Mon. Not. R. Astron. Soc. **351,** L34–L38 (2004) doi:10.1111/j.1365-2966.2004.07946.x

The null result of a search for pulsational variations of the surface magnetic field in the roAp star γ Equulei

O. Kochukhov,[1★] T. Ryabchikova,[1,2] J. D. Landstreet[3] and W. W. Weiss[1]

[1]*Department of Astronomy, University of Vienna, Türkenschanzstraße 17, 1180 Vienna, Austria*
[2]*Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya 48, 119017 Moscow, Russia*
[3]*Department of Physics and Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada*

Accepted 2004 April 23. Received 2004 April 6; in original form 2004 February 3

ABSTRACT

We describe an analysis of the time-resolved measurements of the surface magnetic field in the roAp star γ Equ. We have obtained a high-resolution and high signal-to-noise (S/N) spectroscopic time series, and the magnetic field was determined using Zeeman-resolved profiles of the Fe II 6149.25 Å and Fe I 6173.34 Å lines. Contrary to recent reports, we do not find any evidence of magnetic variability with pulsation phase, and derive an upper limit of 5–10 G for pulsational modulation of the surface magnetic field in γ Equ.

Key words: stars: chemically peculiar – stars: individual: γ Equ – stars: magnetic fields – stars: oscillations.

1 INTRODUCTION

After discovery of the conspicuous radial velocity (RV) pulsational variations in a sample of rapidly oscillating magnetic peculiar (roAp) stars (Kanaan & Hatzes 1998; Savanov, Malanushenko & Ryabchikova 1999; Kochukhov & Ryabchikova 2001a for γ Equ; Baldry et al. 1998; Baldry & Bedding 2000; Kochukhov & Ryabchikova 2001b for α Cir and HD 83368), attempts to search for magnetic field variations over the pulsational period have been made. First, Hubrig et al. (2004) tried to measure pulsational variability of the longitudinal magnetic field B_ℓ in six roAp stars. Their sample included γ Equ – probably one of the most favourable stars for this kind of investigation. γ Equ is a bright northern roAp star with a strong magnetic field, and with one of the largest pulsational RV amplitudes, which exceeds 1000 m s^{-1} in individual spectral lines. The extremely slow rotation of γ Equ, leading to very sharp spectral lines, makes this star the best candidate for any study of the pulsational variability in spectroscopy. Hubrig et al. (2004) used low-resolution Zeeman time-series observations and measured B_ℓ using hydrogen lines and unresolved blends of metal lines. They failed to detect any variability beyond the formal errors of their measurements, which were 40–100 G.

According to a coarse theoretical estimate made by Hubrig et al. (2004), there should exist a linear relation between magnetic field variability over the pulsational cycle and the RV amplitudes. In roAp stars, the largest RV amplitudes are observed in the lines of first and second ions of rare-earth elements (REE), whereas they are usually below measurement errors for the lines of iron group elements. Thus, high-resolution spectroscopy and spectropolarimetry of selected REE spectral lines is a more promising tool for an investigation of possible rapid magnetic oscillations in roAp stars. Taking this into account, Leone & Kurtz (2003) obtained a high-resolution (R = 115 000), high signal-to-noise (S/N) time series of observations of γ Equ with a circular polarization analyzer, and measured B_ℓ using four Nd III lines. They reported the discovery of pulsational variations with amplitudes between 112 to 240 G and, more surprisingly, with discrepant phases of magnetic maximum for different Nd III lines. Leone & Kurtz's result was based on only 18 time-resolved spectra. A year later Kochukhov, Ryabchikova & Piskunov (2004) obtained a time series of polarimetric observations of γ Equ with a smaller resolving power (R = 38 000), but acquired more than 200 spectra over three nights, more than compensating for lesser quality of individual spectra. Kochukhov et al. (2004) used simultaneously 13 Nd III lines for magnetic measurements which allowed them to achieve a substantial reduction of the error of the B_ℓ determinations. They did not confirm longitudinal field variability over the pulsational period in γ Equ and gave a conservative upper limit of ≈40 G for the amplitude of pulsational modulation of B_ℓ determined from Nd III lines.

