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No magnetic field variation with pulsation phase in the roAp star γ Equulei

O. Kochukhov[1], T. Ryabchikova[1,2], and N. Piskunov[3]

[1] Institut für Astronomie, Universität Wien, Türkenschanzstraße 17, 1180 Wien, Austria
[2] Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya 48, 109017 Moscow, Russia
[3] Uppsala Astronomical Observatory, Box 515, 751 20 Uppsala, Sweden

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Abstract. We present an analysis of 210 high-resolution time-resolved spectropolarimetric observations of the roAp star γ 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 III, Nd II and Nd III. In contrast, we find absolutely no evidence for the variation of the mean longitudinal magnetic field over the pulsation period in γ 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 III lines demonstrates that, at the 3σ confidence level, no magnetic field variation with an amplitude above $\approx$40−60 G was present in γ Equ during our monitoring of this star.

Key words. stars: atmospheres – stars: chemically peculiar – stars: individual: γ 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, hereafter LK) announced the discovery of variation of the mean longitudinal field $\langle B_z \rangle$ with the 12.1-min pulsation period in one of the brightest roAp star γ Equ. Magnetic variability with an amplitude between 110 and 240 G was inferred from the study of 4 Nd III lines in only 18 circularly polarized spectra of γ 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 γ 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 γ 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 γ Equ for 2.4 h and have obtained continuous sequences

Send offprint requests to: O. Kochukhov,
e-mail: kochukhov@astro.univie.ac.at

of 70 Stokes I and V spectra using 80 s integration time with a readout time of 42 s. An additional series of 70 polarized spectra of γ Equ was secured on September 11, 2003, when exposure times of 120 s were used. On each of the observing nights the peak $S/N \approx 60$–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,b) 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. (2002) and the effective Landé factors which were calculated from the g-factors published by Bord (2000) 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 $\langle B_z\rangle$ were derived from the center-of-gravities of the RCP and LCP profiles, $\lambda_{\rm R}$ and $\lambda_{\rm L}$, using the expressions

$$\langle B_z\rangle = \frac{\lambda_{\rm R} + \lambda_{\rm L}}{2.34\times10^{-13} g_{\rm eff}(\langle\lambda_{\rm R}\rangle + \langle\lambda_{\rm L}\rangle)^2},$$
$$RV = c\left(\frac{\lambda_{\rm R} + \lambda_{\rm L}}{\langle\lambda_{\rm R}\rangle + \langle\lambda_{\rm L}\rangle} - 1\right), \qquad (1)$$

where c is the speed of light and $\langle\lambda_{\rm R,L}\rangle$ 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 $\langle B_z\rangle$ measurements obtained for each of the Nd III lines. Results of our investigation of the neodimium 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 $\langle B_z\rangle$ and corresponding amplitude spectra.

Table 1. Nd III lines used in the *RV* and magnetic field analysis of γ Equ. The columns give laboratory wavelength, effective Landé factor, excitation potentials and J values of the lower and upper levels.

λ (Å)	$g_{\rm eff}$	Transition (cm^{-1})
4759.54[bc]	1.621	$5093_8 - 26098_7$
4796.49[bc]	1.553	$1138_5 - 21981_6$
4927.49[a]	1.186	$3714_7 - 24003_7$
4942.68[b]	1.479	$3714_7 - 23941_6$
5012.94[d]	1.677	$5093_8 - 25036_7$
5203.92[ad]	0.919	$1138_5 - 20349_5$
5286.75[a]	1.421	$5093_8 - 24003_7$
5294.11[a]	0.615	$0_4 - 18884_4$
5677.18[a]	1.579	$5093_8 - 22703_7$
5802.54[c]	1.531	$2387_6 - 19617_5$
5845.02[a]	1.101	$5093_8 - 22197_9$
5851.54[c]	1.617	$3714_7 - 20799_6$
5987.68[a]	1.163	$3714_7 - 20411_7$

[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.

