A&A 377, L22–L25 (2001)
DOI: 10.1051/0004-6361:20011179
© ESO 2001

Astronomy & Astrophysics

Pulsational and rotational line profile variations of the roAp stars α Cir and HR 3831*

O. Kochukhov[1] and T. Ryabchikova[2,3]

[1] Uppsala Astronomical Observatory, Box 515, S-751 20 Uppsala, Sweden
e-mail: oleg@astro.uu.se
[2] Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya 48, 109017 Moscow, Russia
e-mail: ryabchik@inasan.rssi.ru
[3] Institute for Astronomy, University of Vienna, Türkenschanzstrasse 17, 1180 Vienna, Austria
e-mail: ryabchik@tycho.astro.univie.ac.at

Received 19 July 2001 / Accepted 22 August 2001

Abstract. We report preliminary results of our new time-resolved high-resolution spectroscopic observations of the roAp stars α Cir and HR 3831. Analysis of pulsational behaviour of individual spectral lines in the 6116–6156 Å spectral region revealed that in both stars it is dominated by the strong rapid variations of the Nd III 6145.07 Å spectral line. Oscillations of the Nd III spectral feature are also rotationally modulated. In addition we observed strong rotational modulation of the average HR 3831 line profiles caused by abundance spots on the stellar surface. Weaker rotational modulation was also discovered for the metal lines in the α Cir spectrum. This variability agrees with the rotational period of α Cir obtained from the splitting of the principal pulsation frequency.

Key words. stars: chemically peculiar – stars: oscillations – stars: individual: α Cir, HR 3831

1. Introduction

Rapidly oscillating Ap (roAp) stars belong to the group of cool magnetic chemically peculiar stars, which pulsate in high-overtone p-modes with periods in the range of 4–16 min. Traditionally roAp stars are discovered and studied using high-speed photometric techniques (e.g. Kurtz et al. 1994). There are only a few oscillating Ap stars for which line-by-line analysis of radial velocity variations is available. Among them three stars of similar effective temperature ($T_{\rm eff} \approx 7750$ K) – γ Equ, α Cir and HR 3831 – are best studied. While high-resolution spectroscopic observations were used for γ Equ (see Kanaan & Hatzes 1998; Savanov et al. 1999; Kochukhov & Ryabchikova 2001, hereafter Paper I), pulsational radial velocity (RV) analysis of α Cir and HR 3831 was based on low-resolution spectra (Baldry et al. 1998; Baldry & Bedding 2000), allowing study of lines blended together in short spectral regions, but not of individual metal lines. It was found that in γ Equ spectral lines of Pr III and Nd III show the highest RV amplitudes (Savanov et al. 1999; Paper I). In Paper I we analysed published results of low-resolution time-resolved spectroscopic studies of α Cir and HR 3831 and tentatively concluded that strong Pr III and Nd III lines as well as the lines of singly ionized rare-earth elements (REE) are present in most of the short spectral regions demonstrating the highest RV amplitudes. To confirm our conclusion about an importance of Pr III and Nd III lines in pulsational behaviour of roAp stars we performed high-resolution high S/N time-series observations of α Cir and HR 3831 in the 6116–6156 Å spectral region, which includes the Nd III λ 6145.07 Å line. Both stars were observed at different rotational phases for the future analysis of the 3D distribution of the pulsational velocity and abundance inhomogeneities. In this letter we report preliminary qualitative results of our time-resolved spectroscopic observations.

A description of observations and the reduction procedure is given in Sect. 2. Pulsational behaviour of individual metal lines in α Cir and HR 3831 is presented in Sect. 3, while in Sect. 4 we briefly discuss spectrum variability due to rotation in both stars.

2. Observations and data reduction

We obtained time-resolved spectroscopic observations of α Cir and HR 3831 with the Very Long Camera of the Coude Echelle Spectrograph fiber linked to the Cassegrain focus of the ESO 3.6-m telescope. Observations were conducted during 6 nights in February 2001 using the medium

Send offprint requests to: O. Kochukhov,
e-mail: oleg@astro.uu.se

* Based on observations obtained at the European Southern Observatory (La Silla, Chile).

