Element Stratification in Stars: 40 Years of Atomic Diffusion
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TOWARD 3-D PULSATION MAPS OF ROAP STARS

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Abstract. Time-resolved spectroscopic observations of non-radial oscillations in magnetic Ap stars reveal unexpected and complex pulsation behaviour in spectral lines of individual chemical elements. This diverse rapid spectroscopic variability is closely related to the presence of strong photospheric vertical abundance gradients built up by chemical diffusion. Consideration of chemical stratification and simultaneous interpretation of the pulsational variability of different chemical species have made it possible a tomographic mapping of the radial dependence of pulsation properties of the atmospheres of roAp stars. Combination of the information obtained using pulsation tomography with horizontal mapping using Doppler imaging opens a unique possibility to construct unprecedented three-dimensional maps of pulsation waves, chemical spots and magnetic field in the atmospheres of peculiar A stars.

1 Introduction

Rapidly oscillating Ap (roAp) stars are cool magnetic chemically peculiar stars of the SrCrEu type, pulsating in high-overtone non-radial p-modes. There are 34 roAp stars known at present time. These objects oscillate with periods in the range of 6–21 min and amplitudes rarely exceeding 10 mmag in Johnson B. Photometric investigations of roAp stars (reviewed by Kurtz & Martinez 2000) carried out over the last 25 years have yielded important asteroseismic information on the internal structure and fundamental parameters of roAp pulsators (*e.g.*, Matthews *et al.* 1999; Cunha *et al.* 2003).

Since the discovery of roAp pulsations it became clear that strong magnetic fields in these stars have a defining role in exciting the oscillations and shaping the main pulsation properties. It was found that the amplitude and phase of rapid light variation are modulated with the stellar rotation and that the phases of the magnetic field and pulsation amplitude extrema typically coincide with each

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other. This behaviour was interpreted by *oblique pulsator model* (Kurtz 1982) in which observed oscillations are attributed to axisymmetric dipolar pulsation modes aligned with oblique magnetic field. This simple framework was successful in interpreting certain characteristics of photometric pulsational variability, yet, due to its purely phenomenological character and lack of theoretical justification, it did not lead to a major insight in understanding the physics of non-radial pulsations and their relation to chemical and magnetic structure formation in the atmospheres of cool Ap stars.

Recent theoretical investigations (Bigot & Dziembowski 2002; Saio & Gautschy 2004) directly challenged main assumptions of the classical oblique pulsator model, suggesting that magnetoacoustic oscillation may have significant non-axisymmetric components and its surface geometry certainly departs from a single spherical harmonic description. These new sophisticated (and sometimes contradictory) theoretical predictions cannot be tested with photometric observations due to a limited information content of the latter. Furthermore, time-resolved photometric measurements are exceedingly difficult to interpret because we do not have a physical model of pulsational luminosity variation and, therefore, cannot establish correspondence between theoretical pulsation variables and actual observations. These complications were ignored and it was assumed that relative luminosity changes are proportional to radial component of pulsation displacement (*e.g.*, Bigot & Dziembowski 2002): $\delta L/L \propto \xi_{\rm r}$. This purely geometrical approach permitted only an indirect view on pulsation. In contrast, spectroscopy directly gives us information about pulsation velocity field, which is trivially related to the displacement vector: $\boldsymbol{V} = i\omega\boldsymbol{\xi}$. Thus, high time resolution spectroscopy for the first time enables a direct look at pulsating roAp atmospheres and promises to deliver a breakthrough in understanding 3-D structure and physics of oscillations.

2 Spectroscopic Observations of roAp Pulsations

Early time-resolved spectroscopic studies of roAp stars (Matthews *et al.* 1988; Libbrecht 1988) were focused on the detection of pulsational radial velocity (RV) changes and deriving the ratio of RV and photometric amplitude. Subsequent low spectral resolution investigations of α Cir and HR 3831 by Baldry *et al.* (1998b, 1998a) revealed unexpected diversity of the pulsation amplitude and phase in different wavelength regions, showing that for a roAp star the concept of "typical" amplitude of RV oscillations is meaningless.