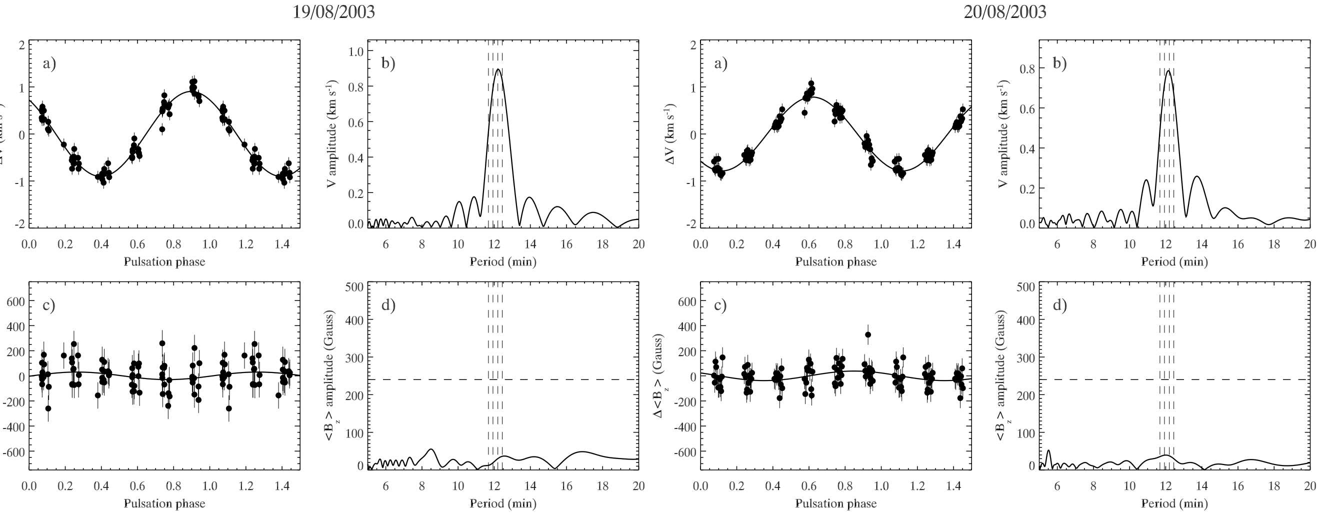

Fig. 1. Pulsational variation of the radial velocity and longitudinal magnetic field measured for Nd III lines on the nights of August 19 and 20, 2003. The average pulsational *RV* curves **a)** are folded with the best-fit oscillation period and are compared with the average variation of $\langle B_z\rangle$ **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 III 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- 2 400 000	N	P (min)	$\langle A\rangle$ (m s^{-1})	φ	$\Delta\langle B_z\rangle$ (G)	$\sigma(\langle B_z\rangle)$ (G)	$\Delta\langle B_z\rangle_{\max}$ (G)
				13 lines of Nd III				
19/08/2003	52 871.5140	70	12.212 ± 0.013	963	0.102 ± 0.004	30 ± 17	105	63
20/08/2003	52 872.3727	70	12.169 ± 0.012	854	0.382 ± 0.004	37 ± 13	80	48
11/09/2003	52 894.2954	70	12.231 ± 0.024	262	0.011 ± 0.012	14 ± 10	59	36

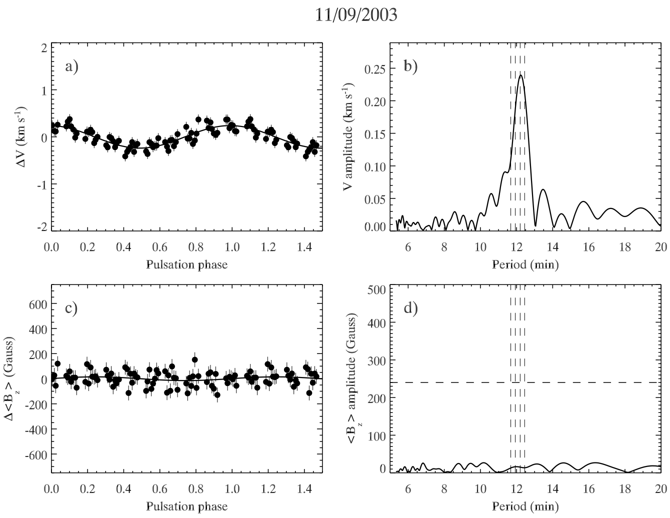

Fig. 2. The same as Fig. 1 for the spectropolarimetric observations of γ Equ obtained on the night of September 11, 2003.

