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Determination of temperature, velocity, and radius profiles of pulsating stars using curve of growth analysis of spectra

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Abstract
Delta Scuti stars are short-period pulsating variable stars that exhibit variations in temperature, radial velocity, and stellar radius. This study presents a comprehensive time-series analysis of these parameters for two Delta Scuti stars: ρ Puppis and CC Andromedae. For ρ Puppis, 117 high-resolution HARPS spectra were analyzed using curve-of-growth diagnostics, line-depth ratio (LDR) thermometry, and radial velocity measurements from Balmer lines. The LDR method revealed clear temperature variations with a peak-to-peak amplitude of 378 K over the pulsation cycle. Radial velocity measurements from the Hδ line yielded a semi-amplitude of 4.89 ± 0.09 km s^{-1} and systemic velocity of 48.93 ± 0.07 km s^{-1}. Integration of the velocity curve produced relative radius variations of $0.0032\,R_\odot$ and $0.0047\,R_\odot$ in two observing blocks, corresponding to fractional changes of 0.15–0.25 %. The sinusoidal variations confirm that the pulsation is dominated by a single radial mode. For CC Andromedae, 242 low-resolution spectra from the Mount Abu Observatory were analyzed; no clear periodic patterns emerged due to lower spectral resolution and signal-to-noise ratio. This study demonstrates that the combination of LDR analysis and radial velocity measurements provides a powerful tool for characterizing pulsations in δ Scuti stars, though the methodology is more effective for high-resolution spectra.

Keywords: Asteroseismology, Delta Scuti Stars, Line-Depth Ratio, Stellar Pulsations, Time-Series Analysis

Introduction

Stellar pulsations serve as a fundamental tool for studying stellar interiors and evolution, enabling insights that static models cannot provide (Aerts et al., 2010). Among pulsating variables, δ Scuti stars occupy a key position in the Hertzsprung-Russell diagram, lying within the classical instability strip near the main sequence (Rodriguez et al., 2000). These intermediate-mass A-F type stars oscillate in low-order pressure modes with periods of 0.02–0.25 days (Breger & Montgomery, 2000), driven by the κ-mechanism operating in the He II ionization zone (Cox, 1963; Zhevakin, 1963). Recent space missions such as CoRoT, Kepler, and TESS have revolutionized photometric studies, but spectroscopy remains essential for characterizing the thermal and dynamical responses of stellar atmospheres.

ρ Puppis (HD 95321) is an evolved Am (metallic-line) star of spectral type F5 II kF2 II mF5 II (Gray et al., 2003) with a 3.37-hour pulsation period (Yang et al., 1987). Historically, Am stars were thought to be non-pulsating because radiative diffusion was believed to suppress oscillations (Kurtz, 1984). The discovery of pulsations in ρ Puppis challenges this view, making it an excellent target for studying pulsation in chemically peculiar stars. CC Andromedae (HD 218555), a high-amplitude δ Scuti (HADS) star with spectral type F3 V, offers a contrasting case with larger amplitude and simpler frequency spectrum (Handler et al., 2000).

The objectives of this study are: (1) to identify unsaturated Fe I lines via curve-of-growth analysis for reliable temperature diagnostics, (2) to apply the line-depth ratio (LDR) method to measure effective temperature changes, (3) to determine radial velocity variations from Balmer lines, and (4) to derive radius variations through numerical integration of the velocity curve.

By applying these techniques to both high- and low-resolution data sets, we evaluate their effectiveness and provide new insights into the pulsation behavior of these two stars.

Methodology/materials and methods

The primary dataset for ρ Puppis consisted of 117 high resolution HARPS spectra (R ≈ 115 000) covering 3781–6913 Å. Observations spanned two blocks: 05:19:48–06:03:09 UT (21.4% of phase) and 07:46:18–09:04:02 UT (38.3% of phase). For CC Andromedae, 242 low resolution spectra were acquired with an ATIK 314L CCD on a 50 cm telescope at Mount Abu Observatory, India over three nights.

HARPS data were pipeline reduced. CCD data were reduced using IRAF with argon-neon comparison lamps. All spectra were continuum normalized using iterative polynomial fitting (degree 6) with 4σ clipping; regions within ±20 Å of Balmer lines were masked.

Equivalent widths were measured with the specutils Python library. Fe I lines used a 5 Å window; Balmer lines used a 15 Å window. Measurements outside 0.001–1.2 Å (Fe I) or 0.1–20 Å (Balmer) were discarded.

For temperature analysis, the LDR method used ratios of low- to high-excitation Fe I line depths. Temperature variations were derived using a sensitivity coefficient of 1500 K per unit ratio, anchored to 6550 K. Excitation temperatures were also computed from Balmer line equivalent widths using the Boltzmann equation.

Radial velocities were measured by fitting Gaussian and Lorentzian profiles to Hβ, Hγ, and Hδ, with barycentric corrections applied. The Doppler formula converted wavelength shifts to velocities.