High-resolution observations of γ Equ by Kanaan & Hatzes (1998) localized RV variations of individual metal lines and confirmed that pulsations change dramatically from one spectral line to another. This phenomenon remained a mystery however, because no clear underlying systematic trends or dependencies were identified. A breakthrough discovery was made by Savanov *et al.* (1999), who demonstrated that in γ Equ the largest pulsational RV shifts of up to 1 km s^{-1} occur in the lines of Pr III and Nd III. Follow up very high spectral resolution time-series observations of γ Equ by Kochukhov & Ryabchikova (2001a) confirmed these results and for the first time detected line profile variation associated with rapid

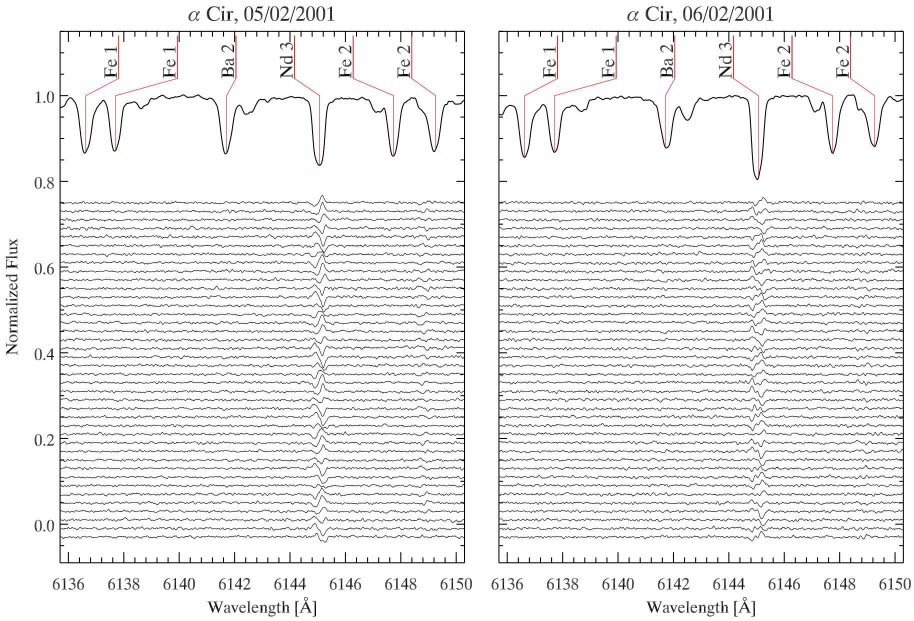

Fig. 1. Typical roAp spectroscopic pulsational behaviour is illustrated here on the example of rapid variation of the brightest roAp star α Cir. The two panels show time-resolved spectra of α Cir obtained by Kochukhov & Ryabchikova (2001b) on two consecutive nights. The upper curve shows the average spectrum, whereas temporal evolution of the residuals is plotted below. Clear pulsation signal is seen in the Nd III 6145 Å line.

oscillations in a roAp star. These high-quality data also revealed phase shifts between variation of singly and doubly ionized lines of rare-earth elements (REE). Our study emphasized a stunning discrepancy (sometimes up to two orders of magnitude in RV amplitude!) between strong pulsations in REE lines and the absence of changes in the lines of light and iron-peak elements, which do not show oscillations above few tens of m s^{-1}. Such an amazing diversity has never been observed in any other type of main sequence pulsating stars.

Discovery of the pulsational spectroscopic variability of 10 Aql (Kochukhov *et al.* 2002) and first analyses of the variation of individual metal lines in α Cir (Fig. 1) and HR 3831 (Kochukhov & Ryabchikova 2001b; Kochukhov 2005b) showed that unusual spectroscopic pulsational behaviour, dominated by REE lines, is not limited to γ Equ but is present in a very similar form in other roAp stars. This conclusion was further strengthened by the wide wavelength region analyses of HR 1217 (Balona & Zima 2002), 33 Lib (Mkrtichian *et al.* 2003) and HD 166473 (Kurtz *et al.* 2003). Consistency of the observed pulsation pattern contrasts with bewildering diversity of all other characteristics of the studied roAp stars. This suggests that pulsational behaviour is determined by certain fundamental processes which act similarly in all roAp atmospheres.

