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Spectroscopy of roAp star pulsation: HD 24712

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Abstract. We present results of the radial velocity (RV) analysis of spectroscopic time-series observations of the roAp star HD 24712 (HR 1217) which were carried out simultaneously with the Canadian MOST mini-satellite photometry. Only lines of the rare-earth elements (REE) show substantial amplitudes of RV pulsations. Based on new Zeeman measurements we found different shapes of the magnetic curves derived by using Fe-peak and REE separately. Frequency analysis of the spectroscopic data showed that the highest amplitude frequencies are the same in photometry and spectroscopy. Photometric and spectroscopic pulsation curves are shifted in phase, and the phase shift depends on the atomic species. The observed distribution of RV pulsation amplitudes and phases with the optical depth as well as the observed phase lag between luminosity and radius variations are explained satisfactorily by the model of nonadiabatic nonradial pulsations of a magnetic star.

Key words. Stars: rapidly oscillating Ap – Stars: atmospheres – Stars: pulsations – Stars:individual: HD 24712

1. Introduction

HD 24712 is one of the spectroscopically best-studied roAp stars (Balona & Zima 2002, Sachkov et al. 2004a, Sachkov et al. 2004b, Mkrtichian & Hatzes 2005). Because of the

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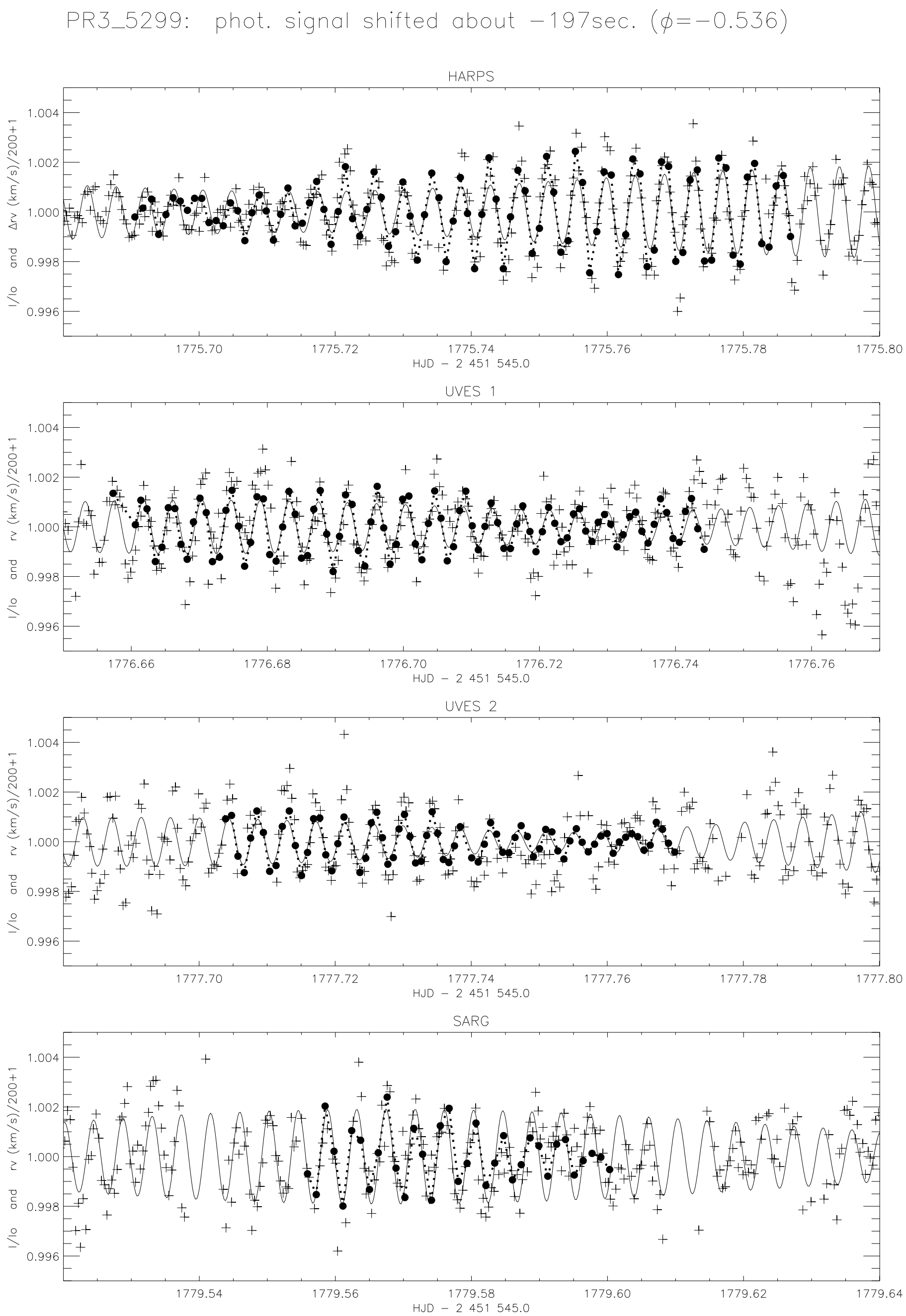

