Conference Paper No: PF-06

Line profile variations of pulsating stars and comparison with observed data

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Abstract

Asteroseismology provides a powerful method for investigating the internal structure of stars through the study of stellar oscillations. Spectroscopic observations are particularly useful because pulsations produce measurable variations in stellar absorption line profiles. In this study, a computational framework was developed to simulate synthetic line profile variations (LPVs) produced by both radial and non-radial stellar pulsations. The model incorporates pulsational velocity fields, rotational broadening, limb darkening, intrinsic line broadening and disk integration effects to generate time-dependent spectral line profiles. The stellar parameters adopted for the simulations were chosen to be representative of the *δ Scuti* star *SZ Lyn* to facilitate direct comparison with observations. The model was verified through a sequence of test cases, beginning with a static non-rotating star and gradually introducing rotation and pulsation effects. Radial pulsation modes produced symmetric periodic shifts in the line centroid, whereas non-radial sectoral modes generated travelling features and asymmetric line profiles. The effects of stellar rotation and inclination angle on LPVs were also investigated and found to play a significant role in the observed morphology of spectral variations. Finally, the synthetic LPVs were qualitatively compared with high-resolution spectroscopic observations of the high-amplitude *δ Scuti* star *SZ Lyn* obtained using the High Efficiency and Resolution Mercator Echelle Spectrograph (HERMES) spectrograph on the Mercator telescope. The synthetic and observed variability patterns showed good qualitative agreement, with the observations being broadly consistent with a dominant radial pulsation mode and possible contributions from low-order non-radial oscillations.

Keywords: Asteroseismology, Line Profile Variations, Stellar Pulsations, Spectroscopy, SZ Lyn

Introduction

Asteroseismology is the study of stellar oscillations and provides one of the most powerful tools for probing stellar interiors (Aerts et al., 2010). While photometric observations provide information about pulsation frequencies, spectroscopic observations contain additional information regarding the geometry of oscillation modes through variations in spectral line profiles.

Non-radial pulsations generate surface velocity fields that produce time-dependent distortions in stellar absorption lines, commonly known as line profile variations (LPVs). The morphology of these LPVs depends on several factors, including the pulsation mode geometry, stellar rotation and the inclination angle of the rotation axis relative to the observer (Telting & Schrijvers, 1997). Sectoral modes often produce travelling features across the profile, whereas axisymmetric modes tend to generate more symmetric variability patterns.

Several diagnostic methods have been developed for spectroscopic mode identification, including the moment method introduced by Balona (1986) and further developed by Aerts et al. (1992). These techniques relate variations in line moments to the underlying pulsation geometry.

Although detailed numerical models exist, simplified computational frameworks remain useful

for understanding the individual physical mechanisms responsible for LPVs and for testing mode-identification techniques. The main objective of this work was therefore to develop a computational model capable of reproducing the fundamental characteristics of pulsation-induced LPVs and to investigate the effects of pulsation mode, rotation and inclination angle on observable spectral behaviour. A qualitative comparison with observations of the δ *Scuti* star *SZ Lyn* was also performed to evaluate the physical validity of the model.

Methodology

The stellar photosphere was approximated as a spherical surface undergoing small-amplitude linear adiabatic oscillations described by spherical harmonics $Y_l^m(\theta, \phi)$. The Cowling approximation was adopted, and only a single dominant pulsation mode was considered at a time. Stellar rotation was assumed to be rigid while centrifugal distortion effects were neglected. These assumptions allow the individual effects of pulsation geometry and rotation on the line profiles to be studied in a controlled manner.

The visible stellar disk was divided into a uniform surface grid consisting of latitude and longitude elements. The contribution from each surface element was calculated separately and integrated numerically to obtain the total observed line profile. Limb darkening was represented using a linear law and the projected area of each element was included during disk integration. The adopted discretization scheme provides sufficient spatial resolution to reproduce the major features of LPVs while maintaining computational efficiency.

The pulsation velocity field was described using spherical harmonics and projected onto the observer's line of sight. Rotational Doppler shifts were combined with pulsational velocities to determine the local velocity field across the stellar surface. Local line profiles were represented using simplified intrinsic broadening functions before integration over the visible hemisphere. The model also incorporated thermal broadening and rotational broadening to simulate realistic stellar absorption lines.

