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Radial velocity pulsations in the atmosphere of the roAp star HD 24712

M. Sachkov[1], T. Ryabchikova[1,3], I. Ilyin[2], O. Kochukhov[3] and T. Lüftinger[3]

[1]Institute of Astronomy, Russian Academy of Science, Pyatnitskaya 48, 119017 Moscow, Russia
email: msachkov@inasan.ru

[2]Astrothysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany

[3]Institute for Astronomy, University of Vienna, Türkenschanzstraße 17, 1180 Vienna, Austria

Abstract. We present results of the analysis of spectroscopic time-series observations of the roAp star HD 24712 obtained at the phase of magnetic maximum. As in previous investigations of roAp stars we found that only lines of the rare-earth elements (REE) show RV pulsational variations. These pulsations in HD 24712 are characterised by gradual phase shifts between RV curves of different REE. The same pulsations of HD 24712 were observed in 2001, giving strong evidence for the stability of the pulsational mechanism in this star. NLTE calculations of Nd line depth formation in stratified atmosphere of HD 24712 allowed us to study the pulsational phase distribution with optical depth, providing strong evidence for a running wave, propagating outward with nearly constant RV amplitude.

Keywords. Stars: chemically peculiar, stars: atmospheres, stars: individual: (HD 24712), techniques: radial velocities, techniques: spectroscopic

1. Observations and radial velocity measurements

Our observations of the roAp star HD 24712 were carried out on November 6, 2003 with the SOFIN high resolution échelle spectrograph at the 2.56-m Nordic Optical Telescope, La Palma, Spain. Fifty-three spectra with resolution $R = 80\,000$, $S/N = 80$, and time resolution 105 s (50 s of exposure + 55 s overhead) in the $\lambda\lambda$5000–6800 region were analysed for radial velocity (RV) pulsations. The spectra were reduced with the 4A package. Observations were obtained near magnetic maximum. High S/N and spectral resolution of the observations allow us to carry out an analysis of RV variations across individual spectral lines. We studied RV variations using moment (center-of-gravity) measurements.

2. RV lines analysis and phase shifts

More than 100 unblended spectral lines were measured in the spectrum of HD 24712. The subsequent measurements show that, as in previous investigations of roAp stars, the lines of rare-earth elements in the first and the second ionisation stages have the maximum RV amplitudes.

Fig. 1 shows the pulsation behaviour of selected lines. Pulsating lines were searched first by calculating the power spectrum image separately for each wavelength pixel. The limited number of spectrograms (53 spectra) does not allow us to perform a comprehensive frequency analysis. We calculated the pulsation period as an additional parameter in the

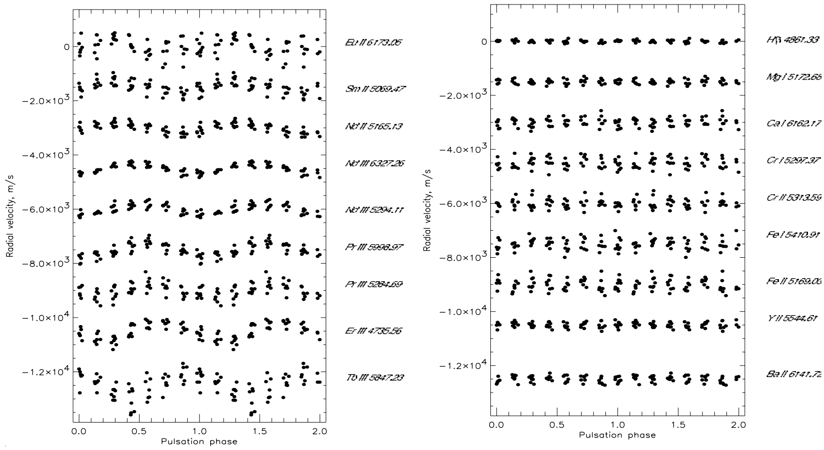

Figure 1. RV curves for pulsating (left) and nonpulsating (right) lines in the spectrum of HD 24712.

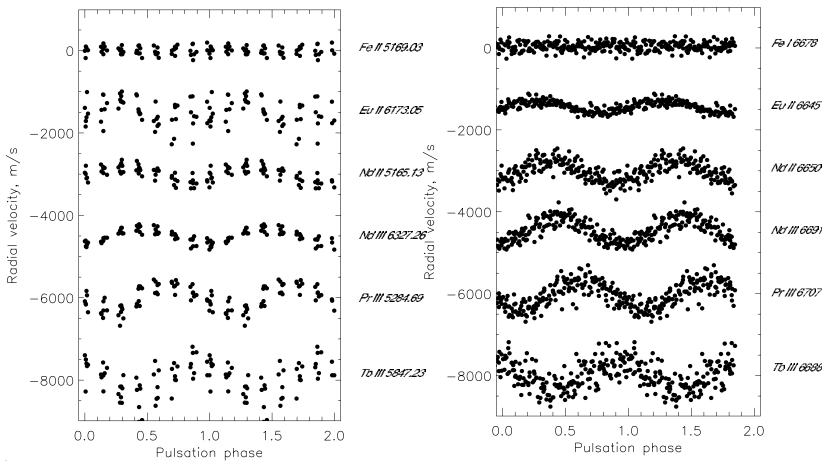

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Figure 2. RV pulsation of REE lines pulsation in the 2001 (right) and the 2003 (left) observation sets.

