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Rapid radial velocity variations in the Ap star HD 965

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Abstract. We present the results of an investigation of the magnetic Ap star HD 965 with high spectral and time resolution. We determine exact radial velocities using spectra obtained with the UVES spectrograph on the ESO VLT. Special attention is given to the spectral lines of the Rare Earth Elements which in roAp stars exhibit the strongest radial velocity variations with pulsation period. Careful time series analysis did not detect any convincing evidence of pulsation in HD 965 with an upper limit in amplitude of $15 - 20\,\mathrm{m\,s^{-1}}$.

Keywords. Stars: chemically peculiar, stars: oscillations, stars: magnetic fields, stars: individual: (HD 965, 33 Lib)

1. Introduction

HD 965 is a slowly rotating cool Ap star with a strong magnetic field. A mean magnetic field modulus of 4.4 kG was found by Mathys *et al.* (1997). Kochukhov *et al.* (2002a) suggested $T_{\rm eff} = 7450$ K. This indicates that HD 965 has a position in the H-R diagram near where the δ Sct instability strip crosses the Main Sequence. The star also has an abnormal Hα profile – the so-called core-wing anomaly (Cowley *et al.* 2001). Very strong lines of Rare Earth Elements (REE) are dominant in the optical spectrum. The photometric parameters shown in Table 1 for HD 965 are similar to those for many roAp stars. All the main characteristics of HD 965 are typical for roAp stars.

It was, therefore, surprising that this star has been shown to have no rapid photometric variability. Kurtz *et al.* (2003a) found an upper limit of 0.2 mmag to any photometric pulsation in the frequency range of the roAp stars.

There are several possible reasons for this null result in the photometry:

(*a*) The star belongs to the group of cool, non-rapidly oscillating Ap (noAp) stars and does not have any rapid variations. The reason why some cool Ap stars seem not to pulsate is unknown.

(*b*) The star has rapid oscillations with an amplitude below 0.2 mmag. The mode driving mechanism is uncertain in roAp stars and the mode selection mechanism is unknown.

(*c*) The photometric observations were made during one short time interval. For roAp stars the oscillations are strongest when the magnetic poles are closest to the line-of-sight and weakest when observed towards the magnetic equator. Possibly the photometric observations were made near a time of pulsation minimum. The modulation period is the rotation period of the star, and for some Ap stars this can be decades.

Recently it has been found that lines of the REE, especially those of Pr III and Nd III, show a strong variation of the radial velocity with the period of photometric oscillations in roAp stars. This is a new additional way to study rapid oscillations.

The spectrum of HD 965 possesses the typical strong lines of Pr III and Nd III which provide a good opportunity for testing the pulsation properties spectroscopically. We

Table 1. Photometric properties HD 965 (Perry 1991) and the range in these indices for roAp stars (Martinez *et al.* 2001)

Strömgren indices	HD 965	roAp star range
$b - y$	0.268	0.08 − 0.31
m_1	0.296	−0.19 − 0.33
c_1	0.444	0.46 − 0.88
β	2.740	2.69 − 2.88
δm_1	−0.114	−0.12 − 0.02
δc_1	−0.216	−0.31 − 0.04

present here the results of a search for rapid radial velocity variations in the spectral lines of REE and some another chemical elements in HD 965 in spectra obtained with the UVES on the ESO VLT.

2. Observations and data processing

Spectroscopic observations of HD 965 were obtained at the ESO VLT telescope in 2003 October. Using the UVES (UV-Visual Echelle Spectrograph), 111 high resolution spectra ($R = 10^5$) were obtained over a 2-hr observing period. The exposure time for each spectrum was 40 s and the readout time 25 s, giving a time resolution 65 s. CCD images were processed and 1D spectra extracted using the UVES pipeline and the ESO MIDAS package. The extracted spectra were normalized to the continuum and the times were corrected to the barycenter of the solar system. The spectra have a range from λ4970 to λ7010 with a gap of about 60 Å centred around λ6000, where the two CCDs join. The signal-to-noise ratio of the spectra is about 50. We smoothed each spectrum using the running average on five points to reduce the noise level. This procedure did not lead to any loss of information about the radial velocity of the whole line when it was tested using roAp stars. The spectra have telluric bands which were used to test for instrumental shifts.

Precise radial velocities were measured for number of spectral lines by fitting a Gaussian and by the centre-of-gravity method, separately for each line or sometimes for each Zeeman component of line, after identification using the VALD data base (Kupka *et al.* 1999) and the line lists for roAp stars from the Vienna AMS team (`http://ams.astro.univie.ac.at`).

3. Radial velocity measurements

As was discovered by Savanov *et al.* (1999) the largest radial velocity variations for the roAp star γ Equ occur for lines of Pr III and Nd III. They found a maximum amplitude in Pr III λ6160 of $700 - 800\,\mathrm{m\,s^{-1}}$ and near $500\,\mathrm{m\,s^{-1}}$ for Nd III λ6145. They discovered that lines of the REE show the largest rapid radial velocity oscillations. Other elements show weaker, or no variability. Later this result was confirmed for other roAp stars. Mkrtichian at al. (2003) obtained rapid radial velocity variations in 33 Lib, Kurtz *et al.* (2003b) in HD 166473, and Kochukhov *et al.* (2002b) in 10 Aql. The maximum semi-amplitude in the radial velocity in the roAp stars found so far is as great as $1 - 1.5\,\mathrm{km\,s^{-1}}$ (Kurtz *et al.* 2005) and as small as below $100\,\mathrm{m\,s^{-1}}$ (Kurtz *et al.* 2003b, Elkin *et al.* 2004).

