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Multi-element Abundance Doppler Imaging of the RoAp Star HR 3831

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Abstract. We investigate the distribution of chemical elements on the surface of the rapidly oscillating Ap star HR 3831. Application of the sophisticated Doppler imaging code to the high-resolution low-noise spectra acquired at the European Southern Observatory allowed us to reconstruct maps of several light, iron-peak and rare-earth elements and correlate these surface distributions with phase variations of magnetic field and pulsational amplitude. We investigate the compound effect of the abundance spots and pulsational velocity field on rapid line profile variations and discuss the possibility of identification of pulsational modes by using spatial filtering produced by an inhomogeneous abundance distribution.

1. Introduction

HR 3831 (HD 83368, IM Vel) is a bright southern rapidly oscillating (roAp) cool magnetic chemically peculiar star. It pulsates with an amplitude of 10 mmag in a single dipolar non-radial mode and pulsation period 11.67 min. In addition to the short-term pulsational changes the star shows variations of spectral line profiles, mean longitudinal magnetic field and brightness with a rotation period of 2.851976 days. Pulsations of HR 3831 have been extensively studied photometrically (Kurtz et al. 1997). However, there is still lack of understanding of the intricate relation between pulsational velocity field, global magnetic field, vertical and horizontal abundance inhomogeneities. The role of chemical diffusion and its possible relation to the excitation of non-radial oscillations is also highly uncertain. We believe that many of these questions can be answered by carrying out detailed simultaneous investigation of abundance spots and pulsations using high-quality spectroscopic observations and applying advanced modelling methods such as Doppler imaging (DI). Here we present first results on DI of HR 3831. We also attempt to correlate surface abundance structures with pulsational radial velocity variations of individual metal lines.

2. Observations

Observational material used in our study consisted of 1860 very high-resolution ($\lambda/\Delta\lambda = 123\,500$) spectra acquired with the CES instrument at the ESO 3.6-m telescope. Exposure times were limited to 70 sec in order to resolve pulsational spectroscopic variability. HR 3831 was observed during 6 nights allowing to obtain a very good coverage of the rotational period. For the purpose of DI we averaged time-resolved CES spectra obtained within 1 hour which gave us 36 spectra with S/N in excess of 700:1. Observations with CES, albeit of very high quality, allowed us to study only a 40 Å wavelength region centred at 6136 Å. To improve reconstruction of the surface maps and to study chemical species with lines outside this short interval we obtained 12 additional observations of HR 3831 with the FEROS spectrograph at the 1.52 ESO telescope at La Silla. These spectra have resolving power of 48 000, S/N of more than 150:1 and cover wavelengths between 3900 to 9000 Å. In addition, for DI in 6710 Å region we used 8 high-resolution CES/CAT spectra described by North et al. (1998).

3. Doppler imaging

Outstanding spectral variability of HR 3831 was first noted by Mathys (1991) and recently studied by Polosukhina et al. (2000) and Shavrina et al. (2001) who focused their analysis on the variations of the resonance Li I line at 6707.8 Å. Examination of our FEROS observations of HR 3831 showed that, in fact, *all metals*, including most abundant iron-peak species, show clear signs of inhomogeneous surface distribution. This makes HR 3831 an ideal target for application of DI.

We started our analysis by deriving stellar parameters of HR 3831. Colours in Strömgren photometric system were used to obtain the value of the surface gravity ($\log g = 4.2$) and initial estimate of the effective temperature. Then $T_{\rm eff}$ was refined by fitting wings of hydrogen Balmer lines. This gave us $T_{\rm eff} = 7650 \pm 150$ K. Using Hipparcos parallax and $v_{\rm e} \sin i = 33.0 \pm 0.5$ km s^{-1} derived from fitting line profiles, we found $M_v = 1.95 \pm 0.02$, $\log L/L_{\odot} = 1.091 \pm 0.010$, $R/R_{\odot} = 2.003 \pm 0.082$ and inclination angle $i = 68.2^{\rm o} \pm 6.2^{\rm o}$. Model atmosphere of HR 3831 was calculated with `ATLAS9` code of Kurucz.

