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3-D mapping of magnetic fields, chemical abundances and pulsations in chemically peculiar stars

O. Kochukhov

Department of Astronomy and Space Physics, Uppsala University, Box 515, SE-751 20 Uppsala, Sweden
oleg@astro.uu.se

Abstract. Improvements in the quality of observations and refinement of the modelling techniques has led to emergence of a new branch of stellar astrophysics, which focuses on the reconstruction and understanding the origin of 3-D structures in the surface layers of chemically peculiar stars. Here we highlight recent results of the detailed modelling of chemical non-uniformities, magnetic and pulsation velocity fields in A stars. Doppler imaging analyses of magnetic fields and chemical spots show unexpected complexity and diversity of the surface formations and suggest that non-magnetic phenomena may play an important role in governing formation of chemical spots. High spectral and time resolution observations of line profile variability has made it possible to probe the radial dependence of chemical abundances and pulsation characteristics in rapidly oscillating Ap stars. These studies discover extreme chemical stratification and, in particular, reveal remarkable rare-earth clouds, located above the stellar atmosphere. An extension of Doppler mapping to the reconstruction of non-radial stellar pulsation structure has provided the first stringent test of modern magnetoacoustic pulsation theories.

Key words: stars: chemically peculiar – stars: magnetic fields – stars: atmospheres – stars: oscillations

1 Introduction

Magnetic chemically peculiar (CP) and related stars represent unique natural laboratories, which give us access to the study of various interesting and important astrophysical processes. CP stars exhibit strong global magnetic fields, vertical and horizontal chemical inhomogeneities, coupled with a non-solar chemistry of the surface layers, and show non-radial oscillations. The underlying physical mechanisms of the radiative diffusion, non-trivial hydrodynamics (mass loss, convective mixing, meridional circulation, etc.), pulsational instability, generation and evolution of the large-scale magnetic fields are active in many other types of low and high-mass stars at different evolutionary phases. However, manifestation of these effects is often obscured by other phenomena, making a direct detection and in-depth analysis impossible. This is why detailed investigations of the magnetic field and atmospheric structure formation and, especially, their intricate interaction with each other and with the stellar rotation and pulsation, are only feasible for magnetic CP stars.

In this review we discuss recent progress in understanding magnetic fields, non-radial pulsations and atmospheric inhomogeneities in CP stars. We focus on the results obtained using new modelling methods, which are based on the realistic theoretical modelling of stellar spectra and infer empirical maps of pulsation velocities, magnetic fields and chemical spots. We emphasize importance of combining these advanced remote sensing techniques into a self-consistent 3-D stellar atmosphere mapping procedure.

2 Magnetic fields in chemically peculiar stars

2.1 Longitudinal field measurements

The most straightforward magnetic measurement is determination of the disk-averaged line-of-sight (longitudinal) component of the stellar magnetic field using circular polarization observations. This technique was used to discover fields and monitor field variation over rotation cycle in the majority of known magnetic CP stars (e.g., Mathys 1991; Bohlender et al. 1993). The longitudinal field diagnostic turns out to be very efficient due to the smooth topology of the global field in CP stars. This property substantially reduces cancellation of the polarization signal coming from different surface zones and hence enables precise magnetic measurements at the variety of large and medium size telescopes equipped with diverse polarimetric instrumentation.

An impressive recent contribution to the studies of CP-star magnetism became possible through the development of the low-resolution spectropolarimetry with FORS1 at the ESO Very Large Telescope. In this observational approach, introduced by Bagnulo et al. (2002), longitudinal field is determined from the circular polarization signal in the wings of the hydrogen Balmer lines. The large collecting area of VLT and multi-object capabilities of FORS1 allowed to extend magnetic field studies to fainter stars and made possible the first systematic large-scale investigation of the incidence of magnetism in open clusters – the study aiming to answer a fundamental question about the link between stellar magnetism and evolution (Bagnulo et al. 2006).