Fig. 1. Normalized RV variations for Pr III (filled circles connected by dotted line) are compared with the simultaneous MOST photometry (pluses). Black solid line represents theoretical curve generated with the frequency solution for the whole MOST observing run, kindly provided by the MOST team. Phase shift between photometric and spectroscopic variations is given on top of the figure.

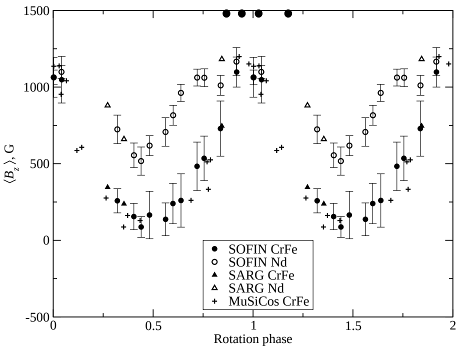

Fig. 2. Magnetic field variation during a rotation cycle for different groups of elements. Large filled circles at the top indicate the rotation phases of the time-series spectroscopy.

known changes of the pulsational characteristics with time, a simultaneous spectroscopic (magnetic) and photometric monitoring during the whole rotation period is needed to avoid ambiguity when interpreting the relation between spectroscopic and photometric evidence for pulsation. Continuous multi-site or space photometry of multiperiodic stars provides a reliable frequency solution needed to derive information about the stellar interior, while radial velocity (RV) analyses allow for a detailed study of the pulsation phenomena in a stellar atmosphere.

2. Spectroscopic observations

Simultaneously with the Canadian minisatellite MOST, which monitored HD 24712 from November 6 to December 5, 2004, we have obtained time-series high-resolution spectroscopic observations. They were carried out at ESO during November 10/11, 2004 (HARPS – 92 spectra, 60 sec time resolution, S/N=120), and, because of the unique coincidence with the space photometry, Director's Discretionary Time (DDT-274.D-5011) was granted for 11/12 and 12/13 (UVES – 92 & 73 spectra, 50 sec, S/N=300). Furthermore, 35 spectra were obtained on November 13/14, 2004 with SARG at TNG. The spectroscopy covers the rotation phases of 0.867, 0.944, 0.028, and 0.176 which coincide with magnetic and pulsation amplitude maximum according to the most recent ephemeris (Ryabchikova et al. 2005). All spectra were reduced and normalized to the continuum level either with MIDAS and IRAF or with a routine specially developed by one of us (DL) for a fast reduction of time-series observations.

Zeeman observations were obtained at NOT with the SOFIN spectrograph during 13 consecutive nights in November 2003 and hence cover a complete rotation period.

3. Radial velocity and magnetic field analysis

Radial velocities of more that 500 unblended spectral lines were measured in the spectral region from 3900 to 6800 Å. For the first time RV measurements were made before and after the Balmer Jump (BJ) using the UVES spectra. About 1/3 of all pulsating lines could not be identified, but according to their pulsation characteristics they should belong to rare-earth elements (REE). We confirmed our previous results (Sachkov et al. 2004b) that only REE lines and the Hα core show large pulsation amplitudes (150 – 400 ms^{-1}), while spectral lines of the other elements are constant (Mg, Si, Ca, Fe-peak) or only weakly pulsating (the very cores of the resonance lines of Ca II and Sr II and the Hβ line core). No difference in the pulsation signature is found for the lines of the same element/ion on both sides of the BJ. We confirm the same phase shifts between RV variations in the lines of different elements/ions found earlier by Sachkov et al. (2004b), indicating stability of the pulsation mechanism in the atmosphere of HD 24712 at least during the last years.