Radius variations were obtained by integrating the pulsation velocity using a projection factor of 1.36 ± 0.02 (Nardetto et al., 2007). The trapezoidal rule was used for integration; each block received an independent offset. Monte Carlo simulations (1000 realizations) propagated uncertainties from RV errors, projection factor, and systemic velocity.

Results and Discussion

The curve-of-growth analysis identified a ∼0.3 Å threshold to isolate unsaturated Fe I lines. The measured line-depth ratios, folded with the 3.37-hour period, reveal a clean sinusoidal temperature variation with a peak-to-peak amplitude of 378 K (∼5.8 % of 6550 K) as in Figure 7. The LDR method reliably tracks temperature changes even with limited phase coverage.

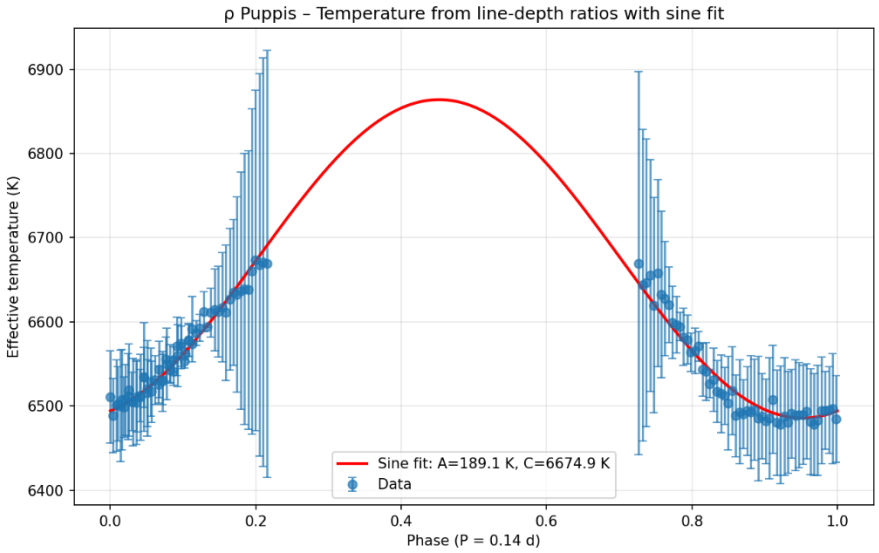


Figure 7 *Phase-folded effective temperature variation of ρ Puppis derived from line-depth ratios. The red curve shows a sine fit with amplitude 189 K, period fixed at 3.37 h. Error bars represent the standard deviation of the three line-ratio estimates.*

For radial velocities, the Lorentzian-weighted fit to Hδ gave the most consistent results. The sine fit (period fixed to 3.38 h) yields $\gamma = 48.93 \pm 0.07$ km s^{-1}, $K = 4.89 \pm 0.09$ km s^{-1}, and $t_0 = 56297.25000 \pm 0.00018$ MJD. The reduced chi-square $\chi^2_\nu = 1.00$ confirms the uncertainties are well estimated. The phased data shows no residuals, confirming a single radial mode as in Figure 8.

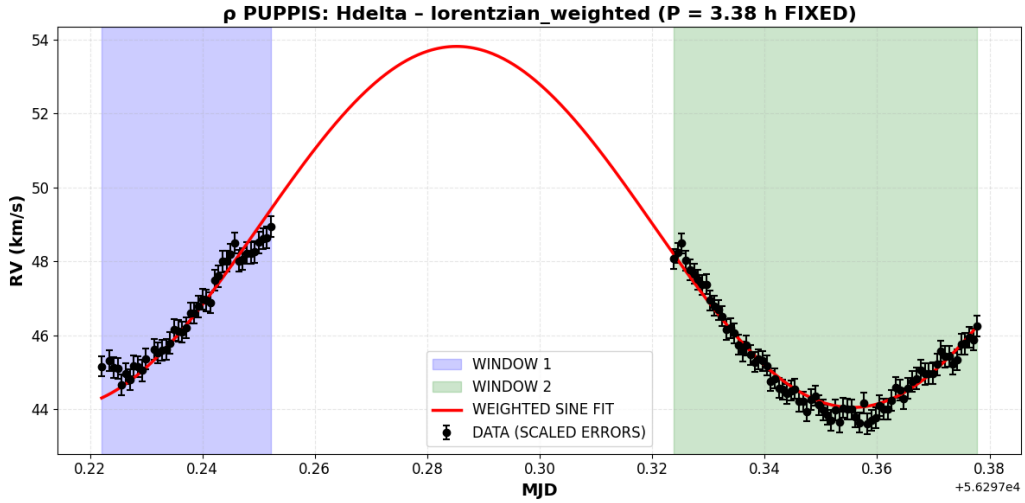


Figure 8 *Radial velocity measurements of ρ Puppis from the Hδ line (Lorentzian-weighted) with sine fit (red). Shaded regions mark the two observing blocks. Bottom: Phased data folded with P = 3.38 h. Error bars are scaled uncertainties ($\chi^2_\nu = 1$).*

Integration of the velocity curve using the global systemic velocity ($\gamma = 48.87 \pm 0.74$ km s^{-1}) gives relative radius variations of 0.016–0.019 R$\odot$ across the two blocks, corresponding to fractional changes of 0.15–0.25 % as in Figure 9. The agreement between blocks validates our approach.

