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Pulsations in the atmospheres of Ap stars

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Abstract. We present recent results of the observational study of rapidly oscillating Ap (roAp) stars. Spectacular progress in this field has been achieved by considering high time resolution spectroscopy in addition to the classical high-speed photometric measurements. Spectroscopic observations of roAp pulsations led to the discovery of a multitude of unexpected phenomena, generally pointing to an extreme vertical chemical nonuniformity of the atmospheres of magnetic CP stars. Detailed analysis of spectroscopic pulsational behavior allows us to establish relationship between pulsations and vertical stratification of chemical elements.

Key words. Stars: pulsation – Stars: atmospheres – Stars: roAp

1. Introduction

Within the edges of the classical instability strip, close to the main sequence the rapidly oscillating Ap (roAp) stars were found (Kurtz 1982). These are stars of spectral type A and early F with especially strong overabundances of rare-earth elements (REE). As a subclass of Ap stars most of roAp stars posess magnetic field of different intensity. HD 166473 has the highest magnetic field among roAp stars: 8.6 kG (Ryabchikova et al. 2004 and references therein). The roAp stars show light variations with typical amplitudes less then a few millimagnitudes. This photometric variability is due to non-radial pulsations with individual oscillation periods between 5 and 15 minutes, which corresponds to high-order low-degree acoustic modes. At present 34 members of the roAp class are known, and most of them have multiperiodic variations. Often pulsation modes are observed in frequency multiplets caused by rotational splitting (Kurtz 1990). The relatively rich p-mode spectra of the roAp stars makes these objects attractive for asteroseismic studies. Frequency analysis of their light curves have yielded rich asteroseismic information on the degrees of the pulsation modes, magnetic geometries and luminosities. Asteroseismic luminosities agree well with HIPPARCOS ones (Matthews et al. 1999).

After discovery of the significant radial velocity (RV) pulsational variations in a sample of roAp stars (Kanaan & Hatzes 1998, Savanov et al. 1999), monitorings with high -time and -spectroscopic resolution have been carried out (see, for examples, Kochukhov & Ryabchikova 2001a for γ Equ; Baldry et al. 1999, Kochukhov & Ryabchikova 2001b, Balona & Laney 2003 for α Cir; Baldry & Bedding 2000, Kochukhov & Ryabchikova 2001b for HR 3831; Balona & Zima 2002,

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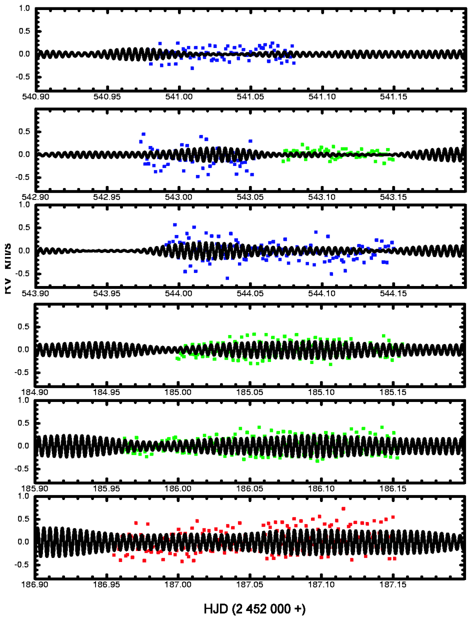

Fig. 1. Rotational modulation and beating effect in roAp star HD 24712. Pulsational RV amplitude depends on rotation phase (smallest in upper panel, highest in bottom panel) and is affected by beatings. Based on data described in Sachkov et al. (2004a).

Sachkov et al. 2004a, Mkrtichian & Hatzes 2005, for HR1217; Mkrtichian et al. 2003, Kurtz et al. 2003 for 33 Lyb).