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20011179

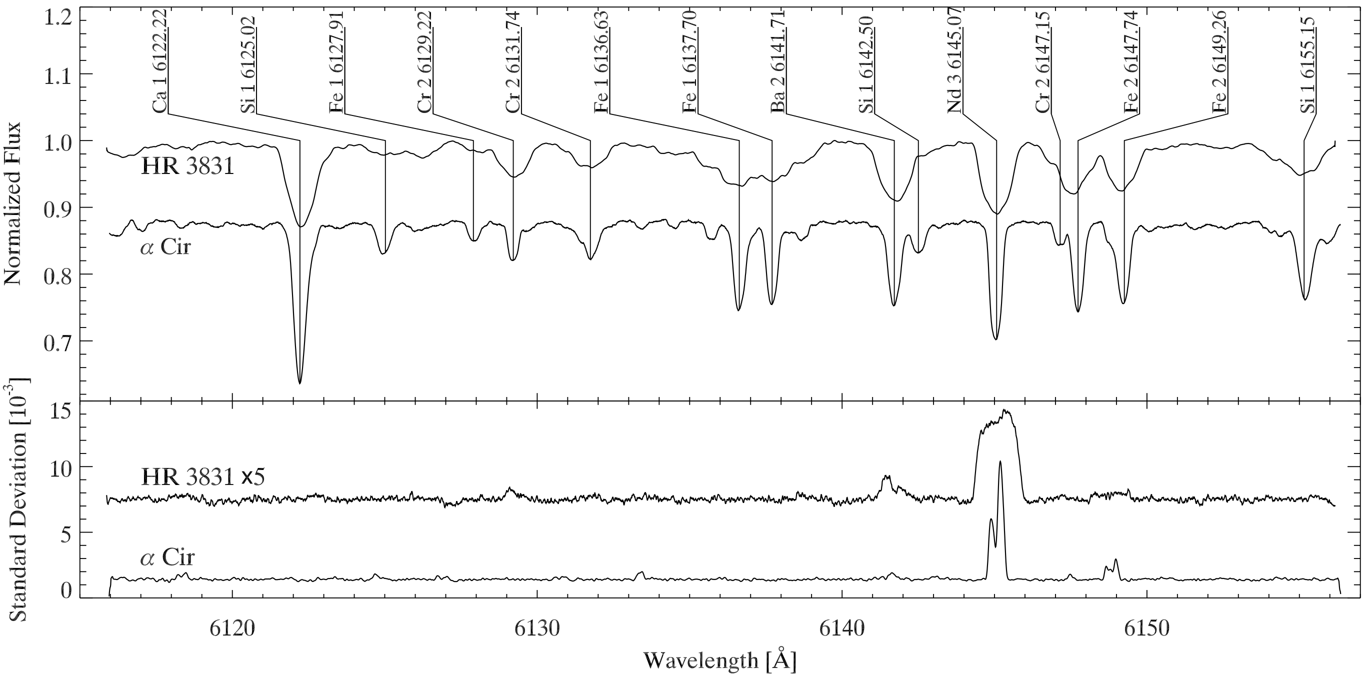

Fig. 1. Comparison of the average and standard deviation spectra of α Cir and HR 3831. The upper panel shows average normalized spectra of the roAp stars. The spectrum of α Cir is shifted by 0.12 in the vertical direction. The lower panel presents the standard deviation for each pixel of the observed spectra. Note, that for clarity of presentation the standard deviation spectrum of HR 3831 was scaled upwards by a factor of 5.

resolution CES image slicer and ESO CCD#61. This instrumental configuration allowed the detector to record a 40.4 Å spectral region centred at λ 6136 Å with a resolution of $\lambda/\Delta\lambda = 123\,000$. The roAp star HR 3831 was the main target of our observing campaign and it was monitored during 8.5 hours each night. We used an exposure time of $70^{\rm s}$ in order to resolve pulsational variations due to the main non-radial mode in HR 3831, which has a period of $P = 11\overset{\rm m}{.}67$ (Kurtz et al. 1997). Additional time-resolved spectroscopy of α Cir was performed for 1 hour each night using the same instrumental settings as we employed for HR 3831. For α Cir we limited integration times to $40^{\rm s}$ in order to resolve spectroscopic changes associated with the pulsation period of $P = 6\overset{\rm m}{.}83$ (Kurtz et al. 1994). During the whole observing run we obtained 1860 spectra of HR 3831 with a typical S/N ratio of 100 per pixel as well as 290 spectra of α Cir with $S/N \simeq 300$.

Basic steps of spectroscopic reduction (bias subtraction, division by normalized flat field, extraction of 1-D spectrum, continuum normalization and wavelength calibration) were performed with a set of IDL routines specially adapted for the optimal extraction of CES spectra. This reduction procedure was very similar to the reduction of time-resolved spectroscopic observations of γ Equ, which we described in detail in Paper I.

