No magnetic field variation with pulsation phase in the roAp star $\gamma$ Equulei

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Abstract. We present an analysis of 210 high-resolution time-resolved spectropolarimetric observations of the roAp star $\gamma$ Equ obtained over three nights in August and September 2003. Radial velocity variations due to $p$-mode non-radial pulsations are clearly detected in the lines of rare-earth elements, in particular Pr$\text{m}$, Nd$\text{m}$ and Nd$\text{n}$. In contrast, we find absolutely no evidence for the variation of the mean longitudinal magnetic field over the pulsation period in $\gamma$ Equ at the level of 110–240 G which was recently reported by Leone & Kurtz (2003). Our investigation of the variability of circularly polarized profiles of 13 Nd$\text{m}$ lines demonstrates that, at the $3\sigma$ confidence level, no magnetic field variation with an amplitude above $\approx$ 40–60 G was present in $\gamma$ Equ during our monitoring of this star.

Key words. stars: atmospheres – stars: chemically peculiar – stars: individual: $\gamma$ Equ – stars: magnetic fields – stars: oscillations

1. Introduction

Since the discovery of high-overtone $p$-mode pulsations in the rapidly oscillating Ap (roAp) stars it became clear that, unlike in other stellar pulsators, strong magnetic fields in these stars have a defining role in exciting the oscillations and shaping main pulsational properties. It was found that the amplitude and phase of the rapid light variation are modulated by the stellar rotation and that the phases of the extrema of magnetic field and pulsational amplitude typically coincide with each other. A phenomenological oblique pulsator model (Kurtz 1982) attributed main characteristics of the photometric pulsational variation of roAp stars to the oblique dipole modes, aligned with the axis of dipolar magnetic field. The apparent connection between global magnetic field of roAp stars and their non-radial pulsations led Hubrig et al. (2003) to propose that atmospheric magnetic structure may also change over the pulsation period and hence pulsational variability of the longitudinal magnetic field can eventually be observed. Hubrig et al. (2003) searched for the magnetic variations in a sample of six roAp stars but failed to detect any coherent magnetic variability in low-resolution Zeeman spectra. This null result is not unexpected given that in roAp stars lines of different elements display dramatically different amplitudes and phases of oscillations, which are combined destructively and result in an extremely weak pulsational signal when averaged over broad wavelength regions.

High-resolution analysis of Stokes profiles of individual metal lines is a much more promising tool for mapping atmospheric pulsational disturbances and investigating possible oscillations of magnetic field. In a recent paper Leone & Kurtz (2003) announced the discovery of variation of the mean longitudinal field $\langle B_z \rangle$ with the 12.1-minute pulsation period in one of the brightest roAp star $\gamma$ Equ. Magnetic variability with an amplitude between 110 and 240 G was inferred from the study of 4 Nd$\text{m}$ lines in only 18 circularly polarized spectra of $\gamma$ Equ, which makes the alleged detection of magnetic variation a statistically marginal result. With the aim of verifying the existence of rapid magnetic variability in $\gamma$ Equ we decided to acquire and analyse a much more extensive time series spectropolarimetric observations of this star.

2. Observations

We obtained time-resolved circularly polarized spectra of $\gamma$ Equ using the cross-dispersed Nasmyth Echelle Spectrometer (NES, Panchuk et al. 1999) installed at the 6-m telescope of the Russian Special Astrophysical Observatory. The NES instrument is equipped with a Zeeman analyzer consisting of a quarter-wave and half-wave retarders and a calcite plate separating the beams with opposite circular polarization. A 2K×2K Loral CCD detector allowed us to record 26 echelle orders with nearly complete wavelength coverage in the 4520–6000 Å region with a spectral resolving power of $R \approx 38{,}000$.

