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Letter to the Editor

Discovery of magnetic field variations with the 12.1-minute pulsation period of the roAp star γ Equulei

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Abstract. We have discovered the first magnetic field variations over the pulsation period in an roAp star. The amplitude of the magnetic variability we have found is significant at the 4.1- to 6.6 σ level measured for four strong lines of NdIII for γ Equ with the highest amplitude found being 240 ± 37 G for the λ5845.07 Å line, with a period of 12.1 min. This magnetic field variation is in good agreement with theoretical expectations, and the period agrees well with the known photometric periods. We have also found that the time of most negative effective magnetic field occurs 0.15 ± 0.05 cycles prior to maximum pulsation velocity of recession. There is a small but significant variation in the equivalent width of two of the NdIII lines, but no equivalent width variation is detectable for the other two lines. Measurements of four lines of CaI show no variations at all in equivalent width, radial velocity or effective magnetic field strength. We find a difference in the mean effective magnetic field strength of four NdIII lines and four CaI lines and speculate that this could be a real effect caused by the surface concentration of NdIII towards the magnetic pole. If true, this provides a new way to map the horizontal abundance distribution of elements in slowly rotating Ap stars for which Doppler imaging is not possible.

Key words. stars: magnetic fields – stars: chemically peculiar – stars: oscillations – stars: individual: HD 201601

1. Introduction

The rapidly oscillating Ap (roAp) stars provide a unique opportunity to study the interaction of stellar pulsation, rotation and strong global magnetic fields. Recently there has been substantial new theoretical investigation of these interactions by Cunha & Gough (2000), Bigot et al. (2000) and Bigot & Dziembowski (2002). The latter have developed an improved oblique pulsator model for the roAp stars that suggests the pulsation modes have pulsation axes inclined to both the magnetic field and the rotation axis and look similar to, but are not exactly, inclined sectoral m-modes. It is this geometry of the modes that allows them to be viewed from varying aspect with rotation – an opportunity provided by no other kind of star.

Observationally stunning new advances have been recently made with high resolution spectroscopic studies of roAp stars. Baldry and co-workers showed a strong line-depth dependence (atmospheric height dependence) of the pulsation amplitude in the Hα line for α Cir and HR 3831 (Baldry et al. 1999; Baldry & Bedding 2000). Even more striking is the demonstration by Kochukhov & Ryabchikova (2001a) that lines of Pr an Nd show large radial velocity variations in γ Equ up to 800 m s^{-1}, whereas many other lines, including those of Fe, show no radial velocity variations at all. Radiative diffusion has stratified many elements in the atmospheres of the Ap stars, with Pr and Nd lying high in the atmosphere where the pulsation amplitude is largest in γ Equ.

Other roAp stars show a variety of behaviour. Mkrtichian, Hatzes & Kanaan (2003) found that lines of NdII and NdIII vary in antiphase with each other in the roAp star 33 Lib. They interpret this as evidence that the two ions have been stratified and lie on opposite sides of a radial pulsation node in the upper atmosphere. Evidence from the Hα studies of HR 3831 and α Cir (Baldry et al. 1999; Baldry & Bedding 2000) also indicates the presence of a radial node in the observable atmosphere. Kurtz et al. (2003) have found clear evidence of an outwardly moving running wave high in the magneto-acoustic boundary layer of the roAp star HD 166473, with the Fe lines forming more deeply in the atmosphere at a radial node. Similar studies with evidence to support these ideas have been made for α Cir and HR 3831 (Kochukhov & Ryabchikova 2001b), for HR 3831 (Balona 2002) and HR 1217 (Balona & Zima 2002).

These observational and theoretical advances naturally lead to the question of what magnetic variations occur over the pulsation cycle in roAp stars. It is clear from the oblique pulsation that the magnetic fields strongly control the pulsation

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geometry, and they are thought to have strong impact on the unknown excitation mechanism. This led Hubrig et al. (2003) to mount a major search for magnetic variations on the pulsation timescale in roAp stars using FORS1 on the VLT. They present first theoretical considerations that the magnetic field in γ Equ, in particular, is expected to vary over the pulsation cycle by about 10%; given its ≈ -1000 G effective field strength, this suggests a pulsational variation of about 100 G. Hubrig et al. (2003), unfortunately, did not get a good data set for γ Equ because of clouds, so were only able to put an upper limit on any magnetic variations of 175 G. They showed a possible detection of magnetic variations in HD 101065 of 39 ± 12 G in one of their data sets, but could not confirm this with a second data set. Four other stars studied showed only upper limits to their possible variations of a similar order to the theoretical expectations: HR 3831 (<110 G), α Cir (<100 G), 33 Lib (<30 G) and HD 217522 (<36 G).