Rotation and multiperiodicity cause modulation of pulsational photometric and RV pulsational variability in roAp stars, resulting in rotation modulation and beating effect. This is demonstrated in Fig. 1. Amplitude modulation with the rotational period favours for the oblique pulsator model proposed by Kurtz & Shibahashi (1986). According to this model pulsation axis nearly coincides with the magnetic axis and both are inclined to the rotation one. In new theoretical work on the interaction of pulsation with both rotation and the magnetic field by Bigot & Dziembowski (2002) they find that the pulsation axis is inclined to both the magnetic and rotation axes.

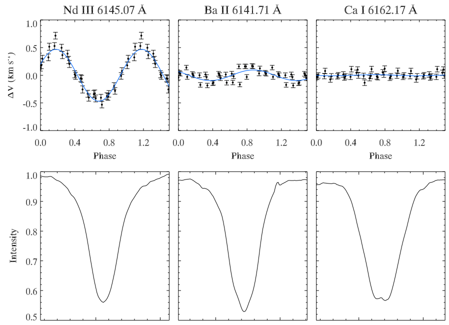

Fig. 2. RV amplitude dependence on individual element/ion for roAp star γ Equ. Based on data described by Kochukhov & Ryabchikova (2001a)

2. Pulsational RV variability

Light variations in the roAp stars have very low amplitudes. But the first spectroscopic observations revealed large RV amplitudes up to 1 km s^{-1} and even more. The most surprising characteristic of the RV pulsations in roAp stars is their selectivity. Kanaan & Hatzes 1998 first noted it in γ Equ spectrum, but only after correct line identification Savanov et al. 1999 might demonstrate that the highest RV amplitudes are observed in the lines of the rare-earth elements (REE), while spectral lines of the other elements are constant or weakly pulsating. An example of pulsational behavior of different spectral lines is shown in Fig. 2. This pulsational behavior is typical for all roAp stars observed spectroscopically up to now.

Another characteristic of the RV pulsations in roAp stars – a phase shift between RV variations in the lines of different elements/ions – was first detected by Kochukhov & Ryabchikova 2001a in γ Equ and was later confirmed for other stars (HD 166473 by Kurtz et al. 2003, Hd 24712 by Sachkov et al. 2004a). Pulsation curves for the lines of the same REE ions differ in phase, and larger gradual shifts occur between RV curves of different REE elements (see Fig. 3). This pulsation pattern is stable at least during the years giving a strong evidence for stability of the pulsational mechanism (Sachkov et al. 2004b).

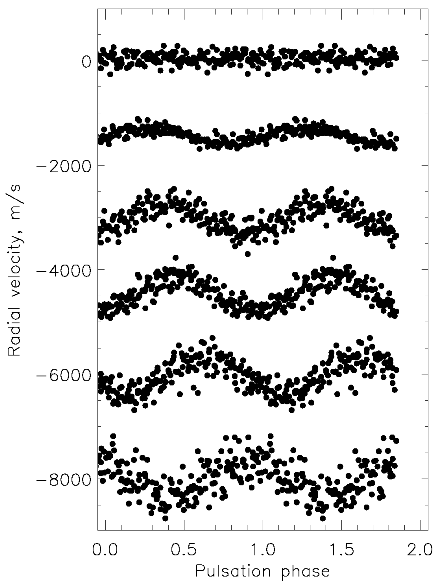

Fig. 3. Pulsating behavior of selected lines in the roAp star HD 24712. Phase shift between RV variations of different element/ion (from bottom to top) occur: Tb III 6688, Pr III 6707, Nd III 6691, Nd II 6650, Eu II 6645, Fe I 6678. A larger phase (in fraction of pulsation period) means that the pulsation reaches maximum later in time. Maximum RV amplitudes have lines of rare-earth elements in the first and the second ionisation stages. Spectral lines of iron-peak elements (Mg, Si, Ca, Cr, Fe, Co), strong Y II and Ba II lines are not variable above the errors of RV measurements (15–30 m s^{-1} for strong lines). Based on data described by Sachkov et al. (2004b)

