Time-Resolved Spectroscopy of the roAp Star $\gamma$ Equ

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Abstract. We report results of the spectroscopic monitoring of the roAp star $\gamma$ Equ with the ESO 3.6-m telescope. Series of very high-resolution and high S/N spectra obtained for this star in the 6138-6165 Å spectral region allowed to resolve changes of $\gamma$ Equ line profiles due to the rapid pulsations. From this unique observational material information on amplitudes and phase shifts of radial velocity (RV) variations was extracted for 29 lines of 17 individual ions. We confirmed that spectral lines of rare-earth elements (REE) have the largest pulsation amplitudes, reaching up to 0.8 km s$^{-1}$. Moreover, we detected a phase shift between RV variations of singly and doubly ionized REE and discovered significant RV shifts of weak Na I lines. Detailed analysis of Pr III and Nd III line profile variations resulted in the estimate of $\ell = 2$ or 3, $m = -\ell$ or $-\ell + 1$ and $v_p \approx 10$ km s$^{-1}$ for the $p$-mode of the main pulsation frequency.

1. Introduction

Since the discovery of the short-period light variations in the cool Ap star HD 101065 (Kurtz & Wegner 1979), this phenomenon has become an object of interest for many studies. At present the group of rapidly oscillating Ap (roAp) stars consists of 32 members. Rapidly oscillating Ap stars pulsate with periods in the range 4–16 min with very low amplitudes ($\Delta B \lesssim 15$ mmag). $\gamma$ Equ is the second brightest roAp star. The latest analysis of its light variation (Martínez et al. 1996) provided support for $p$-modes with four pulsation frequencies corresponding to periods from 11.68 to 12.45 min. Recently Kanaan & Hatzes (1998) performed an extensive study of the radial velocity variations due to pulsations in $\gamma$ Equ. At the same time Malanushenko, Savanov, & Ryabchikova (1998) discovered high-amplitude (up to 800 m s$^{-1}$) RV variations for the lines of Pr III and Nd III. We obtained time-series of high-resolution high S/N spectra of $\gamma$ Equ to study in details line profile variations due to stellar pulsations.
2. Observations and spectrum synthesis

Observations of γ Equ were collected in July 1999 with Very Long Camera of CES at the ESO 3.6-m telescope. Combination of the highest resolution CES image slicer and ESO CCD#38 provided resolving power of λ/Δλ ≈ 170 000. During 1.5 hours we obtained 31 60° exposures of 26 Å spectral region, centred at λ 6152 Å. Signal-to-noise ratio of 130 was achieved in each individual exposure. Th-Ar comparison spectrum was registered immediately before and after observations of γ Equ. Basic steps of spectra reduction were performed with the set of IDL-based routines, specially adapted for the reduction of CES spectra.

For the purpose of line identification we computed synthetic spectrum of γ Equ in 6140-6166 Å spectral region. Model atmosphere parameters, approximate model of the magnetic geometry, and elemental abundances were adopted from Ryabchikova et al. (1997). Synthetic spectra were calculated with Synthmag magnetic spectrum synthesis code (Piskunov 1999). Comparison between spectrum synthesis and average observed spectrum of γ Equ is illustrated in Fig. 1. Line identification in 6140-6166 Å region is fairly complete. The only relatively strong unidentified spectral feature is located at λ 6148.86 Å and probably belongs to REE.

![Figure 1](image_url)

Figure 1. Comparison between spectrum synthesis calculations (thin curve) and the average spectrum of γ Equ (thick curve) is shown in the upper panel. The middle panel displays the difference between individual and average observed spectra. Profiles of the consecutive pulsation phases are shifted in the vertical direction by 0.02; the lower panel shows the standard deviation for each pixel of the observed spectrum.

3. Analysis of radial velocity variations and mode identification

In the first step of the analysis of pulsational changes in γ Equ line profiles we computed the differences between the average and 31 individual spectra and
determined the standard deviation for each pixel of the observed spectral region. Prominent variations of Nd III 6145.07 Å and Pr III 6160.24 Å are immediately seen in the difference spectra (middle panel in Fig. 1). This is the first clear detection of metal line profile variability due to rapid oscillations in a roAp star. Analysis of the standard deviation (lower panel in Fig. 1) reveals weaker variability in other spectral lines.

We measured the RV shifts of γ Equ spectral lines and fitted the RV variations with cosine curves (Fig. 2). Our spectroscopic monitoring of γ Equ was too short for accurate determination of pulsation frequencies, but it allowed us to determine the amplitudes and relative phases of spectral line RV variations with very high precision.

Among the lines in the 6140-6166 Å spectral region, Nd III 6145.07 Å and Pr III 6160.24 Å show the strongest profile changes. We quantified the variability of these spectral features by computing the time variations of a few low-order moments of line profiles (Aerts, De Pauw, & Waelkens 1992) and by considering the variability of the flux in each pixel (Mantegazza & Poretti 1998). This observational material can be used to identify modes of non-radial stellar oscillations. The moment method is the best mode identification technique for slow rotators, and therefore it seems especially suitable for roAp stars. Comparison between observed moment amplitudes and theoretical amplitudes, calculated for given sets of parameters (ℓ, m, angle α between line of sight and pulsation axis, pulsation velocity v_p) using the code of Aerts et al. (1992) resulted in the estimate ℓ = 2 or 3 and m = −ℓ or −ℓ + 1 for both doubly ionized REE lines. This conclusion was supported by the analysis of the shape of the pixel-by-pixel amplitude and phase diagrams for the Nd III and Pr III lines.
Comparison between the average observed spectrum and a synthetic spectrum, computed for \( \gamma \) Equ with the best abundances and model atmosphere parameters (Fig. 1), showed that the theoretical spectrum, in which magnetic broadening and instrumental profile were taken into account, still possesses much sharper spectral features, than those seen in observations. We found that this excessive broadening is different from line to line and correlates with the amplitudes of the RV variations. A macroturbulence of 10 km s\(^{-1}\), required to fit the broad wings of the Nd \( \text{III} \) and Pr \( \text{III} \) lines, is in good agreement with the pulsational velocity inferred from these lines. Lower macroturbulence for other lines is consistent with the lower observable RV amplitudes. Thus we suggest that a study of differential macroturbulent-like line broadening may give important information on pulsation amplitudes.

4. Conclusions

Based on high-resolution high S/N observations we confirmed earlier results obtained by Malanushenko et al. (1998), who discovered strong RV variations of doubly ionized REE lines in the spectrum of \( \gamma \) Equ. In addition to refining the measurements of variations of the third REE ions, we were also able to obtain precise radial velocity amplitudes and phases for singly ionized REE. Our data give indication for the existence of a phase lag of \( \approx 80^\circ \) between RV variations of singly and doubly ionized REE. The lines of all other elements but Na \( \text{I} \) do not show RV variations with amplitudes greater than 100 m s\(^{-1}\). Below this threshold some RV variation are possible for Fe \( \text{II} \) lines and are definitely present for a Ba \( \text{II} \) line (which varies in phase with singly ionized REE), while strong Ca \( \text{I} \) lines are stable to within 30-50 m s\(^{-1}\). We did not confirm a correlation of the RV amplitudes with the line intensity found by Kanaan & Hatzes (1998). Looking through the line list published in their paper we found that many spectral lines with high RV amplitudes were not identified properly and in reality belong to REE lines in different ionization stages.

References

Malanushenko, V., Savanov, I., & Ryabchikova, T. 1998, IBVS No. 4650