least square fitting of the radial velocity curves for different ions. Then we estimated the probability of the derived period. We consider a line as pulsating only if this probability is greater than 0.995. Spectral lines of iron-peak elements (Ca, Cr, Fe, Co), and Mg, Si, Hβ core, strong Y II and Ba II lines are not variable above the errors of RV measurements (15–30 m s^{-1} for strong lines) from this point of view. Although one can imagine that some of these lines (for example, Fe I or Cr II in Fig. 1) pulsate, the probability of such pulsation is extremely low. Scatter in the plots depends on the line strength (for both pulsating and nonpulsating features): stronger lines have smaller scatter.

The pulsation period derived from the REE lines (Pr III, Nd II, Nd III, Eu II, Tb III) coincides with one of seven photometric periods, $P = 6.20$ min.

Pulsation curves for the lines of the same REE ions do not significantly differ in phase, but phase shifts occur between the RV curves of different REE elements. Our previous study (Sachkov *et al.* 2004) of other lines of the same elements shows similar pulsational behaviour, although the star was pulsating with slightly different period, P=6.13 min.,

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which again coincides with one of the photometric periods. This provides strong evidence for the stability of the pulsational mechanism in HD 24712 (see Fig. 2).

Table 1. Unidentified pulsating lines in the spectrum of HD 24712.

Line	Period (min)	Probability of Period	Amplitude ($m\,s^{-1}$)	Phasemax	Depth	EqW (mÅ)
4570.65	6.12(0.01)	1.0000	344(30)	0.425(0.014)	0.675	56
4642.99	6.20(0.04)	0.8993	176(37)	0.343(0.034)	0.778	50
4651.62	6.20(0.01)	1.0000	255(19)	0.422(0.012)	0.531	94
4734.76	6.14(0.04)	0.9922	170(32)	0.449(0.031)	0.733	65
4740.67	6.24(0.05)	0.8212	320(79)	0.402(0.040)	0.898	21
4759.54	6.17(0.02)	0.9999	200(19)	0.435(0.016)	0.584	97
5064.05	6.17(0.04)	0.9998	247(52)	0.382(0.034)	0.838	30
5083.85	6.13(0.04)	0.9967	323(58)	0.446(0.030)	0.847	35
5852.44	6.18(0.02)	1.0000	238(28)	0.339(0.018)	0.760	69
6012.30	6.17(0.03)	0.9993	194(29)	0.387(0.024)	0.799	49
6014.56	6.22(0.02)	0.9999	258(29)	0.431(0.018)	0.769	52
6148.86	3.69(0.03)	0.3565	81(44)	0.362(0.087)	0.882	30
6524.48	6.22(0.02)	0.9999	308(37)	0.363(0.019)	0.850	38
7873.68	6.19(0.02)	0.9955	283(27)	0.425(0.015)	0.779	76
8454.68	6.20(0.02)	0.9052	260(25)	0.492(0.016)	0.776	87

