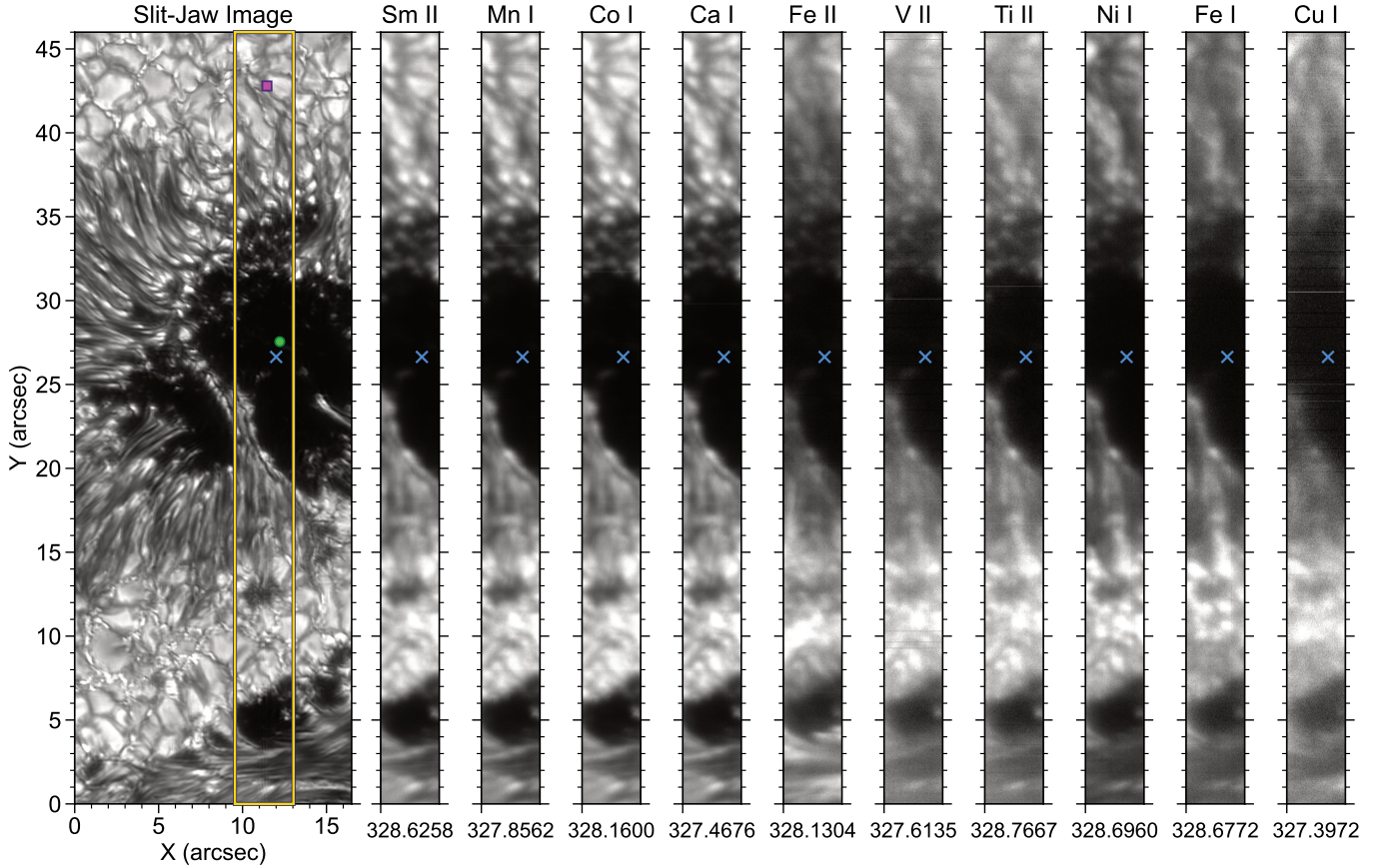


Figure 3. Context for the umbral analysis region. Left: SUSI slit-jaw image showing the sunspot and its surroundings at a (near-)continuum position. The yellow solid line marks the small-raster-scan area, and the blue cross indicates the location in the central umbra used for the time-series analysis. The filled magenta square marks the additional weak-field reference pixel outside the umbra, while the filled green circle marks the secondary umbral core pixel analyzed in Appendix B. Right: example line-core intensity maps for a subset of the selected near-UV lines, ordered from the deep photosphere to the low chromosphere (left to right), illustrating how the same spatial region is simultaneously sampled at different effective heights. The spectral lines' wavelengths (in nanometers) are indicated below each raster image.

at each time step and spatial position. In this Letter, we focus on a small 3×3 pixel region centered on the umbral core, where the magnetic field is expected to be relatively vertical and height comparisons are therefore most straightforward. For this region, we first average the Stokes I spectra over the 3×3 pixels to improve the signal-to-noise ratio, then apply the line-fitting procedure to the binned profiles. The analysis location is close to the umbral center, where horizontal gradients are weak, so this spatial binning does not significantly smear the underlying structure. This yields time series of $I_{\text{core}}(t)$ and $v_{\text{LOS}}(t)$ for each spectral line. An example of the umbral analysis location and its surroundings is shown in Figure 3, displaying the SUSI slit-jaw image with the analysis region marked, together with representative intensity maps for a subset of the selected lines. Please note that the difference in sharpness between the slit-jaw image and the spectral scans is because the former has been phase-diversity-reconstructed while the latter have not.