Our four nights of spectroscopic monitoring are not sufficient for a detailed frequency analysis despite the high accuracy of the RV measurements. We may only conclude that the 3 highest amplitude frequencies are the same in spectroscopy and MOST photometry which is also supported by a direct comparison (Fig. 1). Photometry and spectroscopy are shifted in phase, depending on the atomic species and on the depth of the line forming region. For the first time it was possible to derive a phase lag between luminosity and radius variations

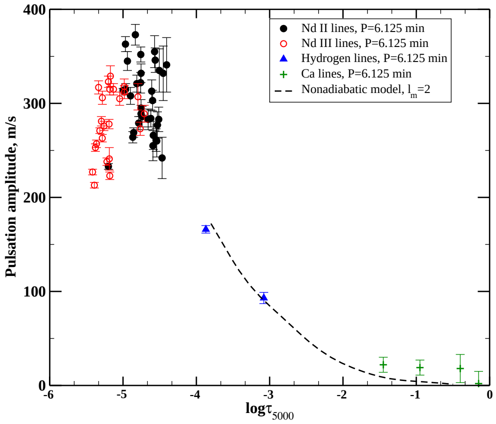

Fig. 3. Pulsation amplitudes vs. depths of line formation.

at different levels in the atmosphere. The luminosity maximum occurs $0.58\,P_{\rm puls}$ (3.7 radian) after the minimum radius of a layer at $\log\tau_{5000}=$ -3.7.

The longitudinal magnetic field $\langle B_z\rangle$ was measured with 7 Cr and Fe, and 5 Nd II and Nd III lines. Fig. 2 shows the $\langle B_z\rangle$ variations with rotation phase and compares them with the most recent measurements taken from the literature (Leone & Catanzaro 2004, Ryabchikova et al. 2005). Obviously, for the two groups of elements the magnetic curves are different. Magnetic Doppler imaging of HD 24712, which is in progress, should answer the question whether this phenomenon is due to a different surface distribution of the species in a star with dipolar magnetic field geometry or due to a more complicated magnetic field geometry. Detailed knowledge of the latter is crucial for modelling pulsation in roAp stars.

4. NLTE analysis of line formation depth and modelling pulsation in HD 24712

The depths of the line forming regions were calculated for Nd based on a NLTE stratification analysis (Mashonkina et al. 2005), for hydrogen on NLTE calculations (Mashonkina, private communication) and for Ca based on a LTE stratification study. The dependency of the RV amplitudes from the optical depth is shown in Fig. 3. A preliminary model for nonadiabatic nonradial pulsation was calculated for $M = 1.65\,M_\odot$, $\log(L/L_\odot)=0.912$, $T_{\rm eff}=7350$ K, and $R = 1.77R_\odot$ (see Saio 2005, and this conference). The model predicts the observed range of photometric frequencies as a superposition of modes with $\ell=1$, 2, 3 for a polar magnetic field of $B_p\approx 6$ kG, although exciting or damping of these modes depends on the radiative transport treatment. Calculated RV amplitudes as a function of depth are shown in Fig. 3 (dashed line) for a quasi-quadrupole mode with a frequency of 2.71 mHz (6.15 min). The model is satisfactory and predicts the existence of a 'nodal layer' at $-0.15 < \log\tau_{5000} < -1.4$ where RV amplitudes are close to zero and where most of the spectral lines not showing measurable pulsation amplitudes are formed. The model predicts also a luminosity maximum at $0.38\,P_{\rm puls}$ (2.4 radian) after the radius minimum at $\log\tau_{5000}=$ -3.7. The difference between the observed and predicted phase lag is only 0.2 (1.2 radian) which is small enough taking the preliminary character of the proposed model into account. The decreasing observed RV amplitudes above $\log\tau_{5000}=$ -5 seem to be real and may be explained by energy dissipation of the propagating wave.

5. Conclusions

Simultaneous photometric and spectroscopic observations of the roAp star HD 24712 allowed to design a consistent picture of stellar pulsation from the envelope to the upper atmosphere which is in good agreement with the proposed model of nonadiabatic nonradial pulsation.

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