Doppler reconstructions have been carried out using multi-element abundance DI code `INVERS12` written by N. Piskunov. Early version of this code was described by Kuschnig et al. (1999). In the present study we focused Doppler mapping on chemical species having only a few usable spectral lines and showing the largest line profile variations. The following spectral lines were analyzed in FEROS spectra: Li I 6707.8 Å, O I triplet at 7772–7775 Å, Na I 5895.9 Å, Pr III 6090.0 and 6195.6 Å, and Eu II 6645.1 Å. Corresponding Doppler images are presented in Fig. 1. CES observations allowed us to study line profile variations of Ca I 6122.2 Å, Co I 6122.6 Å, Si I 6142.5 Å, Ba II 6141.7 Å, and Nd III

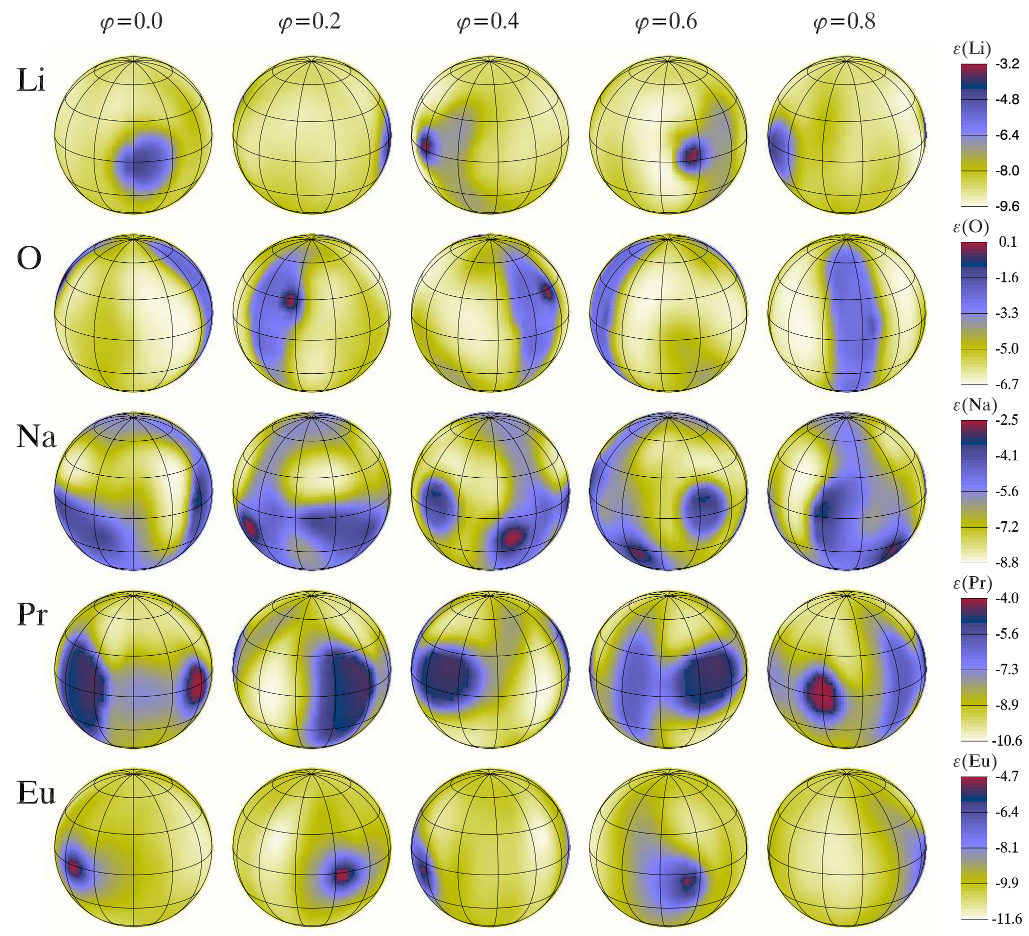

Figure 1. Surface abundance distributions of Li, O, Na, Pr, and Eu reconstructed using FEROS spectra. Darker areas correspond to higher abundance.