The pioneering study of Hubrig et al. with FORS1 on the VLT was done at a spectral resolution of a few thousand. With the aim to obtain higher precision measurements of the magnetic field over the pulsation period we decided to use high resolution spectropolarimetry on individual lines in the bright roAp star γ Equ. This star is known to have multiple pulsation periods near 12 min (Martinez et al. 1996), and, as mentioned earlier, high radial velocity in some spectral lines. We have been successful and made the first clear detection of magnetic variations over the pulsation cycle in an roAp star. γ Equ shows magnetic variations up to 240 ± 37 G with a period of 12.1 min, a period in good agreement with the known photometric pulsation periods.

2. Observations and data reduction

On 2002 May 18 we obtained a series of echelle spectra of γ Equ with the high resolution spectrograph (*SARG*) (Gratton et al. 2003) equipped with the polarimeter (Leone et al. 2003) on the 3.55-m *Telescopio Nazionale Galileo* (TNG) (Bortoletto et al. 1998) at the Observatorio del Roque de los Muchachos (La Palma, Spain). The polarimeter consists of a K-prism as $\lambda/4$ retarder, a Fresnel rhomb as $\lambda/2$ retarder and a Savart plate as beam displacer. Measurements of the Stokes V parameter across spectral lines can be performed when the optical axis of the K-prism forms ±45° angles with respect to the Savart plate. The emerging o-rdinary and e-xtraordinary beams are:

$$s_{+45,o} = 0.5\,(I+V)G_oF_{+45} \qquad s_{+45,e} = 0.5\,(I-V)G_eF_{+45}$$
$$s_{-45,o} = 0.5\,(I-V)G_oF_{-45} \qquad s_{-45,e} = 0.5\,(I+V)G_eF_{-45}$$

where G is the time independent (instrumental) sensitivity at the given wavelength and F is the time dependent sensitivity, for example due to variation of sky transparency and slit illumination. Hence:

$$\frac{V}{I} = \frac{R-1}{R+1} \qquad \text{with} \qquad R^2 = \frac{s_{45,o}/s_{45,e}}{s_{-45,o}/s_{-45,e}}.$$

To measure the effective magnetic field for the $V = 4.7$ star γ Equ to a precision of a few tens of G following the previous method would take about 90 s exposure time for each of the two angle positions and 100 s to read out the CCD in each position, plus a further few seconds to rotate the prism and switch telescope auto-guiding off/on. This gives a total of about five minutes, and that is too long for studying spectral line variability with a 12-min period. Therefore to get higher time resolution, we have obtained 18 spectra with $S/N > 100$ with 90-s exposure times and 100-s readout times for the CCD using only one position, namely +45°, of the K-prism with respect to the Savart plate.

Each spectrum covers the region from 4600 Å to about 7000 Å with a resolution of $R = 115\,000$. Because of the junction of the two CCDs, the λ6147-6235 interval is not recorded. By means of the NOAO/IRAF package, bias subtraction, spectra extraction, flat-fielding and wavelength calibration have been performed for the ordinary and extraordinary spectra for each frame. Particularly important is the wavelength calibration obtained with an internal accuracy of 10^{-4}. Because of the R4 echelle, the S/N is different along any single order, but it is always larger than 100. Stokes I spectra were then obtained by adding the extraordinary and ordinary beams and Stokes V as difference from these beams.

3. Stokes *I* and Stokes *V* profile variations

Following Mathys (1994), to study the possible variability for the Stokes I and Stokes V line profiles we have computed the equivalent widths using:

$$EW = \int \frac{I_c - I_\lambda}{I_c}\,\delta\lambda$$

the centres of gravity:

$$\lambda_I = \frac{1}{EW}\int \frac{I_c - I_\lambda}{I_c}\,\lambda\,\delta\lambda$$

and the first order moment of Stokes V line profiles:

$$R_V^{(1)} = \frac{1}{EW}\int \frac{V_c - V_\lambda}{I_c}\,(\lambda - \lambda_I)\,\delta\lambda.$$

Errors for these quantities were also computed according to Mathys (1994).