3.2. Wavelet-based Power Spectra

To characterize the wave content of the line-core time series, we use the wavelet analysis framework implemented in the `WaLSAtools`²⁵ library (S. Jafarzadeh et al. 2025a, 2025b). For each spectral line, and for both $I_{\text{core}}(t)$ and $v_{\text{LOS}}(t)$, we

compute the Morlet wavelet transform and the associated wavelet power spectrum as a function of time and frequency. Following standard practice, we remove a linear trend from each time series before analysis and apodize the signal using a Tukey window with a 10% taper. In addition, we suppress very-low-frequency components ($\nu \lesssim 2$ mHz), which mainly reflect slow background evolution rather than the wave dynamics of interest here. This is done via wavelet-based filtering: we reconstruct a filtered version of each time series using the inverse wavelet transform, while retaining only coefficients with $\nu > 2$ mHz (the `recon` routine in `WaLSAtools`), and perform the subsequent power analysis on the filtered signals. Representative examples of these time series are shown in Appendix A.

Significance levels are estimated from 1000 randomized surrogate signals, and we define the cone of influence (COI) to identify the regions of each wavelet spectrum affected by edge effects. To obtain a compact measure of the frequency distribution of power, we compute the refined global wavelet spectrum (RGWS) for each time series. The RGWS is defined as the time-integrated wavelet power as a function of frequency, excluding regions affected by the COI and retaining only those frequencies where the local power exceeds the 95% confidence level (S. Jafarzadeh et al. 2025a). This yields a 1D spectrum that captures the dominant oscillatory power while reducing sensitivity to edge artifacts and to fluctuations that do

²⁵ <https://github.com/WaLSAteam/WaLSAtools>

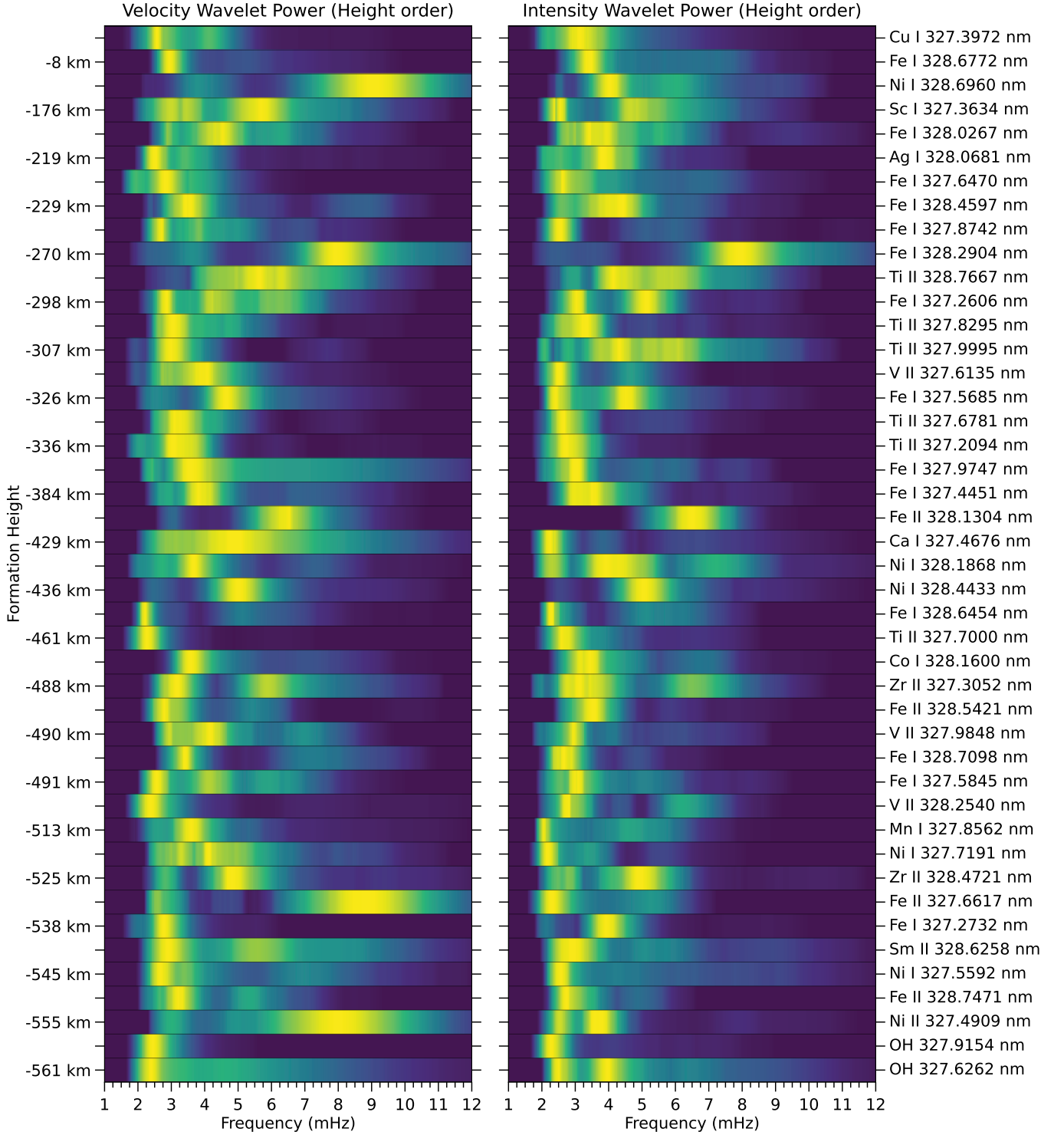


Figure 4. Stacked RGWS for the 44 selected near-UV lines in the umbral core, ordered by their effective line-core formation heights. Left: normalized RGWS for LOS velocity. Right: normalized RGWS for line-core intensity. In each panel, the horizontal axis is frequency, the vertical axis is the effective line-core formation height from the sunspot model (with the corresponding spectral lines labeled on the right), and the color scale shows the RGWS power normalized by the maximum of each individual spectrum.

not pass the adopted confidence threshold. We verified that lowering the threshold to 90% does not change the main qualitative results, but mainly introduces weaker and noisier additional features. The resulting spectra are generally smooth and show excellent consistency with classical fast-Fourier-transform power spectra, while providing better localizations of transient and quasiperiodic behaviors.