Another attempt to search for possible rapid magnetic variability in γ Equ was made by Savanov, Musaev & Bondar (2003). They measured the surface magnetic field B_s variations over the pulsational period using the Fe II 6149.25 Å line observed in unpolarized light. Due to a very simple Zeeman pattern (two equally separated π- and σ-components), this line is ideal for B_s measurements (see Mathys et al. 1997). Savanov et al. reported a 1.8σ detection of B_s variability with an amplitude of 99 ± 53 G. At the same time, they did not find periodic variations of RV measured for the individual Zeeman-resolved components of the Fe II 6149.25 Å doublet exceeding their error limit (100–120 m s^{-1}). The authors used high-resolution R = 120 000 time-series observations, but the S/N ratio

★E-mail: kochukhov@astro.univie.ac.at

of a single spectrum did not exceed 40–60. Clearly, the result of Savanov et al. is marginal and needs to be confirmed or rejected with data of better quality.

In this Letter, we present the results of a new search for pulsational variations of B_s in γ Equ using high-resolution and high S/N time-resolved observations of this star. These observational data allowed us to obtain precise measurements of the magnetic field in γ Equ, and to constrain strongly possible changes of B_s over the pulsation cycle of the star.

2 OBSERVATIONS AND DATA REDUCTION

The time-resolved observations of γ Equ were obtained using the single-order $f/4$ Gecko coudé spectrograph with the EEV1 CCD at the 3.6-m Canada–France–Hawaii Telescope (CFHT). Table 1 gives details of this spectroscopic time-series data set. The spectra cover approximately the spectral window 6104–6194 Å. This wavelength interval contains two Zeeman-resolved lines, Fe II 6149.25 Å and Fe I 6173.34 Å. It also has strong Nd III and Pr III lines, optimal for investigation of pulsational variability of roAp stars, as well as strong and weak lines of other elements such as Si, Ca, Cr, and Ba.

The spectra were reduced using standard IRAF tasks. Each stellar, flat and calibration frame had a mean bias subtracted and was then cleaned of cosmic ray hits and extracted to one dimension. Extracted stellar spectra were divided by an extracted mean flat field, and the continuum was fit with a third-order Legendre polynomial, using the same rejection parameters for all spectra so that the continuum fit is as uniform as possible. The wavelength scale was established using about 40 lines of a ThAr emission lamp, resulting in an rms scatter about the adopted pixel-wavelength polynomial (a sixth-order Legendre polynomial) of about 5×10^{-4} Å. The wavelength scale was linearly interpolated between ThAr lamp spectra taken before and after the stellar series, but the spectra were not resampled to a linear wavelength spacing.

In this Letter, we also used 31 very-high-resolution time-resolved observations of γ Equ analysed by Kochukhov & Ryabchikova (2001a). These time-resolved data were obtained with the Coudé Echelle Spectrograph (CES), fiber-linked to the Cassegrain focus of the ESO 3.6-m telescope. The highest resolution CES image slicer and the ESO CCD#38 were used, allowing us to reach a resolving power of $\lambda/\Delta\lambda = 166\,000$ and record spectra in the 6140–6165 Å wavelength interval. We refer the reader to Kochukhov & Ryabchikova (2001a) for other details of the acquisition and reduction of the CES spectra of γ Equ.

3 MAGNETIC FIELD AND RADIAL VELOCITY MEASUREMENTS

As a first step in our analysis of γ Equ, we computed synthetic spectra in the region of the Zeeman-resolved iron lines Fe II 6149.25 Å and Fe I 6173.34 Å (hereafter we refer to these spectral features simply as the Fe II and Fe I lines) using abundances, Fe stratification and model atmosphere from the study of Ryabchikova et al. (2002). Synthetic spectra of γ Equ were calculated with the SYNTHMAG code (Piskunov et al. 1999), modified to take into account vertical stratification of chemical abundances. The simplest model, with a constant magnetic field over the stellar surface, was adopted. The splitting pattern of the Fe I line is a pure Zeeman triplet with an unshifted central π-component and two σ-components. To fit the relative intensity of the π- and σ-components of this line, the magnetic field vectors in our model have to be inclined by $\approx 50°$ to the stellar surface. To look more carefully at the blending effects, we took into account the hyperfine structure of nearby La II 6172.72 Å and Eu II 6173.03 Å. An unidentified line at λ 6148.85 Å, which shows a pulsational behaviour typical for REE lines, was synthesized with arbitrary atomic parameters to take into account its possible blending of the blue-shifted Fe II component.