Following Kochukhov & Ryabchikova (2001a), for a given line the line barycentre (λ_I^j) measured in the jth spectrum was converted to radial velocity relative to the average centroid wavelength $<\lambda_I>$:

$$RV_I^j = \left(\lambda_I^j - <\lambda_I>\right)\frac{c}{<\lambda_I>}.$$

Following Mathys (1994), the first order moment was used to determine the effective magnetic field $H_{\rm eff}$ using:

$$R_V^{(1)} = 4.67\times 10^{-13} g_{\rm eff}\lambda^2 H_{\rm eff}$$

where the $g_{\rm eff}$ is the effective Landé factor. For the Landé factors of the Nd lines we have assumed the theoretical values given by Bord (2000), for Ca lines the values from the BASS2000 web site[1].

[1] http://bass2000.obspm.fr/home.php

Table 1. A linear least squares fit of the frequency (ν) 1.38 mHz was made to the radial velocity, magnetic and equivalent width data for the NdIII lines. Amplitudes (A) and their errors (σ_A), phases (ϕ) and their errors (σ_ϕ) together with the standard deviations (σ) are listed.

λ	ν	A	σ_A	ϕ	σ_ϕ	σ
Å	mHz	m s^{-1}	m s^{-1}	radians	radians	m s^{-1}
5845.07	1.38	593	66	0.45	0.11	200
5987.80	1.38	482	81	0.26	0.17	245
6145.07	1.38	388	54	−0.05	0.14	163
6327.24	1.38	492	67	0.05	0.14	203
Å	mHz	G	G	radians	radians	G
5845.07	1.38	240	37	−2.34	0.16	112
5987.80	1.38	142	33	−2.38	0.23	100
6145.07	1.38	151	23	−1.06	0.15	69
6327.24	1.38	112	27	−1.99	0.24	82
Å	mHz	mÅ	mÅ	radians	radians	mÅ
5845.07	1.38	2.8	0.7	2.1	0.3	2.1
5987.80	1.38	3.7	0.6	2.2	0.2	1.9
6145.07	1.38	0.8	0.5	2.2	0.6	1.4
6327.24	1.38	1.7	0.8	3.1	0.5	2.4

Table 2. Equivalent Width, Radial Velocity and $H_{\rm eff}$ measurements for the NdIII λ5845.07 Å and CaI λ5857.45 Å lines.

	NdIII λ5845.07 Å			CaI λ5857.45 Å		
HJD	*EW*	*RV*	$H_{\rm eff}$	*EW*	*RV*	$H_{\rm eff}$
52412.0+	mÅ	m s^{-1}	G	mÅ	m s^{-1}	G
0.691251	80.47	392.6	−1433	96.12	−98.7	−1041
0.693551	83.55	−785.1	−869	95.22	−118.1	−1066
0.695861	90.43	−545.3	−1040	96.51	−205.7	−993
0.698161	85.38	347.9	−1541	98.37	−75.8	−1017
0.700461	83.29	277.0	−1289	95.57	−112.5	−998
0.702781	82.15	−436.3	−1176	97.12	−55.0	−963
0.705091	88.34	−325.0	−1331	97.56	−13.0	−946
0.707411	81.84	753.1	−1540	97.00	−13.9	−964
0.709701	79.08	−311.1	−1023	95.39	−179.3	−969
0.712021	82.56	−315.4	−1203	99.16	42.5	−1023
0.714321	85.59	391.4	−1440	97.59	196.6	−1031
0.716641	80.55	529.8	−1391	94.55	−27.6	−1002
0.718961	80.12	−556.0	−1139	96.65	−71.5	−1009
0.721271	83.49	−428.6	−1175	96.50	113.7	−1038
0.723561	81.21	679.1	−1720	95.82	94.1	−1039
0.725871	81.19	269.1	−1288	98.10	132.4	−1027
0.728301	80.10	−153.0	−1294	99.87	232.4	−1019
0.730631	84.32	215.6	−1339	96.77	159.5	−870

Kochukhov & Ryabchikova (2001a) have shown that the NdIII lines have radial velocity variations with amplitudes near 500 m s^{-1}, so we have chosen to study four lines of this ion. They also showed that the CaI lines show no variability, so we have chosen four lines of CaI to compare with the NdIII.

Discrete Fourier Transforms were performed on the equivalent width, radial velocity and magnetic field measurements separately. Two of the NdIII lines show small significant equivalent width variations; the other two and the CaI lines do not. The radial velocity and magnetic field data show clear signals as can be seen in Fig. 1 where we show the case for one of the lines with the highest signal-to-noise ratio ($S/N \sim 120$), NdIII λ5845.07 Å.