Synthetic LPVs were generated for radial and non-radial pulsation modes with different combinations of spherical harmonic degree l and azimuthal order m. In addition, the effects of equatorial rotational velocity and inclination angle on LPV morphology were investigated to study the influence of geometric projection effects on observable spectroscopic signatures.

To assist mode identification, the first three velocity moments of each synthetic line profile were calculated. The first moment represents radial velocity variations, the second moment measures changes in line width and the third moment quantifies profile asymmetry (Aerts et al., 1992). These quantities provide additional diagnostic information regarding pulsation geometry and temporal variability.

For validation, observational spectra of the high-amplitude δ *Scuti* star SZ Lyn obtained using the HERMES spectrograph attached to the 1.2 m Mercator telescope were analyzed. The dataset contained spectra covering fourteen pulsation phases over the wavelength range 3812–8983 Å. Three spectral lines, H_α, H_β and $Mg\ I$ 5183.6 Å, were selected for comparison with the synthetic results because they probe different regions of the stellar atmosphere and exhibit different sensitivities to pulsation-induced variability.

Results and Discussion

The numerical implementation was first verified using a static non-rotating star. The resulting spectral line remained symmetric and invariant with time, confirming the correctness of the disk integration procedure and numerical surface discretization. Introducing stellar rotation broadened the line profile through Doppler effects while preserving symmetry in the absence of pulsation (Figure 1). These results agreed with theoretical expectations and provided confidence in the reliability of the computational framework.

Radial pulsation modes produced periodic shifts in the centroid position while maintaining an approximately symmetric profile shape throughout the pulsation cycle. In the absence of rotation, the line profile oscillated back and forth without significant changes in width or skewness. When rotation was included, additional asymmetry developed due to the interaction between pulsational and rotational velocity fields, resulting in slightly distorted profiles and broader absorption features. This behaviour is consistent with the expected spectroscopic signatures of radial oscillations.

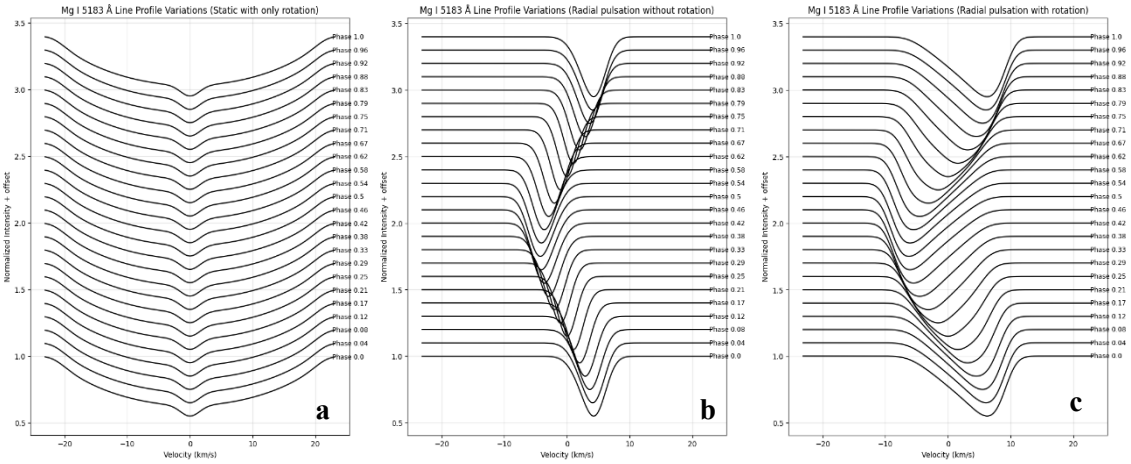


Figure 4. *Stacked Mg I 5183 Å line profile variations (LPVs) for* ***(a)*** *a static rotating star ($V_{eq} = 30\ km\ s^{-1}$), showing rotational broadening without temporal variability,* ***(b)*** *a non-rotating radial pulsator ($l = 0,\ m = 0,\ V_{amp} = 20\ km\ s^{-1}$), exhibiting symmetric periodic velocity shifts, and* ***(c)*** *a rotating radial pulsator ($l = 0,\ m = 0,\ V_{amp} = 20\ km\ s^{-1},\ V_{eq} = 30\ km\ s^{-1}, i = 45°$), showing periodic line shifts with phase-dependent asymmetry.*