For the umbral core region, this procedure yields, for each of the 44 lines, two RGWS: one for intensity and one for LOS velocity. To enable a meaningful comparison across diagnostics with different absolute power levels, each RGWS is normalized by its own maximum value. We then stack the spectra into two 2D diagrams (one for the LOS velocity and one for the intensity), with frequency on the horizontal axis

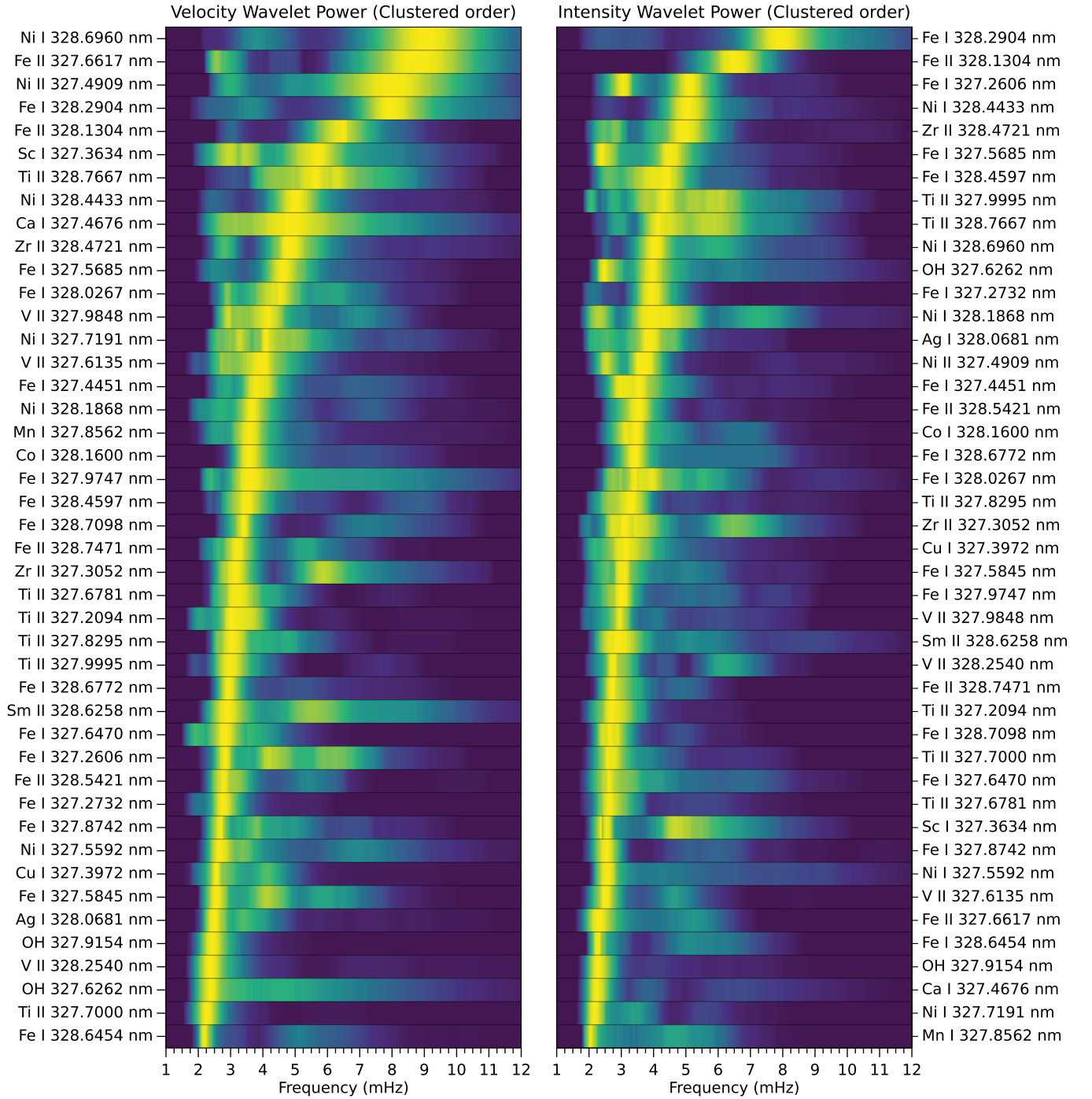


Figure 5. The same RGWS as in Figure 4, but reordered using hierarchical clustering of the normalized RGWS profiles. Left: LOS velocity. Right: line-core intensity. In each panel, the rows correspond to individual spectral lines, reordered so that spectra with similar overall power-distribution shapes are displayed together, with the resulting groups arranged from lower- to higher-characteristic-frequency content for visual comparison. This height-independent reordering highlights differences between intensity- and velocity-based wave signatures.

and the vertical axis ordered by the estimated line-core formation height derived from the sunspot model atmosphere. The resulting height-ordered RGWS maps are shown in Figure 4; the corresponding spectral lines are labeled along the right-hand side, and the color scale represents the normalized power. This model-based ordering is used as a geometrical proxy to explore possible trends with height, while recognizing that the absolute values, and in some cases the relative rankings of individual lines, remain model-dependent or uncertain.