3. Pulsation evidence for element stratification in the atmospheres of roAp stars

Abundance analysis of Ap stars revealed a huge discrepancy of the order of 1.5-2 dex between neodymium abundances derived from the Nd II and Nd III lines in roAp stars (Ryabchikova et al. 2000, Ryabchikova et al. 2004 and references therein), while this discrepancy is less than 1 dex in non-pulsating stars. NLTE formation of Nd lines (Mashonkina et al. 2005) showed that part of the ionization disbalance (0.3 - 0.8 dex dependent on the effective temperature) may be caused by NLTE effects. However NLTE analysis failed to explain 2 dex difference assuming a homogeneous Nd distribution in stellar atmosphere. Mashonkina et al. (2005) showed that the layer with a strongly enhanced Nd abundance in the outer atmosphere above log τ_{5000} = - 3 provides a good explanation of the observed Nd II and Nd III line intensities.

Figure 4 shows a comparison between the observed and calculated line profiles of Nd II and Nd III in the spectrum of HD 24712 (top panel), and the corresponding Nd distribution in the atmosphere. Nd stratification have been already proposed for explanation of the observed intensities and pulsational variability in γ Equ by Ryabchikova et al. (2000), but it was done in LTE approximation and leaded to unrealistic concentration of Nd above log τ_{5000} =-8. NLTE Nd distribution in the atmospheres of roAp stars γ Equ and HD 24712 provides a good explanation for the observed intensities of spectral lines as well as pulsation RV phase and amplitude distribution in the atmospheres of both stars (Mashonkina et al. 2005, Sachkov et al. 2004b).

4. About unidentified lines in the spectra of roAp stars

Described above characteristics of RV pulsations in roAp stars provide a unique possibility for REE line identification using stellar spectra. HD 24712 is one of the best-studied roAp stars. All our pulsation analysis of this star (Sachkov et al. 2004b) based on high spectral resolution data from GECKO(700 spectra), SOFIN (53 spectra) and SARGE (202 spectra) spectrometers as well as recent HAPRS and UVES data (Ryabchikova, private communication) shows that about 200 lines which identification is unknown are pulsating (the total number of measured lines exceeds 500).

In Table 1 we give an example of pulsational data for a few identified and classified lines of REE in HD 24712 and a few unidentified lines (measurements by Sachkov et al. 2004b). The similarity of the RV pulsa-

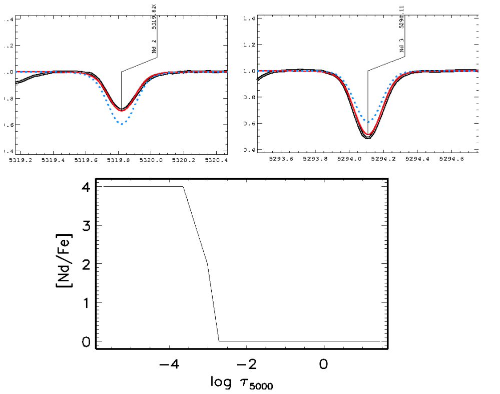

Fig. 4. Stratification NLTE analysis of Nd in the spectrum of HD 24712. The upper panel compares the observed (double line) and theoretical profiles of the Nd II (left) and Nd III computed assuming chemically homogeneous atmosphere (dotted line) and vertical stratification of Nd (solid line). Based on data described by Mashonkina et al. (2005)

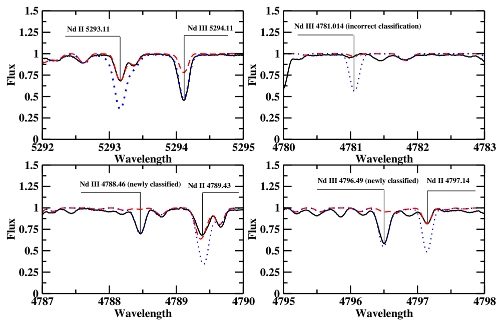

Fig. 5. Well known and newly classified Nd lines in the roAp star HD 24712 spectrum.