The highest peaks for the radial velocity data and magnetic data are at 1.38 mHz corresponding to a period of 12.1 min which agrees well with the periods found in the photometric study of Martinez et al. (1996). With only 57 min of data we cannot resolve the four frequencies they found in their extensive photometric study; the peaks in the amplitude spectra in Fig. 1 encompass their higher-resolution, resolved frequencies. A linear least squares fit of the frequency 1.38 mHz was made to the radial velocity and magnetic data with the results shown in Table 1 for the individual lines. The magnetic field variability is a 4.1–6.6 σ detection for the four lines with the 12.1-min pulsation period. The radial velocity amplitude of the NdIII λ6145.07 Å line of 388 ± 54 m s^{-1} agrees well with the 470 m s^{-1} found by Kochukhov & Ryabchikova. There is a small phase difference between the radial velocity variations and the magnetic variations of 0.15 ± 0.05 cycles. The last column of Table 1 gives the standard deviation per observation to the fit.

The question arises as to whether the line profile variability in this line (see Kochukhov & Ryabchikova 2001b), or the radial velocity variations could falsely give rise to the magnetic field variability we have discovered. To measure the effective magnetic field, we measure the distance between the average positions of right and left circularly polarised (σ) Zeeman components. That is, we measure the distance between the two barycentres of the $(I+V)$ and $(I-V)$ line profiles computing the first moment of the Stokes V profile. During the oscillations for a constant magnetic field, the barycentres of the $(I+V)$ and $(I-V)$ line profiles should move in synchrony. For γ Equ, we observe different radial velocity variations for the two σ components.

Figure 2 illustrates our results for the NdIII λ5845.07 Å and CaI λ5857.45 Å lines that show the extremes of variability and lack of variability in the lines studied in our spectrum of γ Equ. This is not unexpected, given the behaviour of different lines which form at different depths in the roAp stars, as we discussed in the introduction. For those two lines Table 2 lists our observations which span 57 min, or nearly five pulsation cycles.

The average magnetic field strengths for our eight lines are given in Table 3. With the caveat of the uncertainty in the theoretical Landé factors for Nd lines (see Mathys 1990 for the importance of experimental values), we find it interesting that the CaI lines gives an average value of $< H_{\rm eff} > = -980$ G that is much less than the $< H_{\rm eff} > = -1450$ G for the four NdIII lines. This is what we expect if CaI is more uniformly distributed over the visible hemisphere and NdIII is more concentrated towards the magnetic poles – a situation to be expected in an Ap star. If this effect is real, it provides a new way to measure the degree of concentration of ions towards the magnetic pole. It could provide a way to distinguish the horizontal

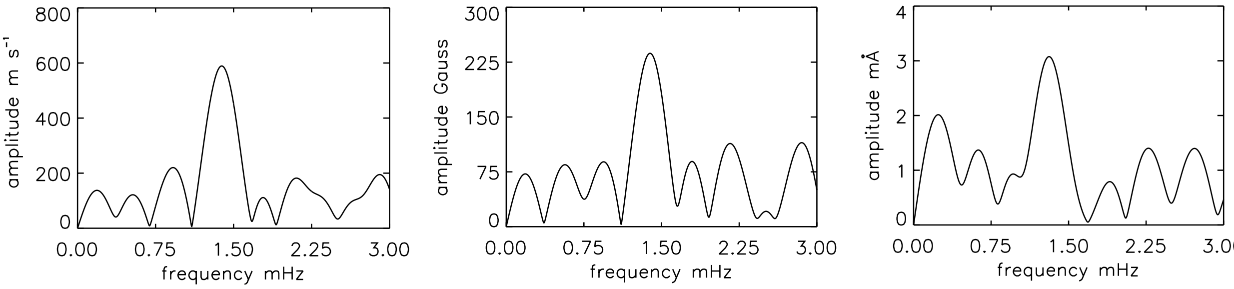

Fig. 1. The amplitude spectra for the radial velocity, effective magnetic field strength and equivalent width for the NdIII λ5845.07 Å line data. The highest peak has a period of 12.1 min and agrees well with the known photometric pulsation periods.