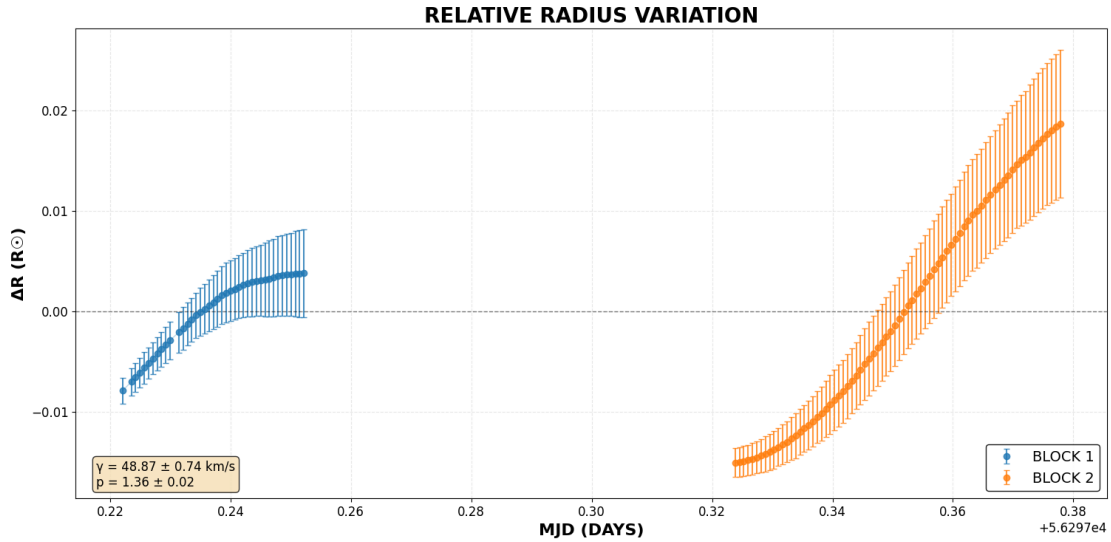


Figure 9 *Relative radius variation ΔR (in solar radii) for the two continuous observing blocks. Error bars denote 1σ Monte Carlo uncertainties. The offsets have been adjusted to center each block.*

Crucially, temperature, velocity, and radius all oscillate with the same period and phase, confirming a dominant radial pulsation. Since ρ Puppis is an evolved Am star – a class thought to suppress pulsations via radiative diffusion – this provides strong evidence that pulsation-induced mixing or convection can overcome diffusion.
For CC Andromedae, the low-resolution spectra ($R < 10\,000$) yielded no coherent periodicity. Balmer-derived RVs showed ±5 km s^{-1} scatter around −9.5 km s^{-1} with no periodic pattern. Radius variations from four methods were inconsistent, confirming insufficient data quality.
Methodologically, the LDR technique achieves 20–30 K precision, adequate for δ Scuti amplitudes of 200–500 K. Curve-of-growth screening is essential to avoid saturated lines. Lorentzian profiles best represent pressure-broadened Balmer wings. Low-resolution data cannot support these diagnostics.

Conclusion

This study successfully characterized the pulsation of the evolved Am star ρ Puppis using high-resolution spectroscopy. The line-depth ratio method yielded a temperature amplitude of 378 K, radial velocity semi-amplitude of 4.89 km s^{-1}, and radius variations of 0.0032–0.0047 R⊙ (fractional changes 0.15–0.25 %). The sinusoidal nature of all three observables confirms that the pulsation is coherent and dominated by a single radial mode, consistent with previous work (Antoci et al., 2014). These findings add to the growing evidence that Am stars can pulsate despite radiative diffusion, suggesting that pulsation-induced mixing or a thick outer convection zone in evolved Am stars may disrupt the diffusion process.
For CC Andromedae, the low-resolution data did not permit robust detection of pulsation variations, underlining the requirement for high-resolution spectroscopy ($R > 50\,000$) for precise asteroseismic studies. The methodological framework developed here – curve-of-growth diagnostics, LDR thermometry, and RV integration – provides a powerful toolkit for analyzing pulsating stars. As space missions like TESS continue to deliver high-precision photometry, these spectroscopic techniques will remain essential for interpreting the underlying stellar dynamics and for advancing our understanding of stellar structure and evolution.

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