3 Tomographic Mapping of the Vertical Structure of Pulsation Modes

A plausible explanation of the nature of puzzling pulsational spectroscopic variation of roAp stars was suggested by Ryabchikova *et al.* (2002). This study of the atmospheric structure of γ Equ found compelling evidence that numerous anomalies of the line strengths and shapes arise from vertical chemical gradients (*i.e.*, chemical stratification) in the line forming atmospheric regions. Under the influence of radiative diffusion light and iron-peak elements are accumulated at the bottom of the atmosphere of γ Equ, whereas REEs form clouds high above normal photosphere. Detailed NLTE analysis by Mashonkina *et al.* (2005) indicates that Nd II and Nd III lines in γ Equ originate from the optical depths $\tau_{5000} = 10^{-4}$–10^{-5}. These high atmospheric layers rich in REEs are characterized by enhanced amplitude of non-radial pulsations. This is confirmed by the presence of large-amplitude RV variation in the core of Hα (Kochukhov 2003), whose formation depth is constrained to be $\tau_{5000} < 10^{-3}$ and is unaffected by stratification of the trace elements.

The rise of pulsation amplitude with height, consistent with theoretical expectations (Saio & Gautschy 2004), occurs due to the fact that kinetic energy of pulsation wave, $\rho v^2/2$, dissipates slower compared to the decrease of gas density with height. Similarity in pulsational behaviour of different roAp stars suggests that they share similar vertical chemical and pulsational profiles. In contrast, atmospheres of normal late A pulsating stars are thoroughly mixed and no diagnostic line can probe high layers and reveal vertical structure of pulsation modes.

Within the framework of the chemical stratification model, the phase shifts between RV curves of different lines are attributed to a running magnetoacoustic wave propagating outwards in stellar atmosphere and increasing in amplitude with height. Figure 2 shows this behaviour in the lines of the roAp star HR 1217. Unique observational material was acquired for this star in November 2004 during simultaneous spectroscopic monitoring at the VLT and other telescopes and photometric observation with the MOST satellite.

Thus, chemical stratification and underlying process of radiative diffusion proves to be extremely relevant for understanding pulsations in roAp stars. Stratification provides a set of spatial filters which can be employed to resolve atmospheric structures and pulsation waves to unprecedented detail. Capitalizing on these unique properties of the atmospheres of magnetic A stars, Ryabchikova *et al.* (2002) and Kochukhov (2003) developed the method of *tomographic mapping* of the vertical structure of roAp pulsation modes. The key idea of this novel application of asteroseismology is to model chemical abundance gradients simultaneously and self-consistently with the derivation of detailed vertical cross-section of pulsation modes.

Application of the pulsation tomography technique to γ Equ is illustrated in Figure 3. This figure demonstrates current state-of-the-art in NLTE modelling of Hα and rare-earth lines in stratified atmosphere of cool Ap star. Pulsation phase is plotted as a function of average formation depth of individual lines. There is a clear trend for different Nd lines and different bisector levels in the Hα core.