On each of the nights of August 19 and 20, 2003 we observed $\gamma$ Equ for 2.4 h and have obtained continuous sequences
of 70 Stokes I and V spectra using 80’ integration time with a readout time of 42’. An additional series of 70 polarized spectra of γ Equ was secured on September 11, 2003, when exposure times of 120’ were used. On each of the observing nights the peak S/N ≈ 60–80 was reached in individual time-resolved spectra. The software package REDUCE (Piskunov & Valenti 2002) was used for the optimal extraction of the NES spectra. A wavelength scale with an internal accuracy of 50–70 m s−1 was established by means of a 2-D wavelength calibration procedure, which made use of ≈700 ThAr lines in all echelle orders. The left- and right-hand circularly polarized (LCP and RCP) beams were calibrated independently using the corresponding beams of the reference spectrum taken before and after stellar observations.

3. Identification of Nd III lines

Investigation of pulsational variability in the spectral lines of the rare-earth elements (REE) offers unique potential to observe non-radial p-mode oscillations and to study in detail the structure of pulsating cavity in roAp stars. It was recently demonstrated by Kochukhov & Ryabchikova (2001a, 2001b) that the largest pulsational variability (RV amplitudes up to 1 km s−1) in individual metal lines in γ Equ and other roAp stars is invariably found in the REE spectral lines, in particular strong absorption features of doubly ionized Pr and Nd, while pulsations could not be detected in the lines of light and iron-peak elements. Since the lines of each REE ion show very similar pulsational behaviour, the accuracy of our search for magnetic oscillations in γ Equ can be substantially improved by simultaneous multiline analysis of Nd III lines, which constitute the most numerous group of strong lines with pronounced variability in the spectrum region available in our observations.

In the present study magnetic field and RV variations were measured using 13 unblended Nd III lines some of which were previously unclassified, but appeared in laboratory spectra (Crosswhite 1976, Aldénius 2001) as well as in the spectra of roAp stars known to have Nd III lines of abnormal intensity (Ryabchikova et al. 2001). We emphasize that all newly classified Nd III lines show strong pulsational signatures, consistent with the behaviour of known lines of Nd III, which by itself provides a convincing support for our line identification. Table 1 contains wavelengths of Nd III lines, proposed transition identification based on the energy level calculations by Zhang et al. 2002b and the effective Landé factors which were calculated from the g-factors published by Bord 2003 and Zhang et al. 2002. The details of the line classification will be presented elsewhere, here we note that the adopted Landé factors and Zeeman patterns are consistent with the observed Zeeman splitting in the sharp-lined Ap star HD 144897 with the surface magnetic field of ≈ 9 kG.

4. Radial velocity and magnetic field measurements

The pulsational analysis of γ Equ followed the procedure outlined in Kochukhov & Ryabchikova (2001a). For each spectral line in the available wavelength region we determined the center-of-gravity as a function of time in the Stokes I spectra. Then a refined analysis of polarization spectra was carried out for the group of Nd III lines aimed at detection of the magnetic variability. An instantaneous position of the line center was determined consistently for the RCP and LCP profiles by integrating over the spectral points below certain residual depth. The same vertical cutoff was applied to the RCP and LCP spectra, but it had to be chosen individually for each line due to different blending in the far wings. This results in up to a factor of two difference in the RV amplitudes for studied Nd III lines, although depth effects may also be partially responsible for that. The RV and ⟨Bz⟩ were derived from the center-of-gravities of the RCP and LCP profiles, λR and λL, using the expressions

\[ ⟨B_z⟩ = \frac{λ_R + λ_L}{2} \frac{A_R + A_L}{2} \frac{g_{eff}((λ_R) + (λ_L))}{c}, \]

where c is the speed of light and \(\frac{A_R + A_L}{2} \frac{g_{eff}((λ_R) + (λ_L))}{c}\) correspond to the time-averaged line center positions.