We note that this normalization removes information about absolute power variations between lines, which may carry physical meaning (e.g., amplitude scaling and energy flux estimates). A quantitative interpretation of absolute power, however, requires better-constrained formation heights and atmospheric parameters, and is therefore deferred to future work using full-Stokes inversions.

Figure 4 summarizes how the distribution of oscillatory power varies across the ensemble of near-UV diagnostics and highlights differences between intensity- and velocity-based

signals. Rather than a single preferred band, the individual spectra show several significant power enhancements across the frequency range of 2–12 mHz: some lines display a single dominant peak, others show enhanced power at two or more distinct frequencies, and the locations of the main peaks change from line to line. The apparent “jumps” in the dominant frequency between neighboring lines therefore point to a genuinely diverse set of frequency responses, rather than a simple monotonic trend with the model-based height ordering. We emphasize that the occurrence of statistically significant power up to ~ 8 –10 mHz in some diagnostics is an empirical property of these RGWS; interpreting such components in terms of cutoff behavior, resonance, or specific mode content is deferred to follow-up work with improved height calibration and full-Stokes constraints.

To obtain a complementary view that does not rely on the model height scale, we also applied an unsupervised machine learning clustering analysis to the RGWS. Specifically, we used hierarchical agglomerative clustering (cosine distance and average linkage; F. Murtagh & P. Contreras 2012) primarily as a shape-based reordering method for the normalized power-versus-frequency profiles in the 1–12 mHz range, separately for LOS velocity and for intensity. In practice, the clustering groups spectra according to the similarity of their overall power-distribution shapes, after which the resulting groups are arranged from lower- to higher-characteristic-frequency content for display. This provides a compact, height-independent organization of the multi-peaked spectra without imposing any prior assumptions about formation height. We verified that this reordered organization is robust to the normalization choice: repeating the clustering on unnormalized RGWS yields essentially the same qualitative spectral grouping and line ordering.

The clustering-based reordering is visualized in Figure 5, where the same RGWS are now displayed according to the similarity of their overall power-distribution shapes. For visual clarity, the resulting groups are arranged from lower- to higher-characteristic-frequency content, so that the reordered stacks provide a convenient progression across the ensemble. Because many diagnostics display multiple significant peaks, this approach is not equivalent to sorting by the dominant peak alone: spectra are first grouped by their overall multi-peaked shape (e.g., the presence, absence, and relative strength of secondary bands), and the final display order is then chosen to provide an intuitive low-to-high-frequency progression. This height-independent organization highlights that similar multi-peaked spectral shapes recur across the ensemble, and that intensity and velocity organize into somewhat different families.

The stacked RGWS show that the umbral oscillations are genuinely multifrequency and that, across the ensemble of near-UV lines, the dominant power peak spans a broad range of frequencies (roughly ~ 2 –10 mHz). This spread is most readily seen in the cluster-ordered view, which provides a height-independent organization of the same spectra by similarity of their power-distribution shapes. At this stage, however, we cannot yet cleanly separate the roles of uncertain formation heights and line-specific radiative sensitivities in shaping the line-to-line differences.

4. Conclusions

In this Letter, we have presented the first systematic multiline study of sunspot wave signatures in the near-UV, using spectral lines observed by SUNRISE III/SUSI in the 327–329 nm window. Exploiting a dense set of diagnostics, we extracted line-core intensity and LOS velocity time series for 44 carefully selected, relatively clean lines (excluding profiles with peculiar/highly dynamic umbral behavior or strongly skewed cores suggestive of potential blends) and analyzed their oscillatory properties in a small umbral core region. Subpixel line-core measurements obtained from an adaptive Voigt-fitting routine were combined with Morlet wavelet analysis to construct RGWS that summarize the frequency content of the oscillations across the ensemble of near-UV lines. By construction, the RGWS retain power only outside the COI and above the 95% confidence level, so power at multiple frequencies—including features substantially weaker than the absolute maximum—represents statistically significant components of the signal. Previous studies have shown that such weaker components, when isolated through appropriate frequency filtering or advanced time–frequency analysis, can correspond to physically meaningful MHD wave modes rather than noise (e.g., D. B. Jess et al. 2017; M. Stangalini et al. 2022; S. Jafarzadeh et al. 2024).

The RGWS diagrams reveal that the umbral oscillations sampled by these diagnostics are intrinsically multifrequency. Many lines display several significant power enhancements between ~ 2 and 12 mHz, and the locations of their strongest peaks vary from line to line. When the spectra are ordered using model-based estimates of line-core formation height, no simple monotonic trend emerges whereby a single frequency band gradually replaces another with increasing height. Instead, low-, mid-, and high-frequency power enhancements are mixed throughout the set of diagnostics. Consistently, we find no clear ordering when grouping the spectra by basic line properties, such as line depth or simple measures of CF width, indicating that these simple proxies do not isolate the frequency progression. This behavior could indicate that: (i) the assumed height scale does not fully capture the true ordering of the line-formation layers; or (ii) line-dependent diagnostic responses (e.g., differing sensitivities to temperature, velocity, and density, as well as varying degrees of scattering) modulate how a common underlying wave field is expressed in each observable. A further contributor may also be the uncertainties in atomic line parameters (e.g., oscillator strengths and damping constants) in the near-UV, which can propagate into radiative-transfer-based height estimates and response functions. Because CFs depend on both opacity and the source function, scattering-sensitive lines (i.e., affected by NLTE radiative transfer) can introduce line-dependent biases in the inferred formation heights when these are estimated under LTE assumptions, in addition to producing different diagnostic responses to the same underlying perturbations (e.g., G. Cauzzi et al. 2008; J. Leenaarts et al. 2012). Additional uncertainty may arise from blends that become important in the umbra but are not obvious from quiet-Sun atlas spectra; while we excluded lines with visually suspicious umbral profiles, subtle blends may still affect some diagnostics and their effective formation heights. At this stage, the analysis does not allow these effects to be cleanly disentangled, but it does show that a simple “one dominant frequency per height”