Important application of the FORS1 and other longitudinal field measurements is to investigate evolutionary state of the field magnetic CP stars. This work has been recently completed by Kochukhov & Bagnulo (2006). We have compared predictions of the stellar evolutionary models with the observed parameters of *all* magnetic CP stars for which accurate parallaxes are available from the Hipparcos catalogue. Analysis of the sample, containing about 200 stars, suggests that the mechanism that originates and sustains the magnetic field in the upper main sequence stars may be different in CP stars of different mass. Massive magnetic stars seem to be distributed homogeneously over the whole width of the main sequence band. On the other hand, stars below $2\,M_{\odot}$ are rare close to the zero-age and terminal-age main sequence.

Improved precision of the magnetic field diagnostics with high-resolution spectropolarimeters now permit obtaining reasonably high-quality longitudinal field measurements using individual metal lines. The resultant line-by-line field determinations provide valuable information about rapid field variability with pulsation phase in roAp stars (Kochukhov et al. 2004c) and can constrain surface distribution of chemical elements in spotted magnetic CP stars (Leone & Catanzaro 2004). Furthermore, a discrepancy in the longitudinal field obtained from the spectral lines before and after Balmer jump was used to diagnose vertical gradient of the global magnetic field (Romanyuk & Kudryavtsev 2004).

These interesting studies notwithstanding, a caution is called for interpretation of the discrepancies in the longitudinal field measured from individual metal lines. Many recent investigations assume that such a scatter characterizes intrinsic difference of the field strength in the formation regions of the respective spectral features. Such an interpretation is not entirely correct *a priori* because the common longitudinal field measurement procedure is carried out under the restrictive assumption that spectral lines are weak (Mathys 1991). Saturation effects for real lines used for magnetic field diagnostics in CP stars may lead to biased and discrepant longitudinal magnetic field results even when the field is constant over the surface and with height in the stellar atmosphere. Fig. 1 shows how large the magnitude of these effects can become. In this plot we present

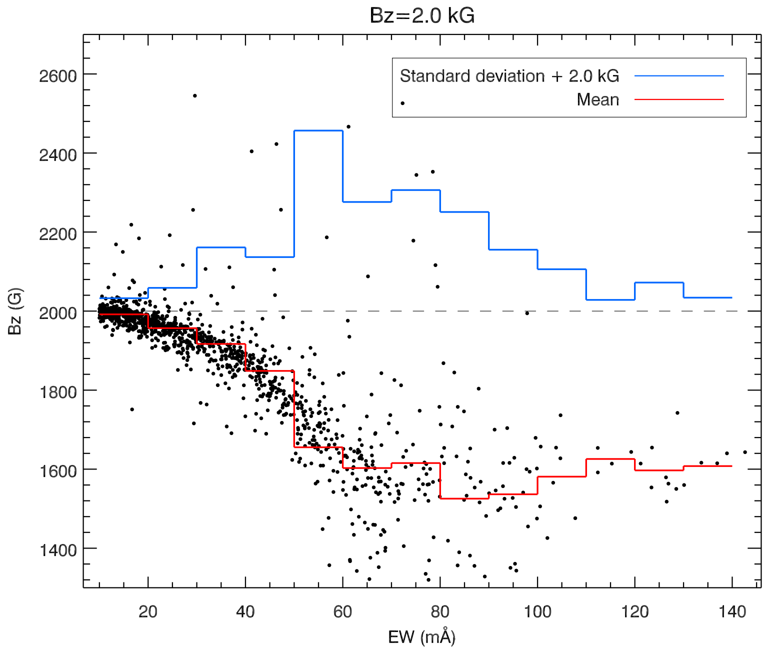

Figure 1: Longitudinal magnetic field inferred from the magnetic spectrum synthesis calculations of several hundred Fe lines. The true line of sight field component is 2.0 kG (dashed line). Symbols show longitudinal field determined from individual lines, the histograms show the mean and standard deviation (the latter is shifted vertically by 2 kG for display purpose).

longitudinal field determined in the usual manner from the polarized profiles of several hundred Fe lines synthesized with the `SYNTHMAG` code (Kochukhov, these proceedings). One finds that the average field strength for lines stronger than some 50 mÅ deviates systematically by ≈ 20% from the true field strength. At the same time, typical line-to-line scatter reaches 15% of the longitudinal field strength. These numerical tests clearly show limitations of the standard longitudinal field measurement procedure. Even though a formal accuracy of a few tens of G can be obtained from a multi-line analysis, these results can still deviate by several hundred G from the true field. Moreover, a difference of up to several hundred G in the field determined from individual lines may indicate a break down of the weak field approximation rather than an intrinsic variation of the field strength in the stellar surface layers.