Preliminary time series analysis of the Nd III lines showed negligible difference between the periods and phases of their RV variability. Therefore, in subsequent least squares sinusoidal fits we allowed for individual amplitudes, but used the same phase and pulsation period for all Nd III lines, effectively coadding information from many lines into a single high S/N RV measure. The same strategy was used to construct the average variation of the longitudinal field after subtracting a constant offset from ⟨Bz⟩ measurements obtained for each of the Nd III lines. Results of our investigation of the neodium line variability are summarized in Table 1 and are illustrated in Figs. 1 and 2 which show the average RV curves (scaled to nightly mean amplitudes) as well as the average variation of ⟨Bz⟩ and corresponding amplitude spectra.

| λ (Å) | g_{eff} | Transition (cm⁻¹) |
|-------|---------|-------------------|
| 4759.54^a | 1.621 | 5093.4 – 26098.7 |
| 4796.49^b | 1.553 | 1118.4 – 21981.6 |
| 4927.49^b | 1.186 | 3714.3 – 24003.7 |
| 4942.68^b | 1.479 | 3714.3 – 23941.2 |
| 5012.94^d | 1.677 | 5093.4 – 25036.7 |
| 5203.92^d | 0.919 | 1118.4 – 20349.2 |
| 5286.75^a | 1.421 | 5093.4 – 24003.7 |
| 5294.11^a | 0.615 | 0 – 18884.4 |
| 5677.18^a | 1.579 | 5093.4 – 22703.3 |
| 5802.54^a | 1.531 | 2387.6 – 19617.6 |
| 5845.02^a | 1.101 | 5093.4 – 22197.9 |
| 5851.54^a | 1.617 | 3714.3 – 20799.5 |
| 5987.68^a | 1.163 | 3714.3 – 20411.7 |

^a Previously identified and classified Nd III lines
^b Lines included in Crosswhite’s (1976) unpublished list
^c Lines detected in the laboratory spectrum (Aldénius 2001 and private communication)
^d Reclassified and newly classified lines
Fig. 1. Pulsational variation of the radial velocity and longitudinal magnetic field measured for Nd m lines on the nights of August 19 and 20, 2003. The average pulsational RV curves a) are folded with the best-fit oscillation period and are compared with the average variation of \( \langle B_z \rangle \) c). Panels b) and d) illustrate the amplitude spectra for the RV and longitudinal magnetic field. The vertical dashed lines show photometric pulsational periods of γ Equ. The horizontal dashed line in panels d) indicates the maximum amplitude of pulsational \( \langle B_z \rangle \) variation reported by LK.

Table 2. Results of our analysis of the time-resolved polarized spectra of γ Equ. The columns list UT date of observation, reference Julian date, number of analysed spectra and a least-squares estimate of the pulsational period, average amplitude and phase (measured in fractions of the period) of the pulsational RV variation in 13 Nd m lines. The last three columns report the amplitude of the magnetic variation, standard deviation of the \( \langle B_z \rangle \) measurements and an amplitude which would have been detected with out data at the 3σ confidence level.

| UT Date       | \( t_0 \) - 2400000 | N  | P   | (A) | \( \varphi \) | \( \Delta(B_z) \) | \( \sigma(\langle B_z \rangle) \) | \( \Delta(B_z)_{\text{max}} \) |
|---------------|---------------------|----|-----|-----|-------------|----------------|----------------|----------------|
| 19/08/2003    | 52871.5140          | 70 | 12.212±0.013 | 963 | 0.102±0.004 | 30±17 | 105 | 63 |
| 20/08/2003    | 52872.3727          | 70 | 12.169±0.012 | 854 | 0.382±0.004 | 37±13 | 80  | 48 |
| 11/09/2003    | 52894.2954          | 70 | 12.231±0.024 | 262 | 0.011±0.012 | 14±10 | 59  | 36 |

For all three nights the pulsation period detected in our data is consistent with one of the frequencies (\( P = 12.201 \) min) identified in photometry (Martinez et al. 1996). Despite unambiguous detection of the pulsational RV shifts, no evidence for magnetic variability is found. A rigorous statistical analysis indicates that, at the 3σ confidence level, no magnetic variability with \( \Delta(B_z) > 40–60 \) G is seen in γ Equ during the nights of our observations.