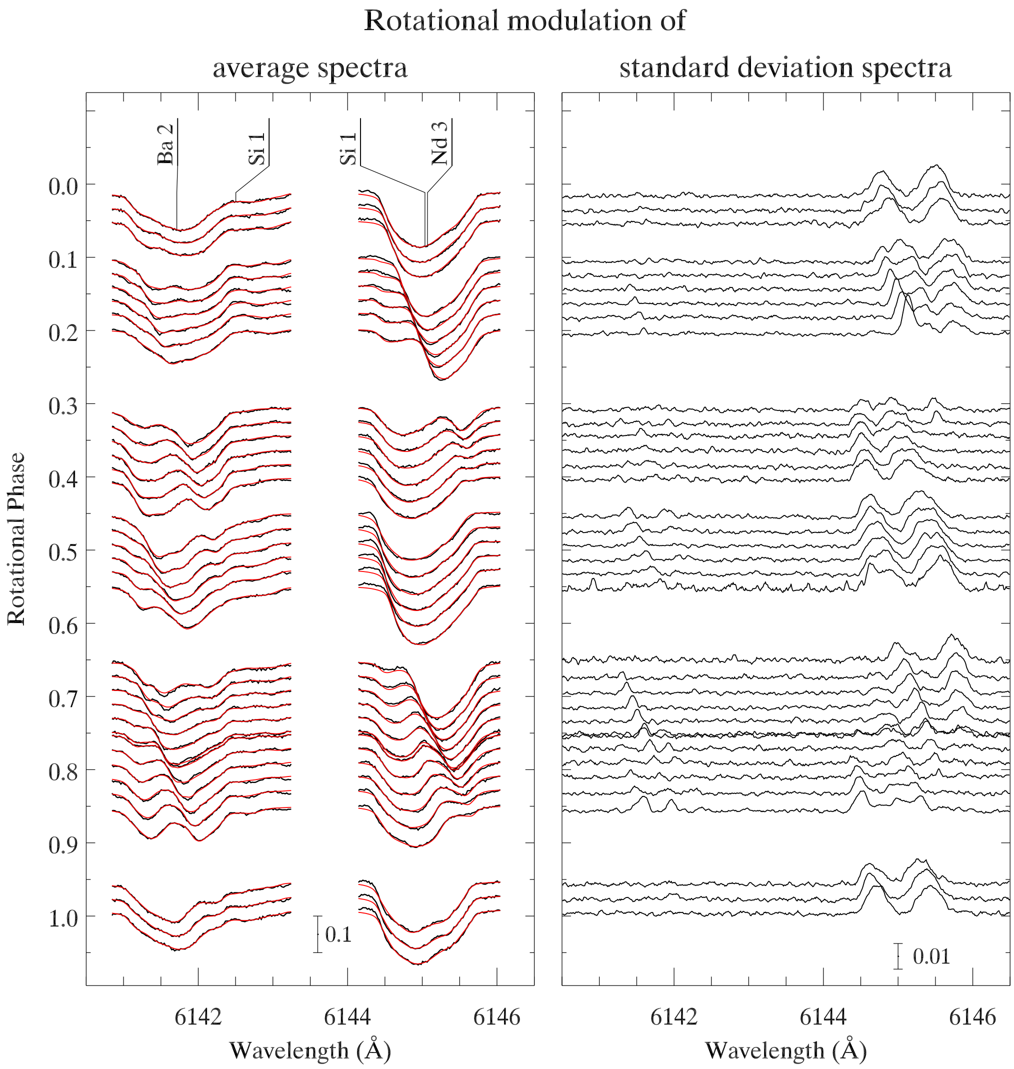

Figure 2. The left panel shows rotational modulation of the average profiles of Ba II 6141.7 Å and Nd III 6145.1 Å lines (both features are blended by weak Si I lines). Observed CES spectra (black curves) are compared with synthetic profiles (red curves), which correspond to maps in Fig. 3. The right panel illustrates rotational modulation of the standard deviation spectra. Excess of deviation points to the region where short-period pulsational variations occur.