picture is inadequate; the more robust conclusion is that different near-UV diagnostics respond in systematically different ways to the same sunspot oscillations. At the same time, the presence of multiple significant peaks does not by itself establish harmonic relationships. The observed peak spacings are not consistent with a simple harmonic sequence, and demonstrating harmonics or resonant-cavity modes would in any case require additional constraints, such as phase relations, spatial mode structure, and multiheight coherence analyses (see, e.g., T. Felipe et al. 2020; D. B. Jess et al. 2020, 2021b; R. Sych et al. 2024; R. Sych & Y. Yan 2025), which are beyond the scope of the present Letter.

Multifrequency umbral spectra—typically a dominant ~ 3 – 6 mHz band with secondary peaks that can extend to ~ 8 – 12 mHz—have been reported in a range of single-line observations (A. Raja Bayanna et al. 2014; T. Felipe et al. 2019; D. Calchetti et al. 2023; M. Berretti et al. 2025). Such multipeak spectra have, in particular, been interpreted as signatures of multiple coexisting sunspot eigenmodes in recent analyses (e.g., M. Stangalini et al. 2022). Our results are consistent with this overall frequency landscape, but the key advance here is the multiline diagnostic mapping: dozens of near-UV lines provide simultaneous observables with different radiative sensitivities (to velocity, temperature, and opacity/source-function variations) and different effective formation depths, offering much richer constraints on how the multipeak spectra manifest themselves across the photosphere and the low chromosphere than are possible with one or two lines. A complementary multiline result has also recently been reported from the ground. S. D. T. Grant et al. (2026, in preparation) analyze 21 spectral lines observed with the FRANCIS fiber-fed integral field unit (D. B. Jess et al. 2023b) at the Dunn Solar Telescope in the 580.7–597.3 nm range. They likewise find that the dominant oscillation peaks in the line-core LOS velocity time series vary across the diagnostics in the umbral core, with significant power spanning 3–12 mHz, despite the different instrument, spectral window, and velocity-estimation methodologies used compared to the present work.

We also find that intensity- and velocity-based diagnostics can display markedly different spectral shapes for the same nominal line. Some diagnostics show broadly similar dominant peaks in both I_{core} and v_{LOS} , while others exhibit pronounced power at certain frequencies in one quantity but not the other. Rather than a single systematic pattern, the near-UV lines sample a diverse mix of responses, again pointing to a combination of physical wave properties and line-formation effects. In general, v_{LOS} is most directly sensitive to Doppler shifts, whereas I_{core} reflects a combination of opacity and source-function variations and can therefore be more sensitive to thermodynamic perturbations (while still retaining some sensitivity to velocity through line-shape changes). Scattering-dominated lines can further weight the signal nonlocally, potentially enhancing or suppressing specific frequency components compared to more LTE-like lines. In addition, in many lines, Doppler-based velocities often have substantial sensitivity contributions from the line flanks, whereas the line-core intensity is most sensitive close to the line-core formation region; thus, the two observables can sample different height ranges even within the same line. These contrasts underscore that intensity and velocity diagnostics need not trace the same wave components, even within the same line, because they sample different combinations of perturbations through line

formation. A full exploitation of these diagnostic differences will require more detailed radiative-transfer modeling than attempted here.

To further probe the diversity of frequency responses, we complemented the height-ordered stacks with an unsupervised clustering analysis of the RGWS. The cluster-ordered diagrams group lines with similar multi peaked power distributions and, when arranged by characteristic frequency, reveal families of diagnostics in which the dominant power shifts progressively from ~ 2 to ~ 10 mHz across the ensemble, for both intensity and velocity (though not necessarily in the same lines). These frequency-based groupings do not map one-to-one onto the model height ordering, which reinforces the need for better-constrained formation heights and more detailed radiative-transfer calculations, including a careful treatment of blends that become important in cool umbral conditions. At the same time, the clustering results strengthen the conclusion that the multifrequency structure seen in the near-UV diagnostics is an intrinsic property of the way these lines sample the sunspot atmosphere, rather than an artifact of a particular choice of height scale. As an additional validation, repeating the same analysis for several random pixels outside the umbra does not reproduce the frequency progression seen in the umbral core, whereas sampling a few nearby umbral core locations yields qualitatively similar behavior. This supports the interpretation that the observed frequency-structured organization is intrinsic to the sunspot umbra rather than a systematic instrumental or calibration artifact. Examples of the corresponding RGWS stacks for an additional umbral core pixel and for a representative weak-field reference location outside the umbra are shown in Appendix B.