tion phases and amplitudes between unidentified lines and well known Nd III lines gives a strong support for identification of these lines as Nd III. For part of lines we thus confirm an identification first proposed by Mrs. H. Crosswite (Crosswhite 2003) and then by Aldenius (2001) (see two last columns in the Table). For two lines in Table 1 an identification is made for the first time. Theoretical calculations of Nd III spectrum made by Ryabtsev (see Mashonkina et al. 2005) allow us to classify the newly identified Nd III lines and make some corrections in previous classifications. Figure 5 demonstrates our procedure. In upper left panel calculations for known Nd III line λ 5394 Å are shown with two Nd abundances: one which is derived from LTE analysis of Nd II lines ($\log(Nd/N_{tot})$=-9.0 - dashed line), and that representing Nd III lines ($\log(Nd/N_{tot})$=-6.9 - dotted line). With the same abundances we synthesized two previously unidentified and unclassified Nd III lines $\lambda\lambda$ 4788, 4796 Å (bottom panels) using our classification and atomic data by Ryabtsev. Both the pulsational behavior and the observed intensities make us sure in the proposed line classification. At the same time spectral feature at λ 4781 is not pulsating and is too weak to be fitted with the typical Nd abundance for Nd III lines. On the bases of our study we reject at least the classification of this line.

Presented in the Table 1 results for the roAp star HD 24712 support results for another roAp star γ Equ obtained by Kochukhov et al. (2004).

Neodimium spectrum, especially Nd III is poorly studied. In the Fig. 5 we show how useful can be pulsation analysis for line identification. The line 4781.014 was suspected as Nd III (right top panel). Synthetic spectrum was calculated firstly with -9.00 (points) for Nd abundance to fit Nd II lines: 5293.16 (left top) and 4797.54 (right bottom). Then was obtained syntetic spectrum with -6.90 (dashed) for Nd abundance to fit Nd III lines: well known 5294.11 (left top), as well as newly classified by us 4788.46 (left bottom) and 4796.49 lines (right bottom). But in both cases we can't fit observations at 4781.014. Moreover, spectral feature at this wavelength don't show any pulsational characteristics. We was able to verify classification for 4780.9908 and give it to newly classified Nd III line 4796.4994.

5. Conclusions

Recent spectacular progress in roAp stars pulsations studies was achieved by using high

Table 1. Pulsating lines in the spectrum of HD 24712.

Line	Amplitude (m s^{-1})	Phasemax	Depth	EqW (mÅ)	Identification	Aldenius	Crosswhite
Classified lines of the REE elements							
5294.1091	183(05)	0.519(0.005)	0.4561	101.41	Nd III	+	+
5299.9860	241(08)	0.636(0.005)	0.6093	88.39	Pr III		
5319.8179	249(08)	0.397(0.005)	0.6270	62.80	Nd II	+	+
5505.3906	291(09)	0.870(0.004)	0.7930	52.17	Tb III		
5845.0167	198(02)	0.457(0.002)	0.6038	86.25	Nd III	+	+
5987.6767	306(12)	0.499(0.005)	0.5957	86.55	Nd III	+	+
Unidentified pulsating lines							
4759.5357	223(04)	0.477(0.003)	0.5884	83.86	Nd III	-	+
4788.4593	306(07)	0.459(0.004)	0.7026	52.89	Nd III	-	+
4796.4994	272(10)	0.469(0.005)	0.5913	80.74	Nd III	+	+
4821.9902	290(09)	0.427(0.005)	0.7351	51.35	Nd III	-	+
4912.9413	323(06)	0.458(0.003)	0.5648	83.43	Nd III	-	-
5566.0117	273(18)	0.444(0.011)	0.7565	57.11	Nd III	-	-

-time and -spectral resolution observations. Photometric studies are still required to obtain frequency spectra. Any analysis of pulsation properties of the roAp atmospheres has to be performed using the NLTE approach. Farther stratification analysis of rare-earth element, especially praseodimium and therbium, is highly desirable. Such analysis together with the pulsation one will provide an extremely important information about the distribution of the pulsations through a stellar atmosphere. The unique pulsational behavior of lines of different element/ions opens a great possibilities in identification and classification study of REE spectra.

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