2.2 Magnetic Doppler imaging

Thanks to the high amplitude of the line polarization signatures observed in many magnetic CP stars, a direct analysis of the Stokes spectra of these objects is currently within our reach. Only a modest equipment at a medium-size telescope is necessary to obtain high-quality Stokes V spectra for bright magnetic stars. These observations are suitable for the circular polarization magnetic imaging, such as the analysis presented by Kochukhov et al. (2002) for the prototype magnetic CP star α^2 CVn. This Stokes I and V Doppler mapping is similar to the Zeeman Doppler imaging (ZDI) procedure applied to active late-type stars (e.g., Petit et al. 2004), but has the advantage of working directly with the polarization profiles of individual metal lines and being based on the realistic spectrum synthesis calculations. However, circular polarization alone does not permit full reconstruction of the global CP-star field topology from first principles. Additional information in the form of multipolar regularization is required to ensure uniqueness of the solution (Kochukhov & Piskunov 2002).

Recently Donati et al. (2006) used Stokes V time-series observations with the newly commissioned ESPaDOnS spectropolarimeter at CFHT to detect moderately strong magnetic field at the surface of the early B-type star τ Sco. Donati et al. (2006) have performed Zeeman Doppler imaging analysis of this star, constraining the field geometry to be a superposition of high-order spherical harmonics – a surface imaging method analogous to the multipolar regularization technique of Piskunov & Kochukhov (2002). Donati et al. (2006) infer a fairly complex field structure, dominated by the spherical harmonic components with $\ell \approx 5$, from the variation of the Stokes V LSD profiles. It would be interesting to verify these tentative results with the analysis of individual spectral lines based on realistic polarized spectrum synthesis and taking into account possible surface chemical inhomogeneities usually associated with the presence of a large-scale magnetic field.

For several bright stars detection of the linear polarization signatures in a few strongest spectral lines has been achieved in addition to the acquisition of high-quality Stokes V spectra (Wade et al. 2000). With the additional constraints on the transverse field, these data proved to contain sufficient information for the very first assumption-free mapping of magnetic fields in early-type stars. Magnetic Doppler imaging (MDI) in four Stokes parameters developed by Piskunov & Kochukhov (2002) is currently the most advanced method to interpret the Stokes spectra of magnetic stars. This technique provided the first possibility to infer the stellar magnetic topology using spectra in all four Stokes parameters. The inversion procedure is based on the detailed polarized radiative transfer spectrum synthesis, which includes all relevant physics of line formation. No *a priori* assumptions are used to recover the field structure. This is the first time such an approach is adopted for CP and related stars. Finally, chemical maps and magnetic field are derived simultaneously and self-consistently. This means that the influence of chemical spots is taken into account not only for Stokes I, but also when computing linear and circular polarization profiles.

Magnetic CP star 53 Cam became the first target of the MDI in all four Stokes parameters. The mapping of this star by Kochukhov et al. (2004a) showed that only a fairly complex magnetic distribution could reproduce observed details of the Stokes V profiles and anomalously low amplitude of the linear polarization signal detected in the MuSiCoS spectra of this star (Wade et al. 2000). The agreement between observations and theoretical Stokes spectra generated with the MDI model is far better than can be achieved for any low-order multipolar field geometry (Bagnulo et al. 2001). The field topology reconstructed for 53 Cam (Fig. 2) is remarkable in its combination of a relatively simple, basically dipolar, field orientation with a complicated structure visible in the field strength maps. Consistent results obtained from independent inversions of different lines confirm reality of the major details in the magnetic maps and of the overall level of field complexity. Quantitative analysis of the MDI magnetic map was performed using high-order multipolar decomposition (Kochukhov et al. 2004a). It was inferred that the maximum contribution to the surface field topology comes from the spherical harmonic components with $\ell = 5$–6, corresponding to the angular scale of $\approx 30°$. Substantial toroidal field contribution was also detected.