The present work is intentionally conservative, focusing on a single umbral location and on robust RGWS diagnostics. This spatial location was chosen because the magnetic field there is expected to be strong and relatively vertical compared with the surrounding regions, so that LOS velocities and intensities provide the cleanest practical proxy for vertically stacked diagnostics and minimize geometric complications. However, we note that even in the umbral core, small residual inclinations and height-dependent expansion can cause different lines to sample oscillations along slightly different field lines, potentially contributing to line-to-line differences. For the relatively small inclinations expected in the umbral core, and over the limited height range sampled here, such effects are not expected to qualitatively alter the main wave-signature organization discussed in this Letter, although a quantitative inclination- and cutoff-based interpretation is deferred to future work, once full-Stokes inversions and more rigorous height-sensitivity constraints become available. This Letter provides a first survey of how oscillatory signatures appear across a large set of near-UV lines in a sunspot, laying the groundwork for more detailed mode identification and energy-budget studies. In future work, we will extend this analysis systematically to multiple positions within and around the sunspot, and complement the RGWS diagnostics with phase and coherence measurements between neighboring lines, to probe propagation, reflection, and possible resonance signatures. A key next step is to better constrain the height sensitivity of the SUSI near-UV diagnostics using detailed radiative-transfer response functions for velocity and temperature, complemented by multiline (full-Stokes) inversions (e.g., T. L. Riethmüller & S. K. Solanki 2019;

J. Hölken et al. 2026), once polarimetric products become available. Response functions provide a direct line-by-line measure of where each diagnostic is most sensitive (and over what height range), while inversions can recover stratified atmospheric parameters, including the magnetic field strength and inclination variations needed for a fuller interpretation of the observed frequency structure in terms of specific MHD modes and propagation paths. Complementary 3D radiative-MHD simulations can then be used for forward modeling to test these interpretations and to link the observed multifrequency spectra to wave modes, resonance structures, and energy-transport pathways.

More advanced data-driven methods (e.g., proper orthogonal decomposition, empirical mode decomposition with Hilbert-based diagnostics, and synchrosqueezing transforms) will also be explored to isolate recurrent patterns and candidate modes more quantitatively. Ultimately, combining the near-UV diagnostics with SCIP (Y. Katsukawa et al. 2026) and TuMag (J. C. del Toro Iniesta et al. 2025) observations will extend the coverage across the photosphere–chromosphere system and enable a more complete multiheight interpretation.

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Appendix A

Representative LOS Velocity and Line-core Intensity Time Series

To illustrate the temporal behavior underlying the wavelet-based analysis, Figure 6 shows representative LOS velocity and line-core intensity time series for five selected lines in the primary umbral core location. The signals shown are the same detrended, apodized, and low-frequency-filtered time series used in the wavelet analysis

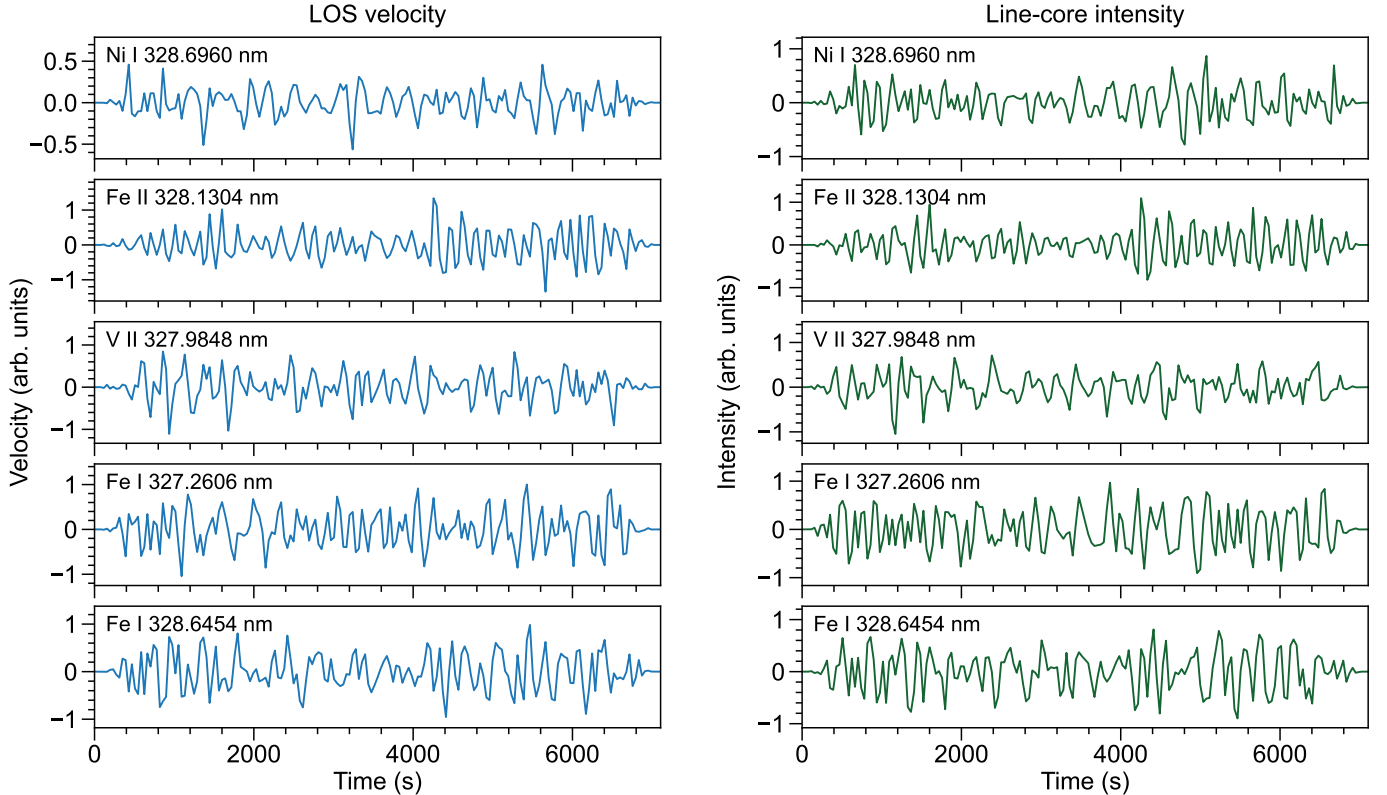


Figure 6. Representative line-core intensity and LOS velocity time series for a small subset of the analyzed near-UV lines in the primary umbral core location.

described in Section 3.2. Because this preprocessing is designed to isolate the oscillatory content of interest, it can also affect the absolute amplitude scale to some extent; the plotted amplitudes are therefore shown in arbitrary units. This does not affect either the analysis or its interpretation in the present work, since our focus is on the frequency structure and relative organization of the oscillatory signals, rather than on absolute amplitudes or absolute power comparisons between lines. These examples are included to illustrate the temporal behavior, intermittency, and relative visibility of different oscillatory components.