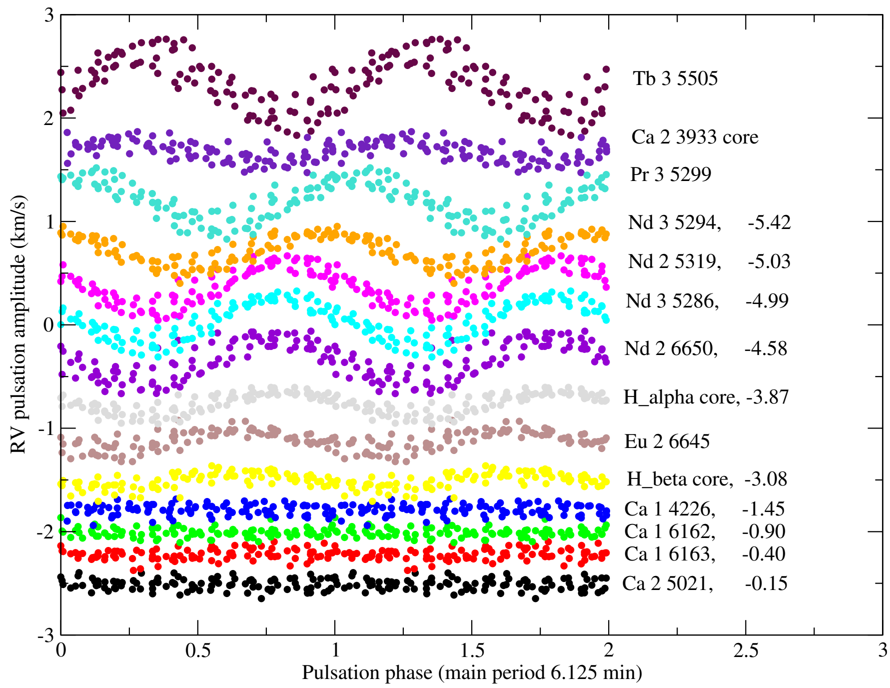

Fig. 2. Pulsation tomography of the atmosphere of HR 1217. Radial velocity curves of different spectral lines measured in the time-resolved VLT/UVES spectra are arranged according to the formation depth (given in the $\log \tau_{5000}$ units in the right part of the figure) of the corresponding absorption features. Pulsation curves are shifted in the vertical direction for display purpose.

In Figure 3 larger pulsation phase corresponds to later maximum RV, hence we see a signature of running pulsation wave propagating outwards. In this model Nd-rich layer is located above $\tau_{5000} = 10^{-3.5}$. Unfortunately a similar analysis of the depth dependence of RV amplitude is hampered by strong increase of pulsation amplitude from core to wings of *individual* REE lines. This effect, first noted by Sachkov *et al.* (2004), is very pronounced in γ Equ (though not so strong in HR 1217), and it distorts integral RV amplitude measured for a REE line even in the presence of relatively weak blends.

Rich information extracted by the tomographic method urges further refinement of theoretical pulsation models and shift of their emphasis to a more detailed analysis of the behaviour of high atmospheric layers. The first steps in this direction are being made by Saio (2005), whose non-adiabatic magnetohydrodynamical model for the first time addresses pulsational behaviour of optically thin layers. Preliminary comparison of the vertical pulsation wave structure predicted by Saio with the outcome of our analysis of γ Equ and HR 1217 shows reasonably good agreement between the theory and empirical modelling.