Application of the MDI mapping to the MuSiCoS spectropolarimetric observations of another CP star, α^2 CVn, revealed a field structure with a dramatically different level of complexity compared to 53 Cam (Fig. 3). The field topology in α^2 CVn does not deviate far from a dipole and certainly lacks small-scale structures found in 53 Cam. For both stars chemical abundance maps were recovered simultaneously with the magnetic field. In α^2 CVn Fe and Cr lines used for the field mapping indicate the presence of large horizontal abundance gradients. Thus, despite a relatively simple field geometry, reliable analysis of the magnetic field in α^2 CVn was impossible with a technique other than MDI because all other methods do not account for the major effects of chemical spots.

Khalack & Wade (2006) compared predictions of the multipolar field models with the time-resolved four Stokes parameter observations of another well-known Ap star, 78 Vir. These authors found that a simple, nearly dipolar field structure gives acceptable fit to the MuSiCoS Stokes I and V observations of 78 Vir and does not contradict observed linear polarization inside individual line profiles. Conclusions of Khalack & Wade (2006) require confirmation with higher S/N observations

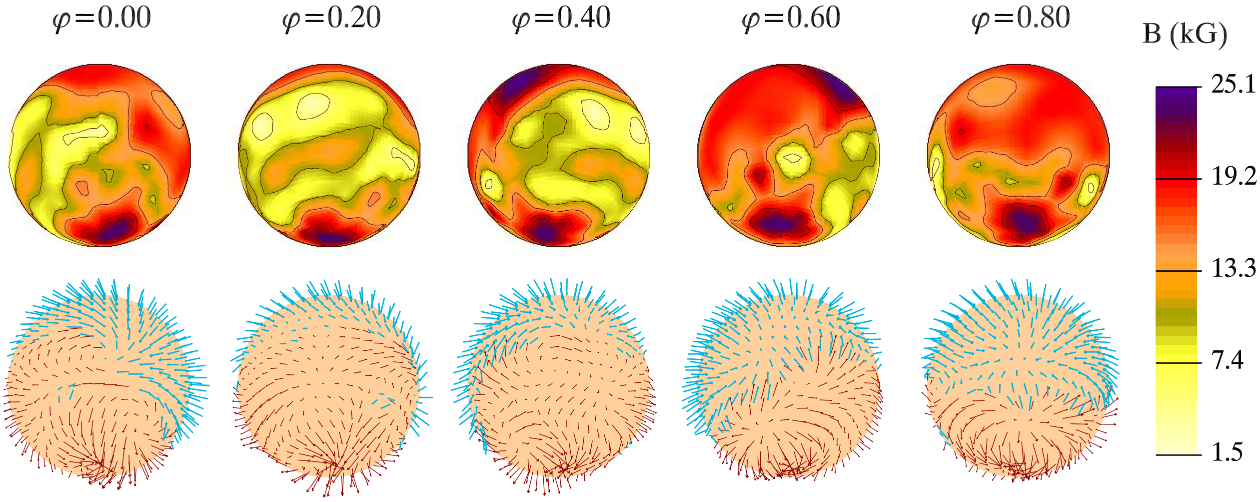

Figure 2: Magnetic field map inferred with the MDI inversion of all four Stokes parameter time-series observations of the CP star 53 Cam. The upper panel shows distribution of the magnetic field strength, whereas the lower panel illustrates the field orientation. The star is shown at five equidistant rotation phases. The aspect corresponds to the inclination angle $i = 123°$ and vertically oriented rotation axis.