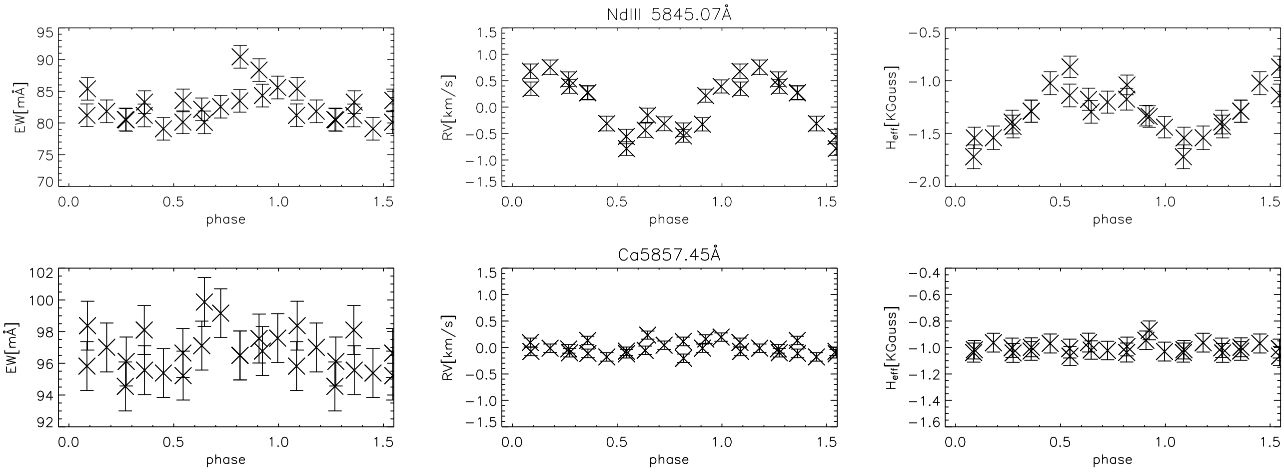

Fig. 2. Phase plots of the variability of the equivalent width, radial velocity and effective magnetic field strength from the NdIII 5845.07 Å line as a function of the 12.1-min oscillation period determined from Fig. 1. The bottom panel shows the lack of variability for the CaI 5857.45 Å line.

Table 3. The average $H_{\rm eff}$ and adopted effective Landé factors for the NdIII and CaI lines studied.

ion	λ Å	$g_{\rm eff}$	$\langle H_{\rm eff} \rangle$ G
NdIII	5845.07	1.101	–1291
NdIII	5987.80	1.065	–1241
NdIII	6145.07	0.995	–1815
NdIII	6327.24	0.965	–1468
CaI	5857.45	1.000	–1001
CaI	6439.07	1.210	–874
CaI	6471.66	1.202	–1124
CaI	6499.65	0.958	–937

concentration from the vertical stratification (see Ryabchikova et al. 2002) in non-rotating stars such as γ Equ where Doppler imaging fails. Further studies will examine this interesting possibility in more detail.

4. Conclusions

We have discovered the first magnetic field variations over the pulsation period in a roAp star. The amplitude of the magnetic variability we have found for γ Equ in the range of 112–240 G for the Nd lines is in good agreement with theoretical expectations (Hubrig et al. 2003) of 10% of the effective field strength which is, in this case, 145 G. We have also found that the magnetic field and radial velocity extrema are shifted in period by 0.15 ± 0.05 cycles. This is the first observation of these kinds of behaviour; no theoretical studies have yet been made to understand it.

These discoveries provide a new measure of the magnetic field geometry, potentially in three dimensions. If the difference in the effective magnetic field strength for different ions is confirmed, this provides a way to make the difficult distinction of how much of the radial velocity variation differences from line-to-line in roAp stars is due to surface variability in the abundances (with concentrations of some ions near the magnetic poles), and how much is due to vertical stratification of the abundances – improving the prospect for full three-dimensional resolution of the abundance distributions, magnetic field geometries and pulsation modes in these stars.

What is still unclear is the origin of the variability of the effective magnetic field with the pulsation period. We have measured the average of longitudinal components of the field weighted by the line strength within the stellar visible disk. Because of the pulsations, any point of the visible disk changes its thermodynamic and kinematics properties and with them its emerging line profile. For this reason, we could conclude that we are observing an *apparent* variation of the magnetic field simply because during the pulsations different areas of the visible disk give the largest contribution to the line profile. Alternatively, if the line formation region is not very large, what we measure is the magnetic field in a thin layer and we cannot rule out that this field becomes stronger and weaker because of compression and expansion during the pulsation.

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