Contrib. Astron. Obs. Skalnaté Pleso **38**, 317 – 322, (2008)

VLT observations of rapid radial velocity variations in roAp stars

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Received: January 9, 2008; Accepted: January 19, 2008

Abstract. We have studied 27 out of the 37 known roAp stars with high resolution spectroscopy using UVES on the ESO VLT. All 27 stars show rapid radial velocity variations with periods similar to those obtained by photometry. Highest pulsation amplitudes are seen for lines of rare earth elements and the Hα core. For some stars other chemical species also have pulsation, but with smaller amplitudes. There are pulsational phase shifts between lines of different rare earth elements. Stars with stronger magnetic fields tend to have lower radial velocity pulsation amplitudes.

Key words: stars: oscillations – techniques: radial velocities

1. Introduction

The history of rapidly oscillating A peculiar (roAp) stars began thirty years ago with the discovery of short term light variability in the famous Przybylski's star (HD 101065, Kurtz, 1978). The initial methods for the study of pulsations in roAp stars were mainly photometric which successfully led to discovery more than thirty of these rapid pulsators, and provided the data to illuminate many unusual properties using the oblique pulsator model (Kurtz, 1982; 1990; Kurtz, Martinez 2000). It appeared that high time resolution spectroscopy could provide further enlightenment on the nature of pulsation in peculiar stars (Matthews *et al.*, 1988). High time and spectral resolution observations opened a new horizon for the analysis of roAp stars. When the magneto-acoustic waves propagate through the spotted and stratified atmospheres of roAp stars, they generate Doppler shifts and variations of the spectral line profiles of certain chemical elements in different manners (Kurtz *et al.*, 2006). We review here the pulsation behaviour of a sample of roAp stars using high resolution spectra obtained with the ESO VLT. Recently Gonzalez *et al.* (2007) discovered a new roAp star and Kochukhov *et al.* (2008) another one, bring the total number of known roAp stars to 37.

We observed 26 roAp stars in two observing sets in 2004 and 2006 using ESO VLT UVES. One roAp star was observed earlier, thus to date we have high time and spectral resolution observations for 27 of the 37 known roAp stars – a good basis for the study of their pulsation behaviour in detail. Twenty

Table 1. $T_{\rm eff}$ and $\log g$ for roAp stars estimated from the Moon and Dworetsky (1985) calibration of Strömgren indices and from Hα fitting. Column 5 shows $v \sin i$ from lines with small Landé factors. Pulsation amplitudes are shown in column 6 (maximum amplitude), column 7 (from the Hα core) and column 8 (photometric amplitude). The mean magnetic field moduli obtained from the Fe II 6149 Å line for stars with strong magnetic fields and slow rotation are presented in last column. For some stars with wide spectral lines upper limits of magnetic field strengths were estimated by comparison with synthetic spectra.