3. Pulsational spectroscopic variability

We computed the standard deviation (SD) of the intensity variations for each pixel of the continuum-normalized spectra and compared it with the average observations of α Cir and HR 3831 in order to identify variable spectral lines. The upper panel in Fig. 1 shows average spectra of the roAp stars, while the lower panel displays SD spectra. These profiles were produced by averaging SD spectra computed for short sequences of time-resolved spectra, obtained typically within 1–1.5 hours, and thus contain information only about spectral variability due to non-radial oscillations, but not due to rotational modulation caused by abundance spots.

Analysis of SD profiles shown in Fig. 1 clearly reveals outstanding variations of the Nd III 6145.07 Å spectral line. Weaker pulsational changes are also seen for Ba II 6141.71 Å and an unidentified feature in the blue wing of Fe II 6149.26 Å, which probably belongs to a singly or doubly ionized REE. The overall picture of the pulsational variability of α Cir and HR 3831 is very similar to the pulsational behaviour of γ Equ (Paper I). In particular, for all three roAp stars we observed maximal variability for doubly ionized REE lines, weaker pulsations for singly ionized REE and Ba II spectral features, and the absence of any variations for strong lines of lighter elements (e.g. Ca I 6122.22, Si I 6155.15 Å).

Another spectroscopic signature that distinguishes all roAp stars from non-pulsating Ap stars with similar effective temperature is anomalous strength of doubly ionized REE lines. Ryabchikova et al. (2001) showed that abundances derived for roAp stars using Nd III and Pr III spectral lines are 1–2 dex higher than abundances obtained from lines of singly ionized Nd and Pr. This spectroscopic anomaly, which is absent in non-pulsating Ap stars points to inhomogeneous vertical distribution of REE in the

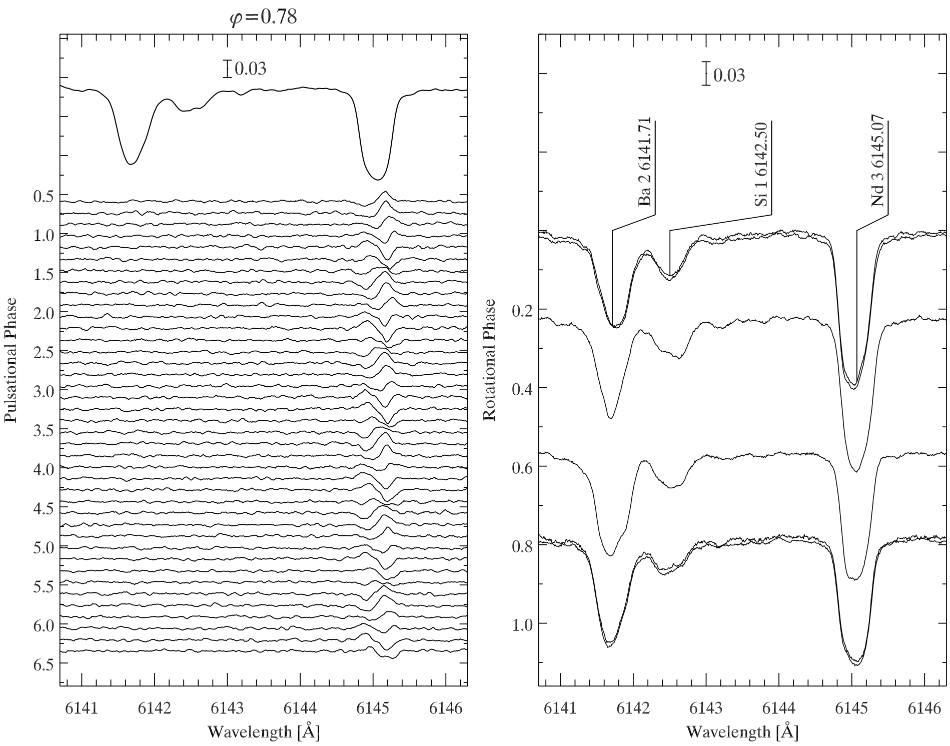

Fig. 2. Rotational and pulsational variability of α Cir spectra. The left panel shows rapid line profile changes due to non-radial oscillations for the rotational phase $\varphi = 0.78$. The average spectrum is plotted at the top of the figure, while the difference between the average and individual time-resolved observations is plotted below. The right panel compares average spectra of α Cir obtained for 6 rotational phases. In both figures profiles for the consecutive pulsational/rotational phases are shifted in the vertical direction. The bar in the upper part of each panel indicates the scale (in units of continuum flux) used for the figure.

atmospheres of roAp stars. Combined analysis of vertical abundance stratification and pulsational amplitudes of individual spectral features allows us to suggest that doubly ionized REE lines are formed in the atmospheric region where pulsational amplitude reaches its maximum. Thus, REE lines serve as invaluable tracers of the roAp pulsations. Pulsational behaviour of all roAp stars analysed with high time and spectral resolution techniques is broadly consistent with this picture and seems not to depend on pulsational periods, magnetic field strengths or rotation rates. This allows us to speculate that all members of the class of roAp pulsators feature similar vertical distributions of REE and pulsational amplitudes.