In addition to the study of the Nd m lines, we identified a number of Pr m and Nd n features showing clear pulsational variability. These lines are not so numerous and strong as to provide an independent and accurate diagnostic of possible rapid magnetic changes. Nevertheless, analysis of these ions is consistent with the results obtained using the Nd m lines: two lines of Pr m with the average RV amplitude between 950 m s\(^{-1}\) (19 Aug) and 280 m s\(^{-1}\) (11 Sep) show \( \Delta(B_z) \leq 100 \) G, while \( \Delta(B_z) \approx 60±50 \) G is derived from four Nd n lines. Remarkably, the lines of singly ionized Nd, which could not be investigated in our first spectroscopic study of pulsations in γ Equ (Kochukhov & Ryabchikova 2001a), show very high average RV amplitudes of 1416 m s\(^{-1}\) (19 Aug), 1118 m s\(^{-1}\) (20 Aug) and 414 m s\(^{-1}\) (11 Sep) and a constant phase shift of 0.13±0.02 of pulsation period with respect to the RV variation of Nd m.

The procedure of the magnetic and RV measurements applied to REE lines was also tested on a sample of 19 unblended strong lines of Ca, Cr and Fe, which are not expected to show any pulsational variability of either RV or \( B_z \). From the Aug 19 data we obtained RV amplitude of 30 ± 19 m s\(^{-1}\), \( \Delta(B_z) = 18±14 \) G and standard deviation \( \sigma(\langle B_z \rangle) = 84 \) G for these lines, in good quantitative agreement with the REE results. This provides a complementary indirect argument for the absence of magnetic variability in REE lines. Since the variation of magnetic field is predicted to be proportional to the RV oscillations (see Hubrig et al. 2003), even for marginal magnetic variation one would expect to find \( \sigma(\langle B_z \rangle_{\text{REE}}) \gg \sigma(\langle B_z \rangle_{\text{Ca,Cr,Fe}}) \), but this is clearly not observed in γ Equ.

5. Discussion

What may be the reason for a major discrepancy between the results reported by LK and the outcome of our study of γ Equ? We consider it improbable that the star itself has changed its pulsational behaviour dramatically. Theoretical estimate of
possible magnetic variability (Hubrig et al., 2003) hints that magnetic and velocity amplitudes are proportional to each other. Therefore, if magnetic variability really exists, on the nights of Aug 19 and 20 (when RV amplitudes of Nd lines were about twice the amplitude measured by LK) we should have observed even larger $\langle B_z \rangle$ variation than found by LK.

It is possible that the difference between our null result and the alleged positive detection of the magnetic variability by LK is related to different approaches to measure $\langle B_z \rangle$ and the effects of blending of the Nd lines studied by LK. We derive longitudinal field from consistent center-of-gravity determination in the RCP and LCP profiles, while LK analysed the first moment of the Stokes $V$ spectra. Strong Nd lines tend to show extended wings and have unusually wide Stokes $V$ signatures. Hence, an insignificant blending in Stokes $I$ may correspond to a substantial overlap of the Stokes $V$ profiles of neighbouring lines. The Nd II 5845.07 Å, which LK offered as the most prominent case of $\langle B_z \rangle$ variation, represents a clear example of the blending problem. This line is blended by the variable line of Pr at $\lambda$ 5844.41 Å, which appears to be reasonably well separated from the Nd line in Stokes $I$, but significantly distorts the corresponding Stokes $V$ signature. In Fig. 3 we use our Aug 19 data to illustrate that the blending of the Nd II 5845.07 Å results in spurious variation of $\langle B_z \rangle$ when integrating Stokes $V$ signal for this line within a fixed wavelength range. In contrast, no variation is seen in the nearby line of Nd II 5802.54 Å which is free from any blends and has higher magnetic sensitivity.

We also point out that the results of the RV and magnetic measurements presented by LK for individual Nd lines are inconsistent. The reported phase shift between $\langle B_z \rangle$ curves of, e.g., the Nd II 5845.07 and 6145.07 Å, reaches 0.20 of the pulsation period (with a typically phase error not exceeding 0.03), while no such shift is seen in RV variation. Unfortunately, LK do not comment on this peculiar behaviour of different Nd lines.

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