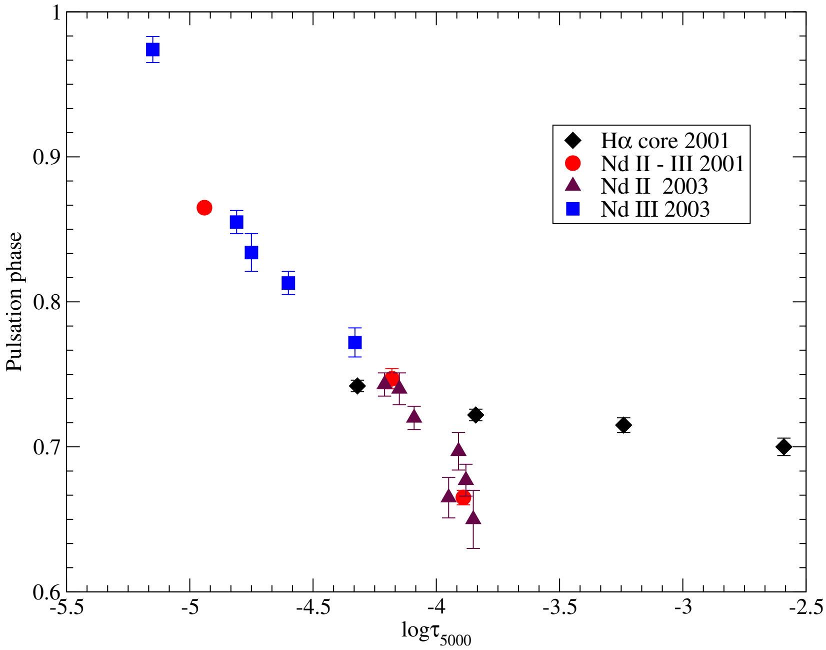

Fig. 3. Pulsation tomography of the atmosphere of γ Equ. Pulsation phases of the Hα, Nd II and Nd III lines are plotted against average formation depth of corresponding spectral features computed taking into account chemical stratification and NLTE Nd and H line formation (Mashonkina *et al.* 2005). Systematic increase of oscillation phase with height traces the structure of running pulsation wave.

In another development Kurtz *et al.* (2003, 2005) proposed that characteristic depth dependence of the roAp pulsation amplitude and different signatures of pulsations in REE and iron-peak lines arise due to a transition at $\tau \sim 10^{-3}$ from acoustic to magnetoacoustic oscillations in what the authors call "magnetoacoustic boundary layer", referring to the concept widely used in theoretical studies of roAp oscillations (*e.g.*, Bigot *et al.* 2000). However, recalling that location of this interesting region is defined by the ratio of Alfven and sound speeds, $\beta \equiv (v_{\rm A}/c_{\rm S})^2 \geq 1$, one finds that, for typical surface magnetic field strengths of roAp stars (1–10 kG), the boundary layer already starts well below visible photosphere and the whole line-forming region is located entirely in the $\beta \gg 1$ regime. Consequently, according to current theoretical models, no special "boundary region" is expected to occur in high atmospheric layers of magnetic stars and interpretation of the depth dependence of pulsations suggested by Kurtz *et al.* cannot be vindicated.

4 Reconstruction of the Horizontal Geometry of roAp Pulsations

Despite a dramatic recent progress in our understanding of the vertical structure of the roAp pulsation modes and the interplay between pulsations and stratification of chemical elements, relatively little attention has been paid to the problem of inferring the horizontal geometry of pulsations in roAp stars. The question of systematic mode identification, central to the studies of other types of pulsating stars, has not been thoroughly investigated in the case of magnetic pulsators. To a large extent such an unsatisfactory situation is explained by the absence of suitable observational material. Studies of the vertical structure of pulsating cavity capitalize on the extreme vertical inhomogeneity of the roAp atmospheres and typically make use of a relatively low S/N spectroscopic time series, sufficient to achieve a detection of pulsations and merely deduce amplitudes and phases of the RV changes in individual spectral lines. In contrast, probing the horizontal structure of pulsation modes is necessarily based on the observations of the rapid *line profile variation* (LPV) and, therefore, requires spectroscopic data of an outstanding quality.

First observations suitable for the quantitative roAp mode identification have been acquired for γ Equ by Kochukhov & Ryabchikova (2001a). In this study we investigated variability of the Pr III 6160 Å and Nd III 6145 Å lines and probed horizontal structure of the magnetoacoustic oscillation using several mode identification methods. Most importantly, application of the moment technique (Aerts *et al.* 1992) to the pulsational LPV in γ Equ showed that characteristic single-wave variability of the second moment (line width) is inconsistent with the picture expected for any axisymmetric ($m = 0$) mode. This discovery of *non-axisymmetric* pulsation in a roAp star posed new questions and demonstrated enormous diagnostic potential of the high-precision time-resolved spectroscopy.

Despite their interesting pulsation properties, γ Equ and other sharp-line roAp stars are not ideal targets for mapping the horizontal mode structure because their extremely slow rotation does not allow us to put useful constraints on the surface chemical inhomogeneities and explore oscillations from different geometrical aspect. Evidently, a more fruitful investigation of the LPV due to non-radial oscillation can be carried out for a roAp star with a high amplitude of pulsational spectral variation and a reasonably short rotation period.