The behaviour of non-radial pulsation modes differed significantly from that of radial modes. The axisymmetric dipole mode ($l = 1, m = 0$) generated nearly symmetric LPVs with little centroid motion and characteristic vertical structures in the dynamic spectra. In contrast, the non-axisymmetric sectoral mode ($l = 1, m = 1$) produced travelling features moving across the profile together with strong phase-dependent asymmetries and systematic centroid shifts (*Figure 2*). Similar behaviour has been predicted theoretically for sectoral oscillation modes and has frequently been observed in spectroscopic studies of non-radial pulsators (Telting & Schrijvers, 1997).

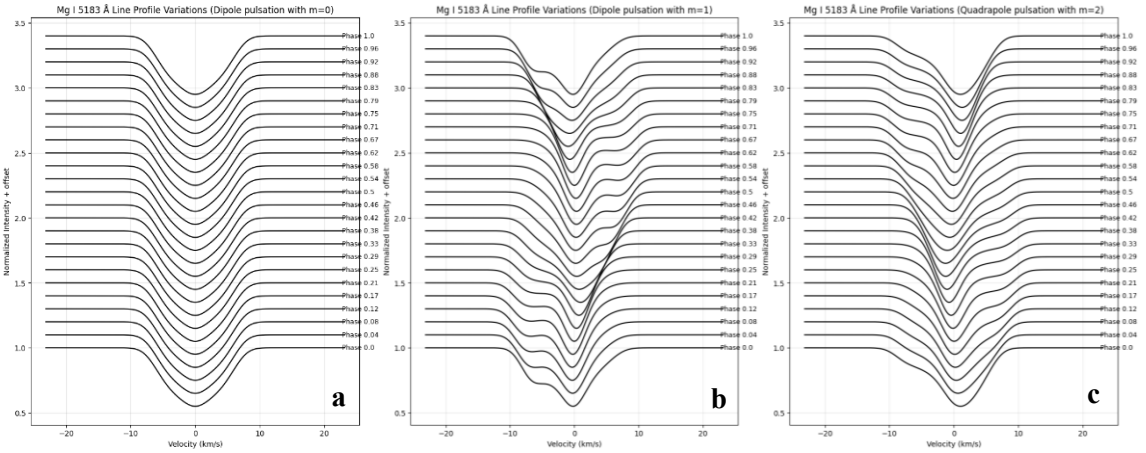


Figure 5. *Stacked Mg I 5183 Å line profile variations (LPVs) for non-radial pulsation modes with* $V_{amp} = 20\ km\ s^{-1}$ *and* $V_{eq} = 10\ km\ s^{-1}$*:* ***(a)*** *axisymmetric dipole mode (*$l = 1, m = 0$*) with symmetric variability,* ***(b)*** *sectoral dipole mode (*$l = 1, m = 1$*) showing travelling bumps and phase-dependent asymmetry, and* ***(c)*** *quadrupole mode (*$l = 2, m = 2$*) exhibiting more complex profile distortions associated with higher-order surface velocity patterns.*

The first three line moments provided additional diagnostic information regarding pulsation geometry. The first moment primarily traced radial velocity variations associated with pulsation, whereas the second and third moments reflected changes in line width and profile asymmetry, respectively. The temporal behaviour of these moments varied considerably between different (l, m) combinations, demonstrating their usefulness for mode discrimination and spectroscopic mode identification.

Rotation and inclination angle were found to strongly influence LPV morphology. Increasing rotational velocity broadened spectral lines and enhanced asymmetry, particularly for non-radial modes. Similarly, larger inclination angles reduced geometric cancellation effects and made travelling features more prominent in the dynamic spectra. At low inclination angles, some non-radial modes became difficult to distinguish due to projection effects, highlighting the importance of stellar orientation in observational mode identification.