Appendix B

Additional RGWS Examples: A Weak-field Reference Location outside the Umbra and a Secondary Umbral Location

To illustrate that the frequency-structured organization reported in the main text—in particular, the frequency progression revealed by the clustering-based reordering in Figure 5—is characteristic of the umbra, we repeated the same RGWS and hierarchical clustering analysis for: (1) a weak-field reference pixel outside the umbra within the raster field of

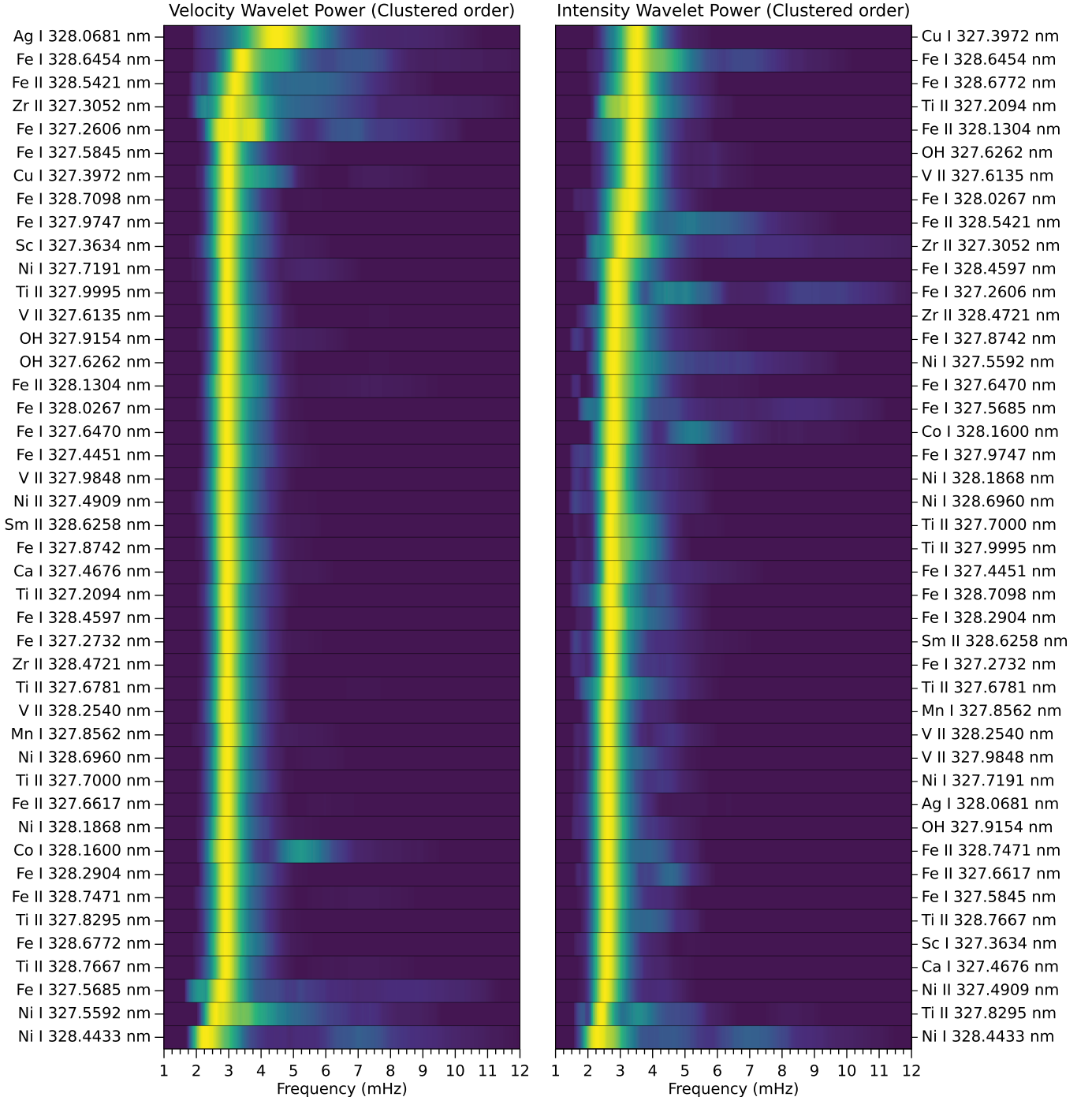


Figure 7. Cluster-ordered, normalized RGWS for a representative weak-field reference pixel outside the umbra, marked by a filled magenta square in Figure 3, shown in the same format as Figure 5. Left: LOS velocity. Right: line-core intensity. The rows correspond to individual spectral lines, reordered using hierarchical clustering of the normalized RGWS profiles and arranged by dominant-frequency content.