HR 3831 is by far the best roAp target for in-depth analysis of the horizontal pulsation structure. Kochukhov & Ryabchikova (2001b) obtained full rotation phase coverage of this star in the time-resolved monitoring of the Nd III 6145 Å line observed at very high spectral resolution. A total of 1860 spectra made it possible to trace rotational modulation of pulsational LPV and were used by Kochukhov (2005b) to establish approximate mode geometry using generalized moment method. The latter technique, introduced by Kochukhov (2005a), represents an extension of the classical moment mode identification method to the oblique distorted pulsations in roAp stars. Moment analysis reveals that LPV in HR 3831 is not fully consistent with the oblique axisymmetric dipole ($\ell = 1$, $m = 0$) mode, implied by the classical oblique pulsator model of Kurtz (1982). Pulsational variation of higher moments, in particular the line width, demonstrated substantial contribution of the axisymmetric octupole ($\ell = 3$, $m = 0$) spherical harmonic which appears due to the distortion of pulsations by the global magnetic field (Saio & Gautschy 2004).

A major progress in unravelling pulsation structure of HR 3831 was achieved through the application of *pulsation Doppler imaging* (Kochukhov 2004a). In this novel modelling approach the principles of Doppler tomography (*e.g.*, Vogt *et al.* 1987) are extended to the reconstruction of the time-dependent pulsation velocity field. The temporal and surface variation of the velocity vector are represented with a superposition of the two constant surface maps of velocity amplitude. These vector distributions are recovered by direct fit of synthetic spectra to the observed LPV via solution of the regularized spectral inversion problem. The new Doppler imaging method permits mapping of pulsation velocity without *a priori* parameterization of pulsations with spherical harmonic functions. Furthermore, surface chemical abundance inhomogeneities are duly taken into account in the line profile modelling. Preliminary results of the application of this revolutionary method to HR 3831 were reported by Kochukhov (2004b). Combining pulsation velocity maps with the information on magnetic field geometry and surface distributions of chemical elements (Kochukhov *et al.* 2004) yields the very first comprehensive map of stellar surface structures (Fig. 4). The most important outcome of the pulsation Doppler imaging of HR 3831 is the finding that pulsations are roughly axisymmetric and are aligned with the dipole component of the stellar magnetic field. This represents the first and so far the only independent validation of the oblique pulsator framework.

5 Conclusions

The precision and wealth of information contained in the pulsation Doppler map of HR 3831 made possible the first direct test of recent theoretical developments in magnetoacoustic pulsation theories of roAp stars. Two main theoretical approaches to the roAp pulsation geometry were suggested. Bigot & Dziembowski (2002) focused on the interaction of pulsation and rotation in stars with weak field ($B < 1$ kG). They predict significant non-axisymmetric dipolar pulsation components and find that in general pulsation and magnetic axes are not aligned. This hypothetical pulsation geometry disagrees with our empirical pulsation model of HR 3831. Velocity maps of HR 3831 could be disentangled into a superposition of the axisymmetric dipolar and octupolar contributions, but show no sign of important non-axisymmetric dipolar components. Thus, it is concluded that theoretical model of Bigot & Dziembowski (2002) is incomplete and cannot be applied for HR 3831.

On the other hand, Saio & Gautschy (2004) neglected stellar rotation, but fully accounted for the effects of strong magnetic field. These authors find alignment of the magnetic and pulsation geometries and predict significant axisymmetric octupolar component. Precisely this kind of pulsation topology is derived for HR 3831 (Kochukhov 2004b, 2005b). In a further theoretical work, carried out by Saio (2005), the treatment of non-adiabatic effects was included and observed pulsation maps of HR 3831 were directly compared with theoretical predictions. Good agreement (see Fig. 12 in Saio 2005) suggests that finally we are on the