The comparison of these calculations with the average CFHT spectrum is presented in Fig. 1. This figure shows that the Fe II line is free from significant blends, which enables accurate pulsational analysis of both the red and blue components of this Zeeman doublet. In particular, we found that pulsational variability of the 6148.85 Å feature has negligible influence on the measurements of the blue component of the Fe II line. On the other hand, the blue σ-component of the Fe I line is blended by the Eu II 6173.03 Å and hence is not suitable for time-resolved measurements of B_s. Consequently, RV analysis and field modulus measurements using the Fe I line were based on the π- and red σ-component.

We determined the time-dependent position of the centres of Zeeman components using centre-of-gravity measurements within the spectral regions indicated in Fig. 1. We note that an alternative technique of fitting a superposition of three Gaussian profiles to the 6148.85 Å and Fe II line represents a better way to derive B_s from *time-averaged* spectra because it allows us to model partially resolved Fe II components and remove the blending contribution of the 6148.85 Å feature. However, this method may encounter difficulties in describing *time-resolved* profiles of REE lines, including the 6148.85 Å line, which show substantial RV shifts and exhibit profile asymmetries associated with non-radial pulsation velocity field. Consequently, we prefer to use the centre-of-gravity technique throughout this Letter and show the Gaussian fitting results in Figs 2–4 for comparison purpose only.

The RVs obtained from the iron lines were compared with the outstanding pulsational variation seen in the Nd III 6145.07 Å line. This feature allows us to verify the presence of rapid spectroscopic variability during our observations of γ Equ and to determine the oscillation period and amplitude with high accuracy. For each available data set, we established the period of the spectroscopic pulsational variation using this Nd III line and then fitted the phase (counted from the start HJD, see Table 1) and the amplitude of the Fe RV measurements using a non-linear least-squares technique. Results of this analysis are summarized in Table 2. We do not find any pulsational variation of the RV determined for the Zeeman-resolved components of the Fe lines exceeding about 5–10 m s^{-1} for the Fe II and $\approx$20 m s^{-1} for the Fe I line.

The measurements of the Fe II line reported in Table 2 supersede the tentative RV amplitude of 64 m s^{-1} given by Kochukhov & Ryabchikova (2001a), who used the same CES data set as studied here. This difference mainly comes from the fact that, in the present

Table 1. Journal of spectroscopic observations of γ Equ.

UT date	Instrument/ telescope	Wavelength region (Å)	Resolution ($\lambda/\Delta\lambda$)	Exposure time (s)	Number of exposures	Start HJD (245 0000+)	End HJD (245 0000+)	Typical S/N ratio
1999 July 22	CES/ESO 3.6-m	6140–6165	166 000	60	31	1381.783 44	1381.823 90	190
2002 September 26	Gecko/CFHT	6104–6194	115 000	90	64	2543.823 14	2543.921 91	230

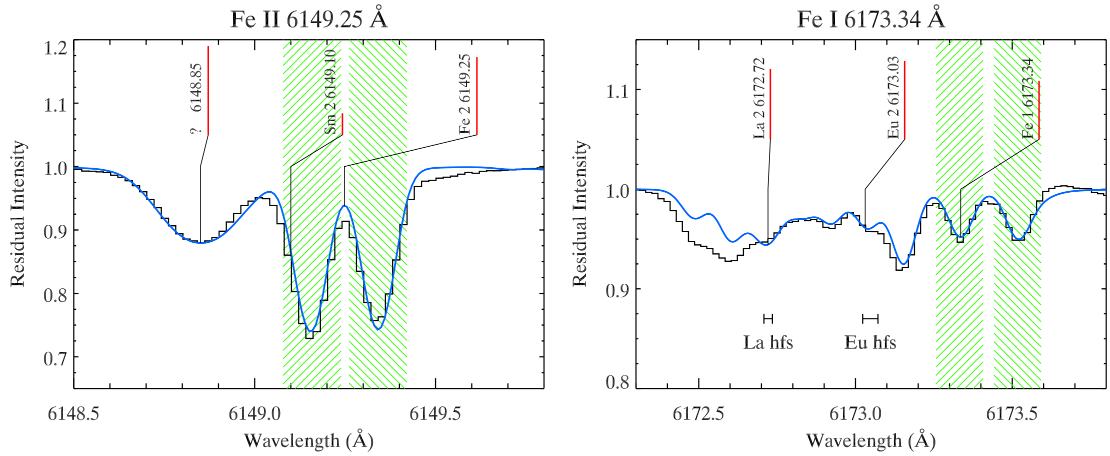

Figure 1. Comparison of the average CFHT spectra of γ Equ (histogram) in the 6149- (left-hand panel) and 6173-Å (right-hand panel) regions with magnetic spectrum synthesis (solid line). The length of the line underlining each identification is proportional to the strength of corresponding spectral feature. The La II 6172.72 Å and Eu II 6173.03 Å lines were computed, taking into account hyperfine splitting. For clarity, we do not show individual hyperfine components, but indicate the range of their central wavelengths with horizontal bars. The shaded areas illustrate our selection of the wavelength intervals for the centroid line position measurements.