Strong pulsational variability of the Nd III 6145.07 Å line offers a possibility to go beyond simple time-series analysis of periodic radial velocity changes and study in detail line profile variability caused by non-radial oscillations in order to identify pulsational mode(s) and deduce other physical characteristics of non-radial pulsations. The high quality of our observational material allows us to pursue this detailed analysis. Indeed, in the left panel of Fig. 2 we show a 1 hour sequence of the time-resolved α Cir spectra acquired at rotational phase 0.78 (according to the ephemeris of Kurtz et al. 1994). High-amplitude rapid profile changes are evident in the difference spectra of α Cir, with pulsational waves propagating from the blue to the red wing of the Nd III 6145.07 Å line profile. (Note the absence of strong variability of the nearby Ba II 6141.71 Å line.) These profile changes cannot be attributed to only RV and/or equivalent width variations. This is the first detection of metal line profile variability induced by pulsations in α Cir.

4. Rotational modulation

In addition to line profile variations induced by non-radial pulsations, many roAp stars show rotational modulation of their metal lines due to inhomogeneous surface distribution of chemical elements. Though well-known for many magnetic Ap stars, this phenomenon has never been reported for α Cir. The rotational period of this star ($P_{\rm rot} = 4\overset{\rm d}{.}4790$) was derived by Kurtz et al. (1994) indirectly from pulsational analysis. Owing to the high resolution and S/N of our α Cir observations we were able to detect subtle changes of the average line profiles from one night of our observations to another. The right panel in Fig. 2 illustrates this rotational variability for Ba II, Si I and Nd III spectral lines. Though poor phase coverage of our spectra does not allow us to make an independent estimate of the α Cir rotational period, we tentatively concluded that our spectroscopic data agrees with the period found by Kurtz et al. (1994). Further spectroscopic monitoring of Ba II and REE lines is needed to verify this conclusion.

According to the phenomenological oblique pulsator model, pioneered for roAp stars by Kurtz (1982), the pulsational axis of oscillations in roAp stars is aligned with the axis of the (roughly dipolar) magnetic field, which is usually inclined with respect to the rotational axis. As a roAp star rotates, the angle between an observer and pulsational axis changes and therefore one expects to see rotational modulation of the amplitude and phase of non-radial oscillations. For α Cir we detected modulation of RV amplitude of the Nd III 6145.07 Å spectral line, which varied between 300 and 500 m s^{-1} during our observing run. However, preliminary analysis showed that this