Star	$T_{\rm eff}$ M&D	$\log g$	$T_{\rm eff}$ Hα	$v \sin i$ km s^{-1}	$A_{\rm max}$ km s^{-1}	A(Hα) km s^{-1}	ΔB mag	$H_{\rm z}$ kG
6532	8200	4.3	7900	30.0 ± 3.0	1.15	0.97	5	
9289	7700	4.1	8000	10.5 ± 1.0	0.85	0.48	3.5	
12932	7500	4.1	7500	2.5 ± 0.5	1.40	0.72	4	1.2
19918	7900	4.3	7800	3.0 ± 0.5	1.30	1.10	2	1
42659	7700	4.4	7500	19.0 ± 1.0	0.70	0.15	0.8	
60435	8200	4.4	7800	10.8 ± 1.0	1.9	0.58	16	
80316	8160		7700	32.0 ± 1.0	0.32	0.32	2	
84041	7800	4 3	7500	25.0 ± 1.0	0.5	0.20	6	
99563	7700	4.4	8000	28.0 ± 1.0	4.9	3.40	10	
101065			6800	4.0 ± 1.0	1.03	0.34	13	2.3
116114	7700	4.1	7600	2.2 ± 0.5	0.65	0.03	-	6.0
122970	6700	4.2	7000	4.2 ± 0.5	1.05	0.14	2	1.7
128898	7700	4.2	7500	13.5 ± 1.0	0.80	0.26	5	
134214	7250	4.5	7400	2.6 ± 0.5	0.72	0.18	7	2.7
137909	7800	4.4	7800	3.5 ± 0.5	0.04	0.03	-	5.3
137949	7700		7700	3.0 ± 0.5	0.33	0.33	3	4.7
150562	7300	4.4	7500	1.5 ± 0.5	0.14	0.14	0.8	5.0
154708	7050		7200	4.0 ± 0.5	0.09	-	-	25.0
166473	7700		7700	2.5 ± 0.5	0.10	0.06	2	8.5
176232	7600	4.1	7400	2.7 ± 0.5	0.54	0.11	0.6	1.4
185256	7000	4.3	7250	6.2 ± 0.5	0.15	0.14	3	
190290	7600		7500	16.0 ± 1.0	0.50	0.49	2	
193756	7600	4.3	7500	17.0 ± 1.0	0.74	0.12	0.9	
201601	7600	4.2	7600	2.5 ± 0.5	0.58	0.30	3	3.8
203932	7400	4.2	7200	4.7 ± 0.5	0.33	0.05?	2	1.1
217522	6700		7100	2.7 ± 0.5	0.12	0.07	4	1.7
218495	8100	4.4	8000	16.0 ± 1.0	0.79	0.40	1	

six stars were observed with VLT for 2 hr with exposure times typically from 20 to 80 s and readout times about 25 s with an average spectral resolution of $\sim 10^5$. The UVES pipeline was employed for reduction and extraction of 1D spectra. Synthetic spectra computed with the programs SYNTH (Piskunov, 1992) and SYNTHMAG (Piskunov, 1999) using Kurucz and NeMo models atmospheres

(Heiter *et al.*, 2002) were exploited for the analysis. Spectral line lists were taken from VALD (Kupka *et al.*, 1999) and the DREAM data base (Biemont *et al.*, 1999) extracted via VALD. Gaussian fitting and centre-of-gravity methods were employed for measuring the central positions of individual spectral lines to get precise radial velocities.

2. Physical parameters

The list of stars and their parameters determined from the calibration of Strömgren photometry by Moon and Dworetsky (1985) and from Hα profile fitting with synthetic spectra are presented in Table 1. The effective temperatures obtained from the Moon and Dworetsky (1985) calibration, which was developed for normal stars, still provide reasonably acceptable results for roAp stars that are comparable to those obtained from Hα fitting. The gravity estimate from Strömgren photometry is poor because of the peculiar δc_1 indices of the roAp stars, thus some values that are obviously too large were removed from the table. The $\log g$ values estimated from Hα profiles have a precision no better than 0.2; the $T_{\rm eff}$ values have standard errors of about 200 K, and lower for particular stars. We found that most roAp stars are extremely slow rotators. Almost 70% show projected rotational velocities below 12 km s^{-1}, as can be seen in Table 1.

Of the 27 stars we studied, 16 stars (59%) have $v \sin i \leq 6$ km s^{-1}, 7 stars (26%) have 10 km s^{-1} $< v \sin i \leq 20$ km s^{-1} and 4 stars (15%) have 20 km s^{-1} $<$ $v \sin i \leq 32$ km s^{-1} . To estimate $v \sin i$ we used lines with low Landé factors to avoid the influence of magnetic broadening. We also took into account instrumental broadening, but we did not consider possible micro- and macro-turbulent broadening which require further study. For many roAp stars the broad wings of strong rare earth lines such as Nd III and Pr III require additional turbulence parameters. This broadening is much smaller or even negligible for the iron lines used for $v \sin i$ determinations. In cases of possible turbulent broadening the real values of $v \sin i$ may be even slightly smaller. For HD 101065 we measured $v \sin i = 4$ km s^{-1} from narrow lines belonging to rare earth elements. To fit the partially magnetic split line of Gd II 5749 Å we needed a smaller $v \sin i = 1.5$ km s^{-1}.