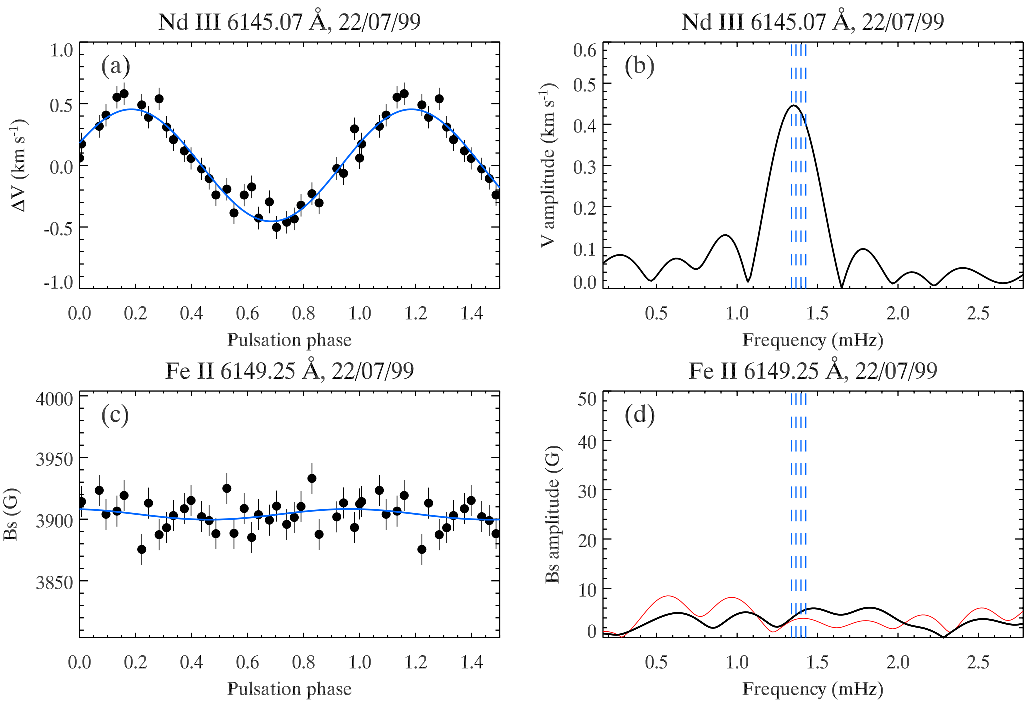

Figure 2. Measurements of radial velocity and surface magnetic field obtained for γ Equ on 1999 July 22. The Nd III 6145.07 Å pulsational RV curve (a) is folded with the best-fit oscillation period and is compared (c) with the variation of B_s measured from the separation of the Zeeman components of the Fe II 6149.25 Å (centre-of-gravity line position measurements). Panels (b) and (d) illustrate the amplitude spectra for the RV and B_s (thick line: centre-of-gravity measurements; thin line: multiple fit of Gaussians). The vertical dashed lines show the photometric pulsational periods of γ Equ (Martinez et al. 1996).

Letter, we adopt a fixed pulsation period ($P = 12.29$ min) for the analysis of the individual Fe II Zeeman components, whereas a set of four photometric periods was tested in our previous paper and the corresponding maximum RV amplitude for $P = 11.93$ min and for the whole line was reported.