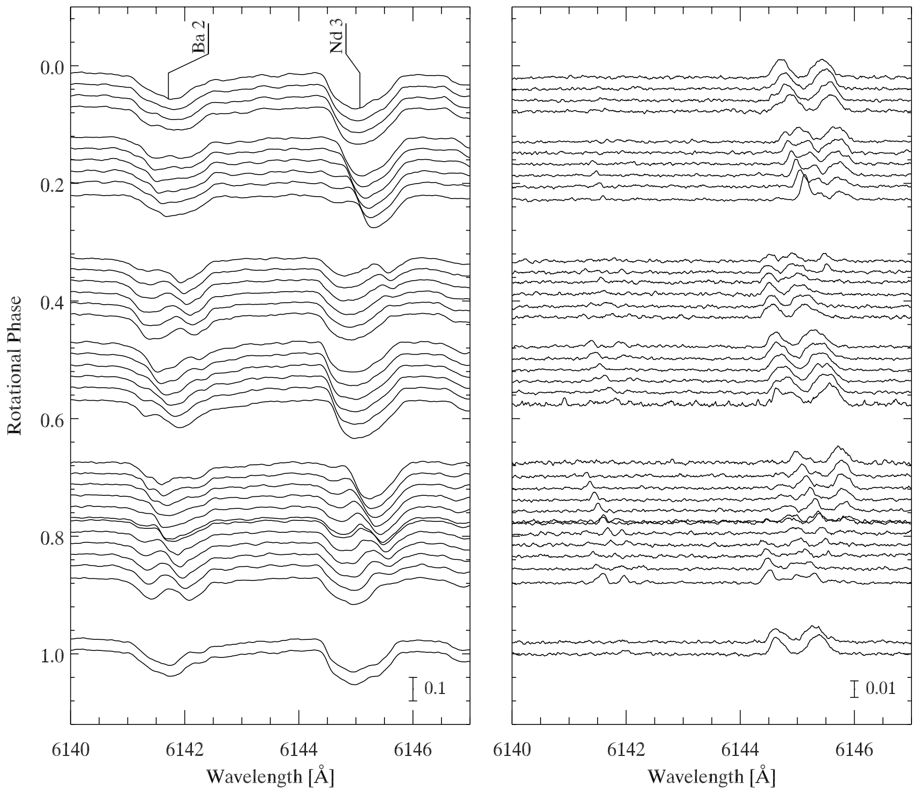

Fig. 3. Comparison between rotational variability of the average (over 50 pulsational cycles) line profiles of Nd III 6145.07 Å and Ba II 6141.71 Å (left panel) and rotational modulation of the standard deviation spectrum (right panel) for the same wavelength region in HR 3831. The profiles for the consecutive rotational phases are shifted in the vertical direction. The bars at the lower right corner of each panel indicate the scale (in units of continuum flux) used for the figures.

modulation is not consistent with simple sinusoidal variations of the photometric amplitude obtained by Kurtz et al. (1994). Furthermore we detected changes in RV amplitude on time scales much shorter than the rotational period of α Cir. Clearly further analysis of line profile variations of REE lines as well as additional observations are required to clarify the question of the modulations of non-radial pulsations in α Cir.

We observed even more dramatic rotational modulation of the average line profiles and pulsational behaviour for HR 3831. This star has a well-known rotational period $P_{\rm rot} = 2\overset{\rm d}{.}851976$ (Kurtz et al. 1997), supported by the variability of light, magnetic field, line strengths and non-radial oscillation amplitude. For HR 3831 the dense phase coverage of our observations allowed us to follow in detail both modulation of rapid profile variability and changes of the average profiles caused by abundance spots. Figure 3 illustrates how the average and the SD spectra of HR 3831 change with rotational phase. HR 3831 pulsates in the principal dipole ($\ell = 1$) non-radial mode (Kurtz et al. 1997; Baldry & Bedding 2000). Its signature is clearly visible as a jump in the pattern of SD profiles of the Nd III 6145.07 Å line, occurring at phases 0.25 and 0.75 (see right panel in Fig. 3), as well as modulation of RV pulsational amplitude of the same line, which changes from no detectable variability at phases 0.25 and 0.75 up to 200 $\mathrm{m\,s^{-1}}$ at phases 0.0 and 0.5. The strong influence of the inhomogeneous abundance distribution on the shape of the average line profiles must be studied in detail with Doppler imaging techniques. Spatial filtering associated with abundance spots must also be taken into account in pulsational analysis based on modelling rapid variations of individual spectral lines. Such analysis (which we plan to present in forthcoming papers) will reveal the relation between the inhomogeneous surface abundance distribution and the pulsation velocity field. It will also help to understand which of the two abundance inhomogeneity effects, vertical stratification or surface patches, is primarily responsible for the high-amplitude rapid variations of the Nd III spectral feature.

Acknowledgements. This work was supported by Swedish Naturvetenskapliga forskningsrådet and by the Fonds zur Förderung der wissenschaftlichen Forschung (project *S 7003-AST* and *P 11882-PHY*). T. R. also acknowledges financial support by the "Jubilaeumsfonds der Oesterreichischen Nationalbank". We thank the referee Dr. I. K. Baldry for very constructive remarks.

References

Baldry, I. K., Bedding, T. R., Viskum, M., Kjeldsen, H., & Frandsen, S. 1998, MNRAS, 295, 33
Baldry, I. K., & Bedding, T. R. 2000, MNRAS, 318, 341
Kanaan, A., & Hatzes, A. P. 1998, ApJ, 503, 848
Kochukhov, O., & Ryabchikova, T. 2001, A&A, 374, 615
Kurtz, D. W. 1982, MNRAS, 200, 807
Kurtz, D. W., Sullivan, D. J., Martinez, P., & Tripe, P. 1994, MNRAS, 270, 674
Kurtz, D. W., van Wyk, F., Roberts, G., et al. 1997, MNRAS, 287, 69
Ryabchikova, T. A., Savanov, I. S., Malanushenko, V. P., & Kudryavtsev, D. O. 2001, Astron. Rep., 45, 382
Savanov, I. S., Malanushenko, V. P., & Ryabchikova, T. A. 1999, Astron. Lett., 25, 802