Accordingly we started our examination of HD 965 using lines Nd III and Pr III and other REE. For the best lines we obtained a noise level for the highest peaks in the

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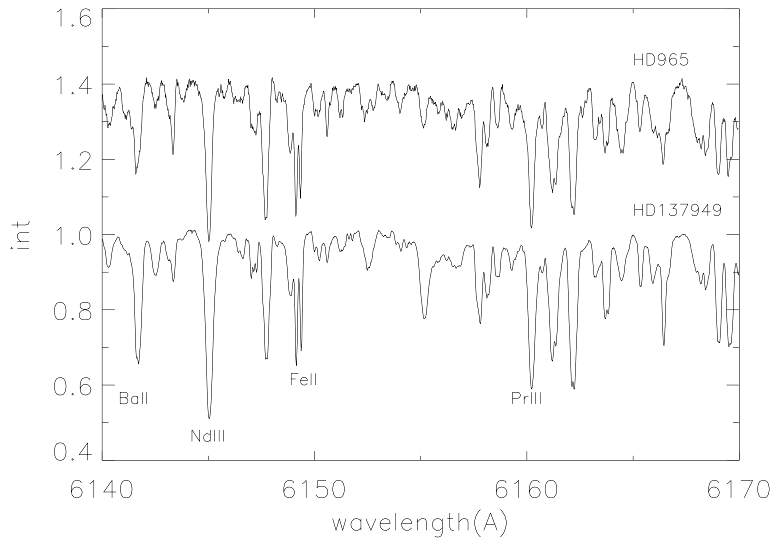

Figure 1. Comparison between the spectra of HD 965 and the roAp star HD 137949 (33 Lib).

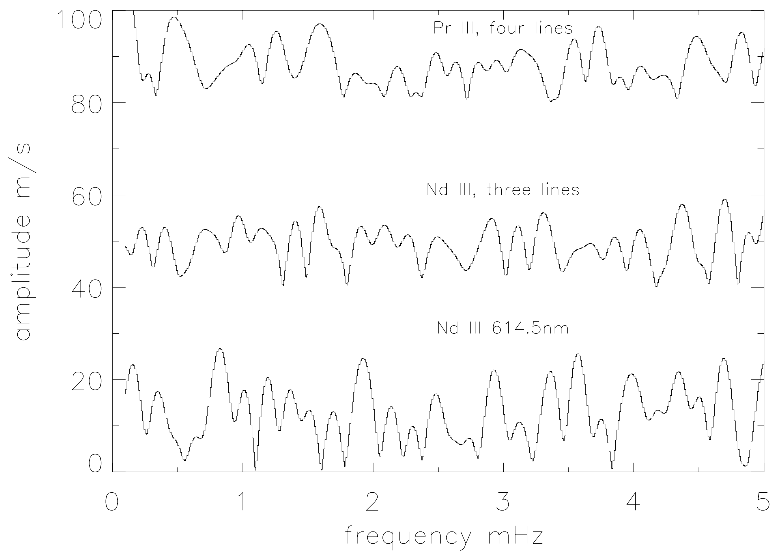

Figure 2. Amplitude spectra for Nd III λ6145 for three lines of Nd III and for four lines of Pr III (the last two shifted by 40 $m\,s^{-1}$ and 80 $m\,s^{-1}$ on the y axis).

amplitude spectrum of $20 - 35\,m\,s^{-1}$. We combined results for several lines to improve the precision. In Fig. 2 we present the amplitude spectra for the line Nd III λ6145, for the sum of three lines of Nd III and sum four lines of Pr III. After combination the precision is slightly better. We can place an upper limit on any possible oscillations of $20\,m\,s^{-1}$ for the lines of Nd III and Pr III. We also tested lines of Nd II and several other REE, such as

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Ce II and Zr II, but the noise level was too high for many of them. The results for other elements (Mg, Ca, Fe, Cr, Ti) with an upper limit of $15-20\,\mathrm{m\,s^{-1}}$ also did not show any pulsation variability.

Sachkov *et al.* (2004) and Kurtz *et al.* (2005) found large variations of the oscillation amplitude as a function of depth within individual spectral lines. Bisector measurements show that some parts of the profiles have a higher amplitude oscillation than others. They also found that lines of a particular ion have amplitudes that are correlated with line strength, indicating pulsation amplitude variation with atmospheric depth, i.e., resolution of the vertical structure of the pulsation mode. These higher amplitudes could increase the chance to detect oscillations. Taking into account their results we also tried to study the velocity field across the profile of several spectral lines in HD 965. We did not detect any significant peaks in the amplitude spectra as a function of depth in some spectral lines of REE with an upper limit from $20\,\mathrm{m\,s^{-1}}$ in the middle part of line to $60\,\mathrm{m\,s^{-1}}$ near the continuum.

4. Concluding remarks

Despite that the cool Ap star HD 965 has many physical parameters that are typical for roAp stars, we did not find rapid radial velocity variations. This could be because we observed star from an unfavourable aspect above the magnetic equator. This conclusion is confirmed by measurements of the longitudinal magnetic field obtained at 6-m telescope in Special Astrophysical Observatory (Wade *et al.* 2004). Our observations were when longitudinal field was near zero. The rotation period of the star is unknown, but appears to be more than five years. The long rotation period is also a possible reason why rapid photometric variations were not found by Kurtz *et al.* (2003a) who observed one year prior to our observations.

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