3. HD 101065 (Przybylski's star) and 10 Aql

As one of example of our study we present results for the famous Przybylski's star that shows extremely peculiar atmospheric abundances (Cowley *et al.*, 2000). The radial velocity curve for the Hα core, the Pr III 5300 Å line together with a cross-correlation for an iron-only template are shown in Fig. 1. Most of lines in the spectrum belong to rare earth elements and show rapid radial velocity variations with a period of 12.15 min. Different elements demonstrate different pulsation amplitudes. The highest amplitude ($\sim$1 km s^{-1}) is found for lines of Tb III. The lines of Pr III have smaller amplitudes (about $0.7\,\mathrm{km\,s^{-1}}$). The most numerous lines in the spectra are of Nd II and Ce II which demonstrate amplitudes of $0.3\,\mathrm{km\,s^{-1}}$ and $0.1\,\mathrm{km\,s^{-1}}$, respectively. A whole picture

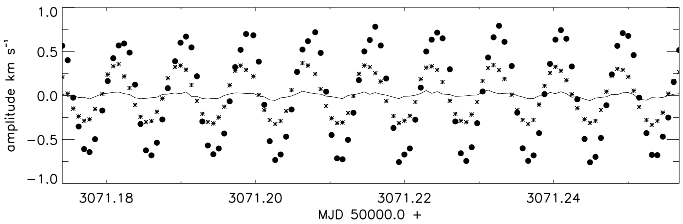

Figure 1. Radial velocity curves for the Hα core (stars) and Pr III 5300 Å (dots) line. The solid line shows the cross correlation curve for a synthetic template calculated only for iron lines.

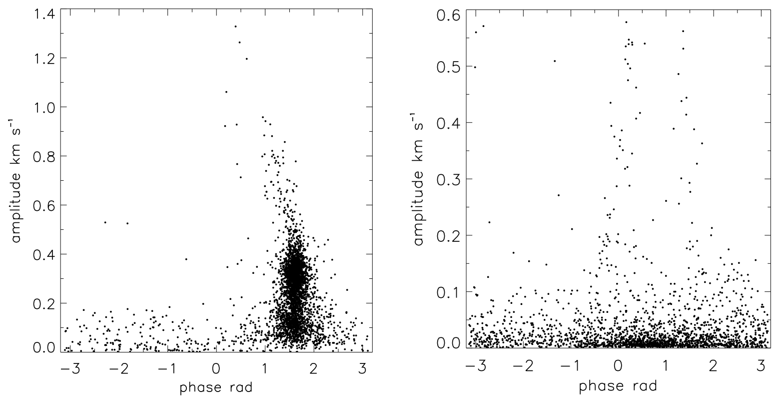

Figure 2. Left: Pulsation amplitudes versus phases for more than 3000 spectral lines in HD 101065 and **right**: for 2000 lines in the spectra of 10 Aql. Many lines of light and iron peak elements do not show detectable pulsation and concentrate in the lower part of diagram. There are clear vertical sequences visible at several different phases.

of pulsation amplitudes according to phase for more than 3000 spectral lines is presented in Fig. 2. There are still questions about pulsation behaviour of non-rare earth elements in this star. It is not easy to find unblended lines. We used the best lines and found weak pulsation amplitudes for iron and chromium. The phases are similar to those found for lines of rare earth elements and may be evidence of blending. We also used the whole list of iron lines from VALD and calculate a synthetic template for iron only; lines of all other elements were