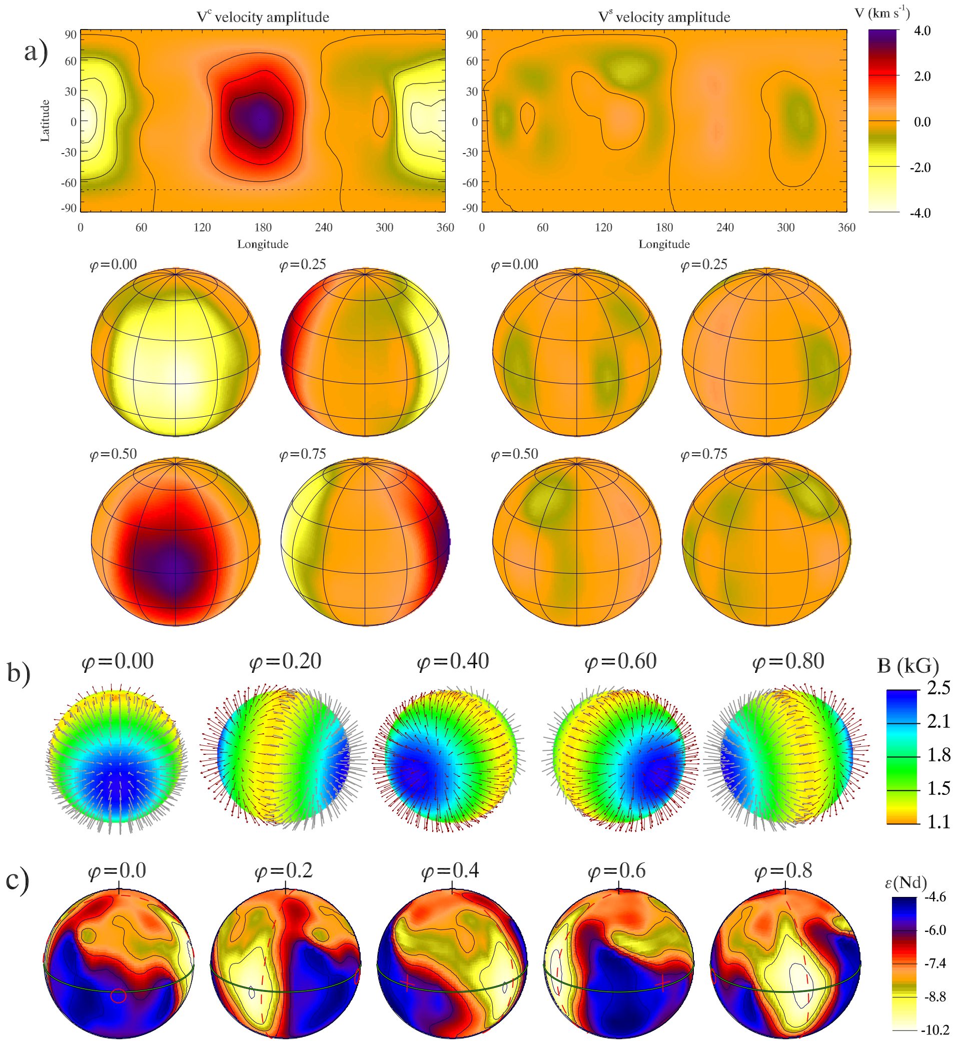

Fig. 4. The interplay of pulsation, magnetic field and chemical spot structure discovered in the roAp star HR 3831. **a)** Rectangular and spherical projections of the $V^{\rm C}$ and $V^{\rm S}$ pulsation velocity maps reconstructed with the help of pulsation Doppler imaging method (Kochukhov 2004a, 2004b); **b)** dipolar magnetic field geometry of HR 3831 (Kochukhov *et al.* 2004); **c)** surface map of Nd abundance inhomogeneities. In all spherical plots the star is shown at the specified set of rotation phases and inclination angle $i = 68^{\rm o}$.

right track and have truly made a significant progress in understanding non-radial oscillations in magnetic stars.

Detailed horizontal cross-section of pulsations reconstructed for HR 3831 diagnoses pulsation geometry at the upper atmospheric boundary. To obtain a

3-D pulsation map we would ultimately need to study profile variation of lines formed at different optical depths. We will acquire necessary observational material in near future and analyse the data by combining various remote sensing techniques into a new procedure suitable for constructing unprecedented 3-D maps of pulsation, magnetic field and chemical inhomogeneities in roAp stars.

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