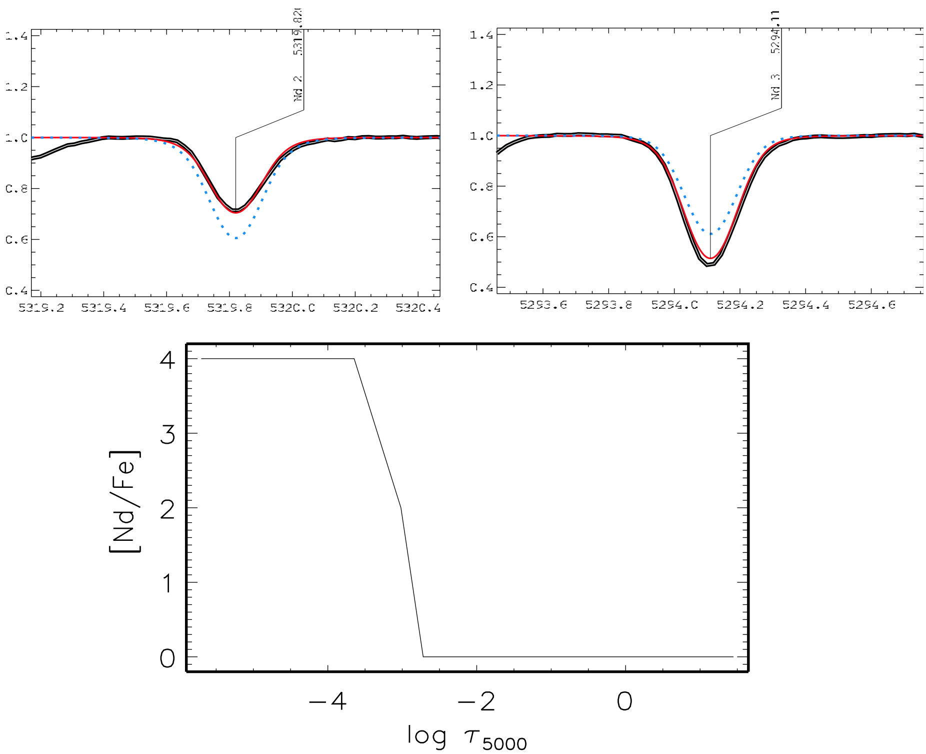

Figure 3. Stratification NLTE analysis of Nd in the spectrum of HD 24712. The upper panel compares the observed (double line) and theoretical profiles of the Nd II (left) and Nd III computed assuming chemically homogeneous atmosphere (dotted line) and vertical stratification of Nd (solid line).

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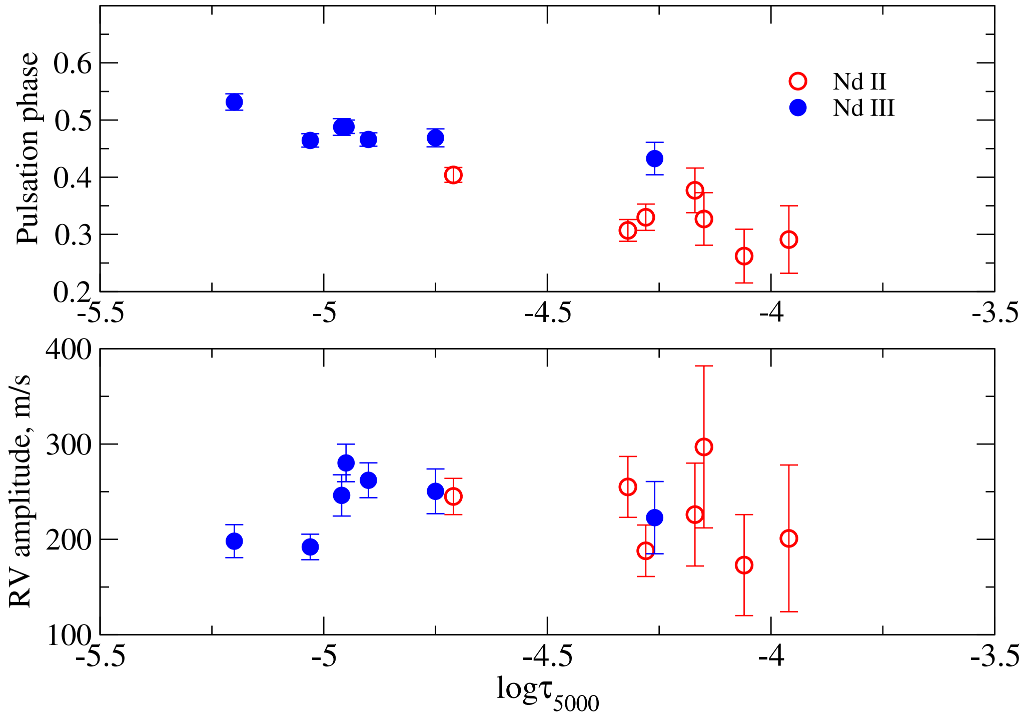

Figure 4. Pulsation phase (top panel) and RV amplitude (bottom panel) as a function of the line formation depth in the stratified atmosphere of the roAp star HD 24712.

3. NLTE analysis for HD 24712 and element stratification

NLTE analysis of Nd lines (see Mashonkina *et al.* 2005) shows that Nd is concentrated above $\log\tau \approx -3$. This distribution describes well the observed line profiles (Fig. 3). The depth formation of a few spectral lines was calculated for stratified model. The phase of the pulsation maximum increases with optical depth, supporting a hypothesis of a running wave in the atmosphere, which propagates towards the upper layers with a nearly constant RV amplitude. Clearly, NLTE calculations for other REE, in particular Pr III and Tb III, are needed for a better understanding of the pulsation phenomenon in the roAp atmospheres. There are some indications that the RV amplitude may decrease in the uppermost layers (see Fig. 4).

4. Unidentified lines in roAp stars' spectra

In roAp stars only lines of the rare-earth elements (REE) show high amplitude RV pulsational variations (up to 1 $\mathrm{km\,s^{-1}}$ and even more). Such unique pulsational behaviour can serve to identify unknown lines in roAp stars' spectra. In Table 1 we give pulsational data for unidentified lines in HD 24712. Unpublished Mrs. Crosswhite's lists (Crosswhite 2003) of Nd III lines (both classified and unclassified) contain the λ4570.65, λ4651.62, λ4734.76, λ4740.67, λ4759.54, and λ5083.85 lines. Our study strongly supports the identification of these lines as Nd III. Pulsational amplitudes and phase shifts of the λ6014.56, λ7873.68 and λ8454.68 lines permits us to propose these lines as Nd III lines too.

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