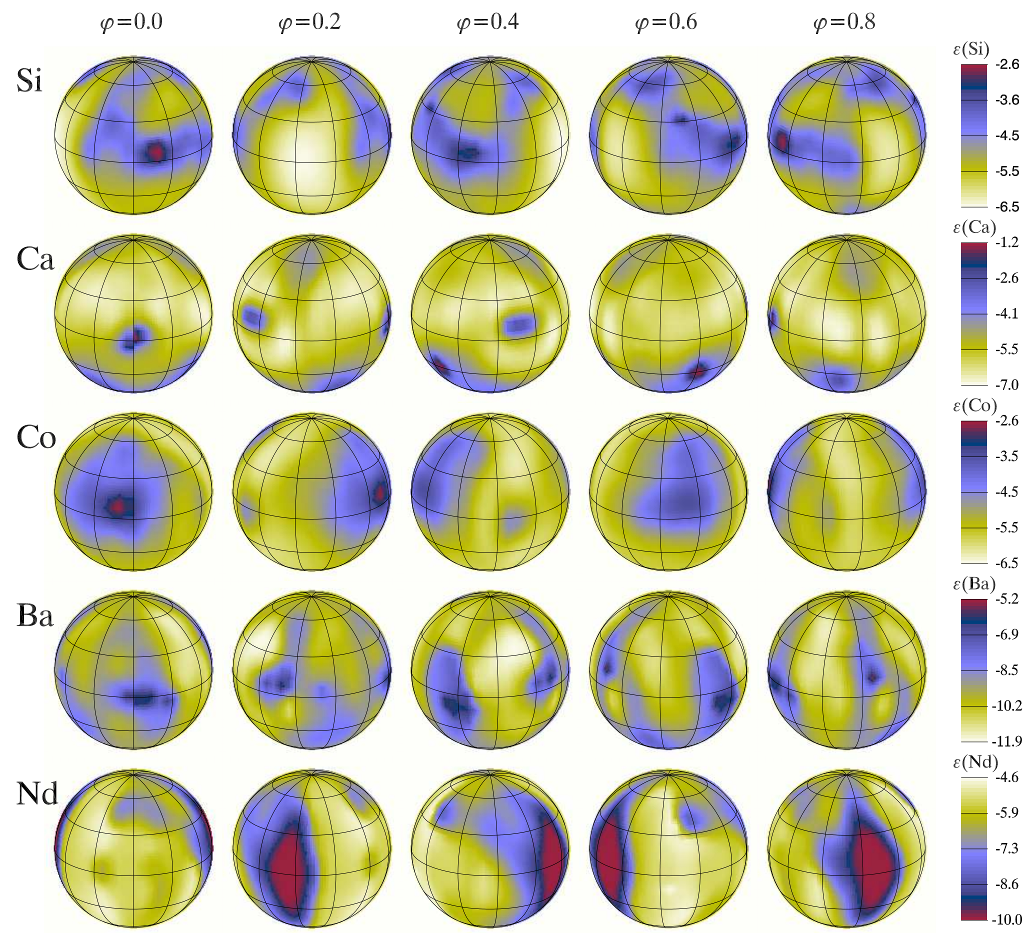

Figure 3. Surface abundance distributions of Si, Ca, Co, Ba, and Nd reconstructed using CES spectra. Darker areas correspond to higher abundance in all images except for Nd map, where color table was inverted for clarity of presentation.