The measurements of the line centre positions were converted to surface field using the expression:

$$B_s = \frac{\Delta\lambda_{mag}}{4.67 \times 10^{-13} \lambda_0^2 \overline{g}}, \quad (1)$$

where $\Delta\lambda_{mag}$ is half of the wavelength difference between the red and blue Zeeman components of the Fe II line or the distance between the red σ- and the π-component of the Fe I line, $\overline{g}$ is the mean Landé factor and λ_0 is the laboratory wavelength of a line. Based on the information available from the Vienna Atomic Line Data base (Kupka et al. 1999), we adopted $\overline{g} = 2.5$ and 1.35 for the Fe I and Fe II lines, respectively. The internal precision of our magnetic measurements is estimated to be ~ 10 G for the Fe II line and $\approx$70 G for the weaker Fe I line. At the same time, the average field strengths derived from the two lines are substantially different in the CFHT spectra:

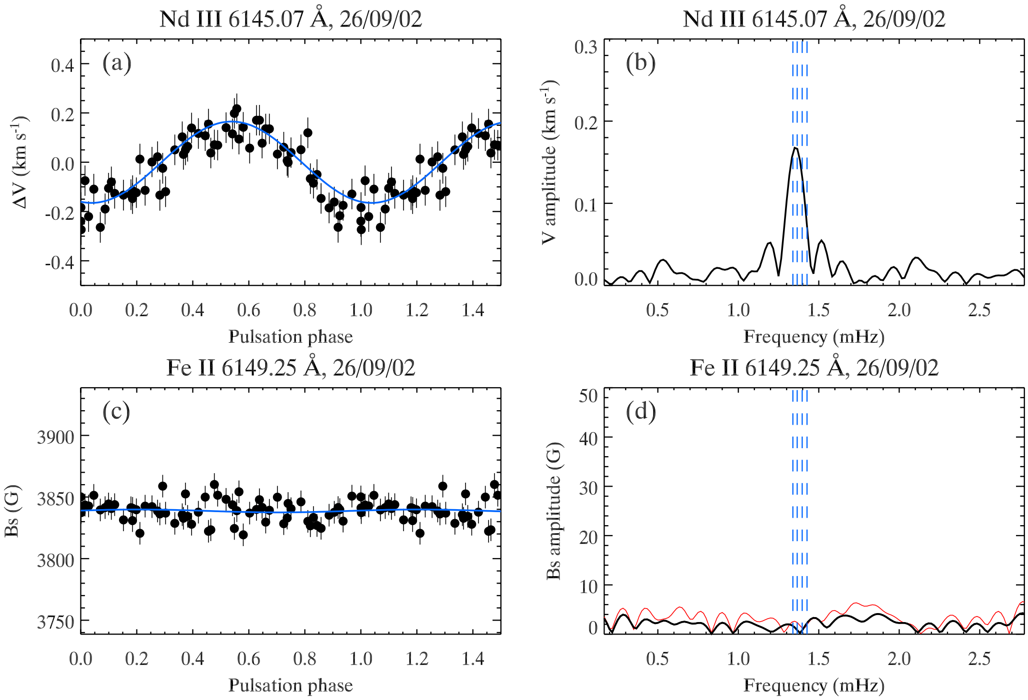

Figure 3. The same as Fig. 2 for the RV and B_s determined with the time-resolved spectra of γ Equ obtained on 2002 September 26.

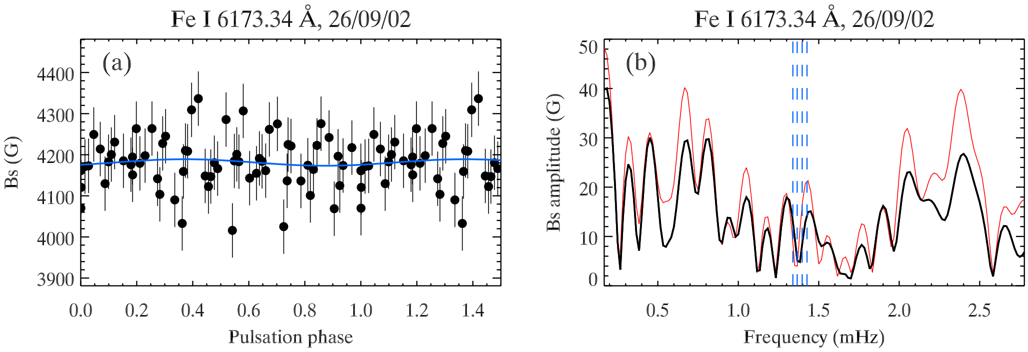

Figure 4. Magnetic field measurements obtained for γ Equ on 2002 September 26 using the Fe I 6173.34 Å line. Panel (a) shows B_s phased with the best-fit pulsation period, whereas panel (b) presents the amplitude spectrum for B_s (thick line: centre-of-gravity measurements; thin line: multiple fit of Gaussians).