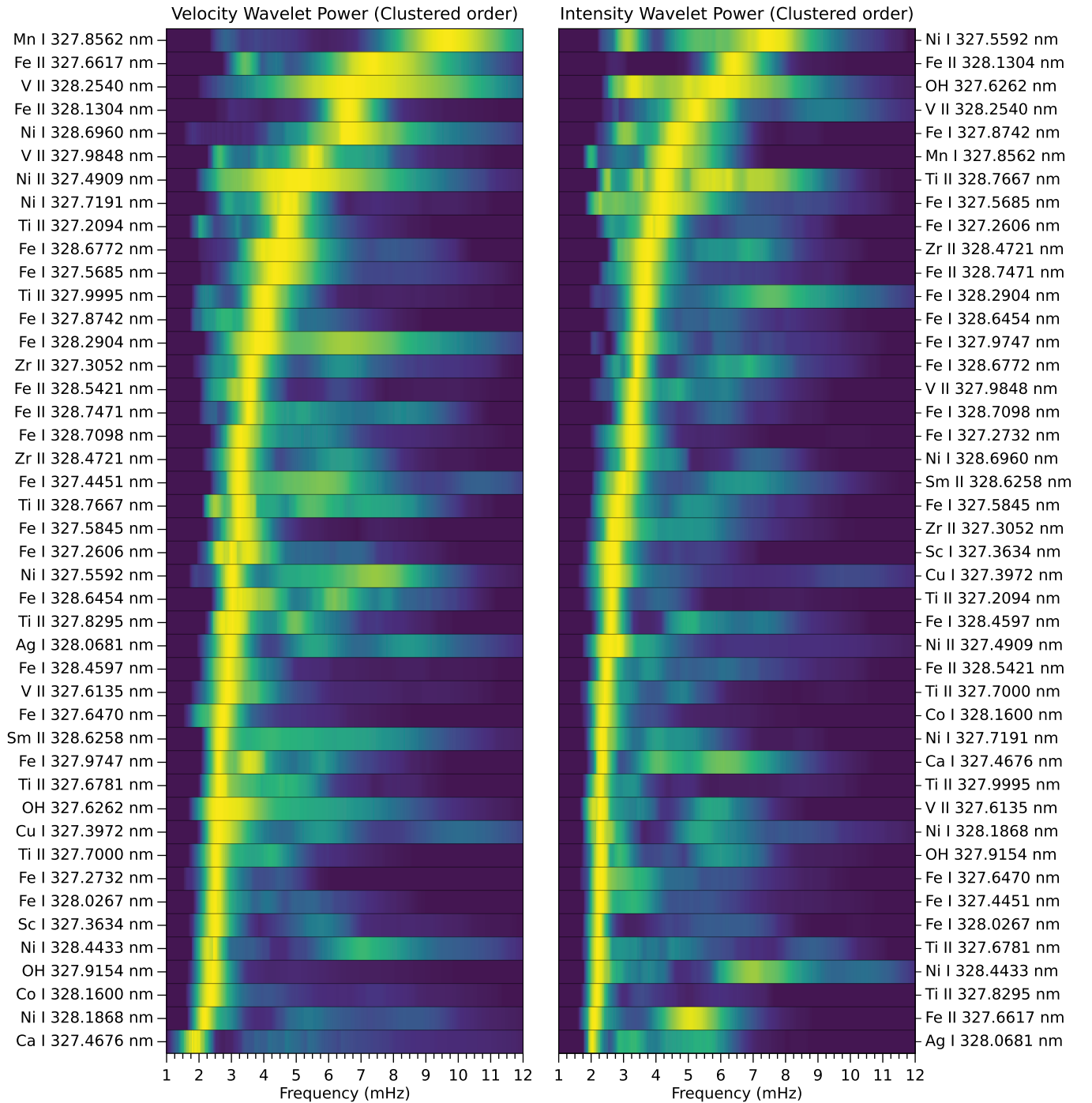


Figure 8. The same as Figure 7 but for an additional umbral core pixel, marked by a filled green circle in Figure 3. While the detailed line ordering can vary between neighboring umbral pixels, the qualitative progression of dominant frequencies across the ensemble is recovered.

view; and (2) an additional umbral core pixel close to the primary analysis location. Both supplementary locations are indicated in the slit-jaw context image (Figure 3) using different marker colors.

In the weak-field reference example outside the umbra (Figure 7), the clustering-based reordering does not reveal a comparable progression of dominant frequencies across the line ensemble. Instead, most lines concentrate their dominant power near ~ 3.5 mHz (within ± 0.5 mHz), with only minor deviations in a small number of diagnostics. This contrast supports the interpretation that the structured frequency

organization seen in the umbral core is not a generic property of the analysis procedure or the instrument, but is linked to the sunspot umbra.

For the secondary umbral core pixel (Figure 8), we recover qualitatively similar behavior to the primary umbral location: the cluster-ordered stacks again show a progression of dominant frequencies spanning roughly ~ 2 – 10 mHz, for both the LOS velocity and intensity (though not necessarily in the same diagnostics). The detailed line ordering and, for some lines, the dominant peak frequency differ from the primary umbral pixel. Such differences are expected: even within the

umbral core, small lateral variations in atmospheric structure and magnetic configuration (e.g., field strength/inclination, thermodynamic stratification, and flows), together with height-dependent dynamics, can shift line-formation weighting and the relative visibility of coexisting oscillatory components, such that the strongest peak in a multipeak spectrum may change between neighboring pixels. Consistent with this, the 3D MURaM sunspot model shows substantial pixel-to-pixel lateral variations in effective formation height within the umbra across the 327–329 nm range, with a typical span of several hundred kilometers (median ~ 615 km) and extremes exceeding 1 Mm. Therefore, an identical cluster-based line ordering is not expected from one umbral pixel to another, even when the overall multifrequency character and the qualitative frequency progression persist.

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