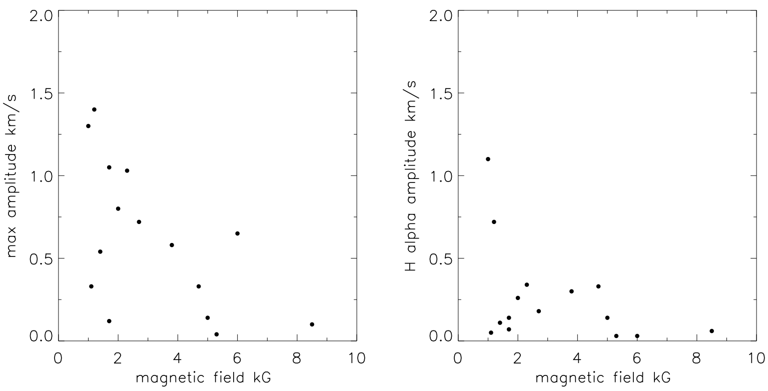

Figure 3. Pulsation amplitudes *vs.* magnetic field strength for narrow lines in an roAp star sample. **Left**: results for maximum estimated amplitudes, **right**: for the Hα core.

removed. In Fig. 1 the solid line shows the cross correlation radial velocity curve for this iron line template.

Another example from our study is the well-known pulsating star 10 Aql which is less peculiar than Przybylski's star. In Fig. 3 pulsation amplitudes and phases are presented for more than 2000 lines in the spectrum of 10 Aql. The highest pulsation amplitudes of more than 0.5 km s^{-1} with the known photometric pulsation period, 11.7 min, are found for rather weak lines of Tb III and Dy III. The pulsation phases obtained for lines of Tb III and Dy III differ by π radians, perhaps an indication of a radial node between their line-forming layers. Surprisingly, the lines of Pr III show the lowest detected pulsation amplitudes in strong contrast to the majority of roAp stars for which this ion has some of the highest radial velocity amplitudes. Lines of Nd III with different intensities have different pulsation amplitudes, with weaker lines that are formed more deeply in the atmosphere having higher amplitudes. Line bisectors for strong Nd III line profiles show significant changes of phase, and even phase jumps for some lines, indicating complex variations in the pulsation phase as a function of atmospheric depth.

4. Pulsations amplitudes in roAp stars

Table 1 presents pulsation amplitudes for the studied stars. The maximum values in the sixth column are taken from an average for several lines of chemical elements which show highest amplitudes in our spectral region from 4970 to 7010 Å. The rare earth elements are strongly inhomogeneously distributed on the stellar surface. The pulsation amplitudes obtained from these lines depend on horizontal and vertical distributions and the sizes of the spots which differ significantly from star to star.

The line forming region of the Hα core has a more homogeneous distribution and seems more suitable for comparison of roAp stars. Therefore, we also add to Table 1 the amplitudes obtained from Hα core. A comprehensive analysis measuring all suitable spectral lines has not been done for all stars in Table 1. Improvements and changes are to be expected after more complete analysis. We found seven stars with pulsation amplitudes more than 1 km s^{-1}: HD 6532, HD 12932, HD 19918, HD 60435, HD 99563, HD 122970. A majority of 17 stars reveal maximum amplitudes in the range $0.1 - 1$ km s^{-1}; some of these stars may move to the first group of high amplitudes stars with further study. Weak pulsation amplitudes below 0.1 km s^{-1} have been detected for three stars: HD 116114, HD 137909 (β CrB) and HD 154708. There is no obvious correlation between the photometric and radial velocity pulsation amplitudes.

However, there may be a link between the magnetic field strength and pulsation amplitude. Fig. 3 shows the relation between the magnetic field strengths and pulsation amplitudes for stars for which we could determine the magnetic field modulus (H_z). The magnetic field is weaker for stars with higher amplitudes. Two extreme cases, HD 99563 and HD 154708, are not shown on Fig. 3, but are consistent with this suggestion. For HD 99563 we cannot get direct measurements of H_z because of the high $v\,sin\,i$, but estimate it to be about 2 kG from the longitudinal field curve and stellar parameters. HD 154708 with very strong field of $\sim$25 kG has very low pulsation amplitude.

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