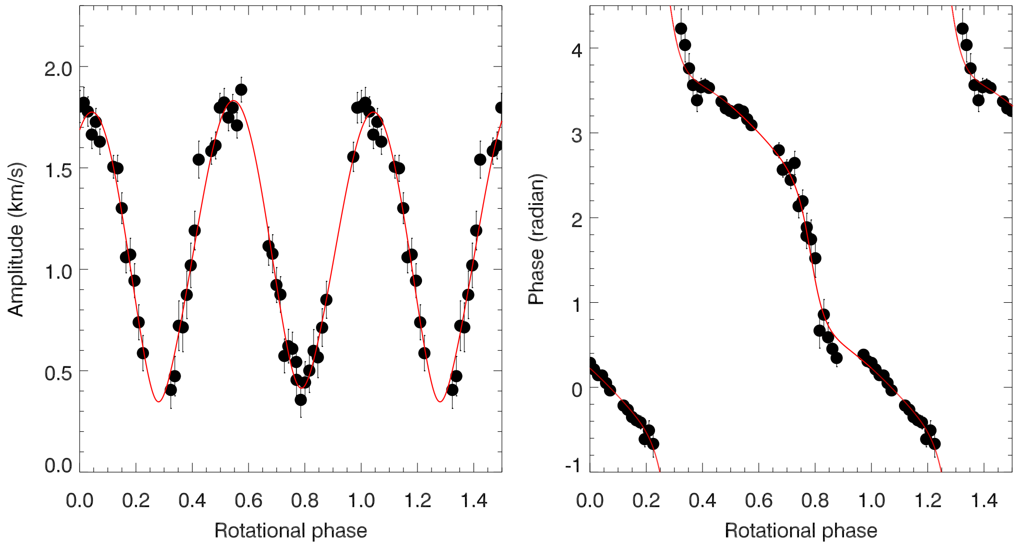

Figure 4. Rotational modulation of the pulsational amplitude and phase of RV variations in Nd III 6145.1 Å line. Symbols have been calculated by fitting the main pulsation frequency ($\nu = 1428.009$ μHz) to sequences of 5 cycles (57 min) of time-resolved CES data. The solid line shows the fit by the frequency septuplet derived from raw RV measurements.

6145.1 Å. The maps for these chemical elements are displayed in Fig. 3. Fig. 2 illustrates spectral variations of HR 3831 in 6140–6145 Å region and shows the fit achieved by the DI code. Surface abundance maps show a varying degree of correlation with the magnetic geometry of HR 3831, which is probably close to dipole oriented along the line of sight at phases 0.0 and 0.5. The most striking evidence of the action of chemical diffusion in the presence of global magnetic field is provided by Li (concentrated in two small areas close to magnetic poles) and O which is strongly enhanced along the magnetic equator.

4. Pulsational variability

Preliminary account for the results of our time-resolved observations of HR 3831 using CES spectra was given by Kochukhov & Ryabchikova (2001). They showed that in 6116–6156 Å interval Nd III line at 6145.1 Å has the highest amplitude of pulsational radial velocity (RV) variations. Refined analysis allowed us to detect much weaker pulsational variability in other lines, but the Nd III feature remains the most useful for time-series pulsational analysis. Analysis of RV measurements in this line allowed us to detect components of the main frequency triplet and to detect the first harmonic. We found that the semi-amplitude of the RV variations of the Nd III line changes between 0.4 and 1.8 km s^{-1} (see Fig. 4), while phase shows a typical jump expected for dipolar non-radial mode.

Surface map derived from the same Nd III line (see Fig. 3) indicates that neodymium is not strongly concentrated towards magnetic and pulsational poles.

The main feature of the Nd III map is a ring of relative underabundance located roughly at the magnetic equator. Furthermore the shape of amplitude variations of pulsations in the Nd III line is surprisingly similar to the behaviour of photometric amplitude (Kurtz et al. 1997). Thus abundance spots is not the most likely explanation of the discrepancy in pulsational behaviour of different chemical elements. We suggest that vertical abundance gradients play a major role in shaping observed pulsational behaviour of HR 3831. In particular lines of doubly ionized rare-earth elements may originate from very high atmospheric layers (Ryabchikova et al. 2002) and trace large amplitude pulsations, while other spectral lines are probably formed in intermediate and low layers of the atmosphere of HR 3831 where pulsations have lower amplitude. Thus our results suggest that chemical stratification provide very efficient vertical spatial filtering of pulsations in roAp stars and may be used to derive radial variations of pulsational amplitude and phase.

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