Table 2. Results of the analysis of RV pulsational variability of γ Equ. The table gives pulsation period P, amplitude ΔRV and phase φ (measured in units of oscillation period). Superscripts 'b', 'r' and 'c' denote, respectively, the blue-shifted, red-shifted and central components of the Zeeman-resolved Fe lines.

Line	P (min)	ΔRV (m s^{-1})	φ
	1999 July 22, CES/ESO 3.6-m		
Nd III 6145.07	12.290 ± 0.071	454.6 ± 23.4	0.815 ± 0.016
Fe II 6149.25[b]	12.290	10.1 ± 5.7	0.383 ± 0.089
Fe II 6149.25[r]	12.290	9.4 ± 5.1	0.215 ± 0.085
	2002 September 26, Gecko/CFHT		
Nd III 6145.07	12.281 ± 0.039	165.1 ± 10.8	0.462 ± 0.021
Fe II 6149.25[b]	12.281	3.6 ± 2.5	0.000 ± 0.113
Fe II 6149.25[r]	12.281	5.2 ± 3.2	0.415 ± 0.219
Fe I 6173.34[c]	12.281	5.4 ± 14.9	0.222 ± 0.143
Fe I 6173.34[r]	12.281	17.2 ± 15.8	0.628 ± 0.234

centre-of-gravity measurements of the Fe II line give 3839 ± 9 G (3935 ± 14 G is obtained with multiple fit of three Gaussians), whereas $\langle B_s \rangle = 4181 \pm 66$ G (4200 ± 84 G) is derived using the weaker Fe I line. This ≈300 G difference is confirmed by the spectrum synthesis. The discrepant B_s might be related to inaccuracy of the tabulated Landé factors, or it could be real and reflect different horizontal and/or vertical formation regions of the two diagnostic lines, or the effects of saturation in the Fe II line. An average field strength of 3903 ± 13 G (3941 ± 19 G) was obtained from the Fe II line in the ESO spectra of γ Equ.

Table 3 and Figs 2–4 present results of our time-series analysis of the surface field measurements. We see absolutely no evidence for any magnetic variations during the pulsation cycle in γ Equ. Formal results of the least-squares fits with a fixed pulsation period as derived from the Nd III line indicate insignificant amplitudes, all below 10 G. Our most precise time-resolved magnetic measurements are derived from the CFHT data set. Analysis of the 6149.25 Å line

Table 3. Results of the analysis of time-resolved B_s measurements for γ Equ. The columns give spectral lines used for B_s determination, magnetic pulsation amplitude ΔB_s, phase φ and rms scatter σB_s of B_s. The last column reports an amplitude δB_s of surface field variability which would have been detected with our data at the 3σ confidence level.

Line	ΔB_s (G)	φ	σB_s (G)	δB_s (G)
	1999 July 22, CES/ESO 3.6-m			
Fe II 6149.25	4.3 ± 3.2	0.037 ± 0.120	13.0	13
	2002 September 26, Gecko/CFHT			
Fe II 6149.25	1.2 ± 1.6	0.294 ± 0.219	9.2	5
Fe I 6173.34	7.9 ± 11.8	0.628 ± 0.234	66.4	28

in these spectra results in formal B_s amplitude of just $\approx$1 G, with the highest noise peaks in the amplitude spectrum (Fig. 3d) not exceeding 5 G over the whole period domain typical for roAp pulsations.

A 3σ upper limit of the amplitude of magnetic variability was estimated from Monte Carlo simulations by sampling a sinusoidal signal at the phases of our observations and adding a random noise, characteristic of the scatter of the B_s measurements. This rigorous statistical estimate is reported in Table 3 and indicates that, at the 3σ confidence level, no magnetic variability with the amplitude $\geqslant$5 G is seen in γ Equ during the night of our CFHT observation.

4 CONCLUSIONS

Our time-resolved magnetic measurements of γ Equ have achieved the highest precision for a roAp star, but reveal no evidence of pulsational modulation of the field strength. We constrain possible magnetic variability to be below $\approx$5 G in Fe lines. These results suggest that the marginal detection of $\approx$100 G B_s variability during the pulsation cycle reported in γ Equ by Savanov et al. (2003) is spurious, and probably stems from insufficient precision of the B_s measurements in that study.