A qualitative comparison was performed using observations of the high-amplitude δ *Scuti* star SZ Lyn obtained with the HERMES spectrograph mounted on the Mercator telescope. The observed H_α and H_β lines exhibited periodic global shifts with little evidence of travelling structures, while the $Mg\ I$ line showed weak asymmetry and smaller amplitude variations (Figure 3). The dominance of global Doppler shifts and the absence of significant travelling bumps suggest that the dominant oscillation mode of SZ Lyn is radial in nature. However, weak asymmetries in the metal line may indicate the presence of additional low-order non-radial modes, consistent with recent photometric studies that detected several non-radial frequencies in the star (Adassuriya et al., 2021).

Overall, the model successfully reproduced the fundamental theoretical behaviour expected from pulsation-induced LPVs and provided a computationally efficient framework for investigating spectroscopic signatures of stellar oscillations. Although the comparison with observations was primarily qualitative, the agreement between synthetic and observed trends supports the physical validity of the adopted assumptions and demonstrates the usefulness of synthetic LPV modelling as a tool for spectroscopic asteroseismology and mode identification.

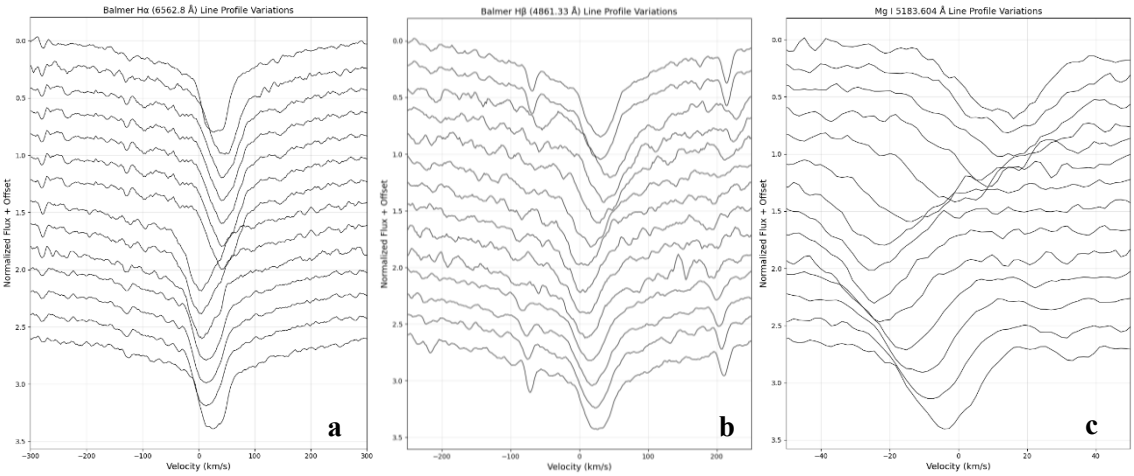


Figure 6. *Observed line profile variations of SZ Lyn for* ***(a)*** H_α *6562.8 Å,* ***(b)*** H_β *4861.3 Å, and* ***(c)*** *Mg I 5183.6 Å. The Balmer lines exhibit broad, nearly symmetric profiles with periodic global shifts, whereas the Mg I line is narrower and shows weak asymmetry, consistent with predominantly radial pulsation behaviour.*

Conclusion

A computational framework was developed to simulate line profile variations produced by radial and non-radial stellar pulsations. The model incorporated pulsational velocity fields, stellar rotation, limb darkening and disk integration effects to generate time-dependent synthetic spectral lines.

The simulations reproduced several theoretical characteristics of LPVs. Radial modes generated symmetric periodic line shifts, while sectoral non-radial modes produced travelling features and profile asymmetries. Stellar rotation and inclination angle were found to have significant influence on LPV morphology and visibility.

The comparison with observational data from SZ Lyn showed good qualitative agreement with the synthetic radial pulsation models. The observed behaviour suggests that the dominant pulsation mode of SZ Lyn is radial, although weak asymmetries may indicate the presence of additional low-order non-radial oscillations.

These results demonstrate that synthetic LPV modelling provides an effective diagnostic tool for spectroscopic mode identification and offers a useful foundation for future studies involving multi-mode pulsations and quantitative parameter estimation.

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