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 $\Delta\langle B_z\rangle > 40$–$60$ G is seen in γ Equ during the nights of our observations.

In addition to the study of the Nd III lines, we identified a number of Pr III and Nd II 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 III lines: two lines of Pr III with the average *RV* amplitude between 950 m s^{-1} (19 Aug.) and 280 m s^{-1} (11 Sep.) show $\Delta\langle B_z\rangle \lesssim 100$ G, while $\Delta\langle B_z\rangle \approx 60\pm50$ G is derived from four Nd II 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 III.

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 $\langle B_z\rangle$. From the Aug. 19 data we obtained *RV* amplitude of 30 ± 19 m s^{-1}, $\Delta\langle B_z\rangle = 18 \pm 14$ 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 complementory 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 $\sigma(\langle B_z\rangle_{\rm REE}) \gg \sigma(\langle B_z\rangle_{\rm Ca,Cr,Fe})$, 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 III 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 III 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 III 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 III 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 III at λ 5844.41 Å, which appears to be reasonably well separated from the Nd III 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 III 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 III 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 III lines are inconsistent. The reported phase shift between $\langle B_z\rangle$ curves of, e.g., the Nd III 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 III lines.

Based on our observations we conclude that we see no evidence for pulsational variation of magnetic field in γ Equ contrary to the recent claim by LK. We show that systematic problems exist in the latter study and hence the alleged detection of the magnetic variability in γ Equ may be spurious.

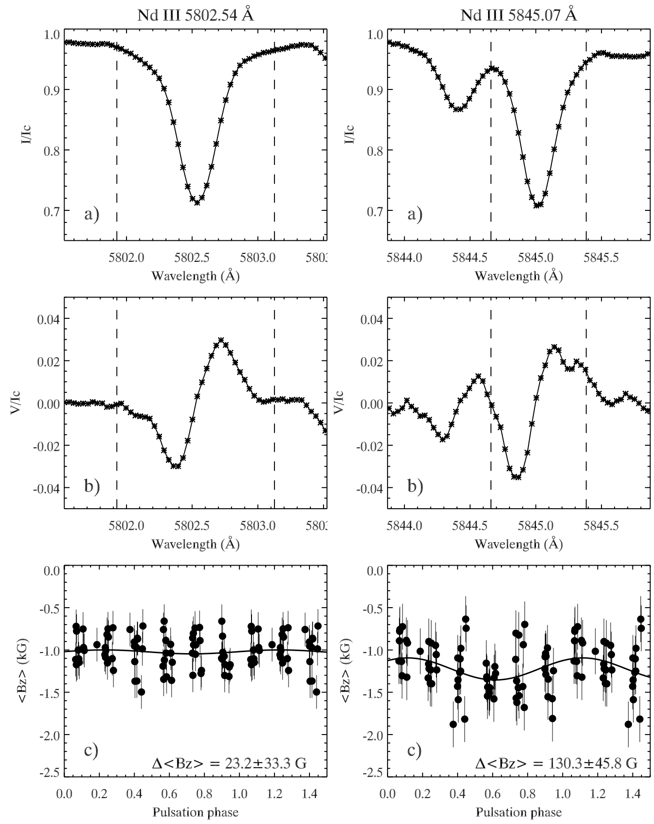

Fig. 3. The average Stokes *I* **a)** and *V* **b)** profiles of the Nd III lines at λ 5802.54 and 5845.07 Å. The vertical dashed lines illustrate selection of the spectral region for the *RV* and magnetic measurements. The panel **c)** shows variation of the $\langle B_z\rangle$ measure obtained from the Stokes *V* profiles. Blending by the Pr III 5844.41 Å leads to spurious variation of $\langle B_z\rangle$ determined for the Nd III 5845.07 Å.

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