The null result reported in the present Letter complements non-detection of the pulsational variability of B_ℓ determined from Nd III lines (Kochukhov et al. 2004). It should be recalled that the Fe lines studied in our Letter and the REE lines showing strong pulsational RV modulation are formed at substantially different atmospheric depths due to the extreme stratification of chemical abundances in cool Ap stars and in γ Equ in particular. Stratification analysis presented by Ryabchikova et al. (2002) allows us to conclude that Nd III lines sample very high atmospheric layers with optical depths $\log \tau_{5000} \lesssim -7$, whereas the Fe lines are formed below $\log \tau_{5000} \approx -1$. The striking difference in the RV amplitudes of Fe and Nd III lines is then attributed to an outward increase of pulsational amplitude by roughly a factor of 50–100. This increase is none the less not accompanied by an increase or even the presence of any observable oscillations of the magnetic field structure. Combining the results of this Letter with the study of Kochukhov et al. (2004), and taking into account that $B_s \approx 2.6\ B_\ell$ for γ Equ, we find that, at all observed atmospheric depths, B_s changes by less than about 0.5 G per m s^{-1} of corresponding velocity oscillations. Hence, possible magnetic variability is constrained to be below 1 per cent of the field strength.

We note that γ Equ is distinguished among the roAp stars by its strong magnetic field, sharp lines and the exceptionally high amplitude of pulsational line profile changes. Yet this star defies any attempts to detect magnetic variability with pulsation phase. This suggests that rapid magnetic modulation may be even more difficult to detect in other roAp pulsators. The outcome of our monitoring of B_ℓ and B_s in γ Equ demonstrates that very accurate measurements of the Zeeman-resolved lines can yield more precise magnetic time series compared with the polarimetric B_ℓ observations. Therefore, the most promising direction for future attempts to detect magnetic oscillations in γ Equ (which are, in any case, unlikely to exceed a few tens of gauss) would be to observe those Nd II, Nd III and Pr III lines which are characterized by large pulsational RV shifts and at the same time show Zeeman-resolved profiles. Unfortunately, the extra broadening of the pulsating lines (see Kochukhov & Ryabchikova 2001a) strongly smears observed Zeeman structure and makes proposed study of B_s oscillations extremely difficult.

ACKNOWLEDGMENTS

This Letter is based on observations obtained at the European Southern Observatory (La Silla, Chile) and at the Canada–France–Hawaii Telescope. We acknowledge support by the Lise Meitner fellowship to OK (FWF project M757-N02), by the FWF project *P 14984*, by the Natural Sciences and Engineering Research Council of Canada, by the Russian Federal program 'Astronomy' (part 1102) and by RFBR (grant 04-02-16788).

REFERENCES

Baldry I. K., Bedding T. R., 2000, MNRAS, 318, 341
Baldry I. K., Bedding T. R., Viskum M., Kjeldsen H., Frandsen S., 1998, MNRAS, 295, 33
Hubrig S., Kurtz D. W., Bagnulo S., Szeifert T., Schoeller M., Mathys G., Dziembowski W. A., 2004, A&A, 415, 661
Kanaan A., Hatzes A. P., 1998, ApJ, 503, 848
Kochukhov O., Ryabchikova T., 2001a, A&A, 374, 615
Kochukhov O., Ryabchikova T., 2001b, A&A, 377, L22
Kochukhov O., Ryabchikova T., Piskunov N., 2004, A&A, 415, L13
Kupka F., Piskunov N., Ryabchikova T. A., Stempels H. C., Weiss W. W., 1999, A&AS, 138, 119
Leone F., Kurtz D. W., 2003, A&A, 407, L67
Martinez P. et al., 1996, MNRAS, 282, 243
Mathys G., Hubrig S., Landstreet J. D., Lanz T., Manfroid J., 1997, A&AS, 123, 353
Piskunov N. E., 1999, in Stenflo J., Nagendra K. N., eds, 2nd Workshop on Solar Polarization. Kluwer Academic Publishers, Dodrecht, 515
Ryabchikova T., Piskunov N., Kochukhov O., Tsymbal V., Mittermayer P., Weiss W. W., 2002, A&A, 384, 545
Savanov I. S., Malanushenko V. P., Ryabchikova T. A., 1999, Astron. Lett., 25, 802
Savanov I., Musaev F. A., Bondar A. V., 2003, Inf. Bull. Variable Stars, 5468

This paper has been typeset from a TEX/LATEX file prepared by the author.