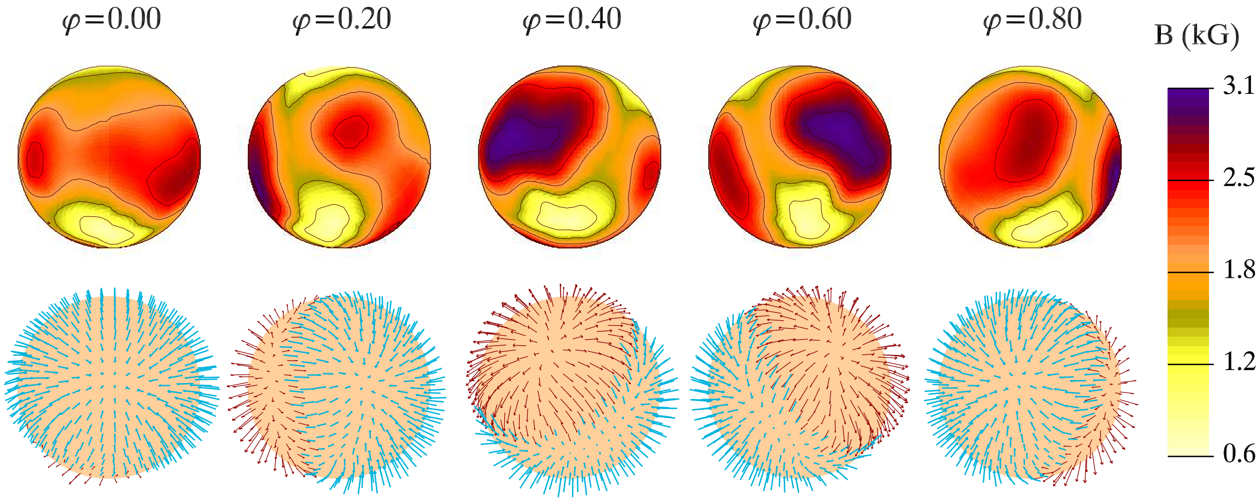

Figure 3: Magnetic field map of α^2 CVn inferred from the MDI inversion of spectropolarimetric time-series observations in all four Stokes parameters.

in the Stokes Q and U parameters, but, taken at face value, the magnetic topology obtained for 78 Vir hints that the complex field structure of 53 Cam may be rather unusual for an A-type magnetic star.

Successful mapping of the fields in 53 Cam and α^2 CVn confirms efficiency and robustness of the MDI approach and brings us to the conclusion that available inversion methods and four Stokes parameter observations make possible obtaining high-resolution magnetic stellar maps. The sample of stars studied so far is too small for any firm conclusions to be put forward. However, we can certainly expect to find diverse and complex fields in other CP stars. Among the future challenges of the magnetic Doppler imaging the most important one is extension of the analysis to a larger number of stars and investigation of the field structure in stars at different evolutionary phases. We also want to address the question raised by the apparent complexity of the field in 53 Cam. Are the small-scale features seen in the MDI maps of this star indeed represent a signature of higher-order multipoles or they approximate unresolved fields at even smaller scales? Finally, we hope to be able to compare empirical magnetic maps with the predictions of time-dependent 3-D MHD simulations of the evolution of stable fields in the radiative stellar envelopes (Braithwaite & Spruit 2004). The main feature of the magnetic topology emerging from these theoretical calculations is a mixture of poloidal and toroidal field components, not unlike the field structure we found in 53 Cam.

3 Vertical and horizontal chemical inhomogeneities

3.1 Surface mapping of chemical spots

Doppler mapping of the surface chemical inhomogeneities is a well-known tool, which has been applied to spotted Ap stars over several decades. The recent progress in this field is associated with the improvements in the numerical methods and in the quality of observational material. These factors allow us to construct more accurate chemical maps for a larger number of elements. Recently Kochukhov et al. (2004b) presented a detailed abundance Doppler imaging study of the roAp star HD 83368. This analysis became the most thorough examination of the surface chemical patterns for an Ap star. Some of the chemical maps obtained for HD 83368 were derived from the exceedingly high quality spectra collected by Kochukhov & Ryabchikova (2001b) ($R = 123\,000$, $S/N > 500$, 36 rotation phases), which enabled exploration of the surface spot patterns down to the fundamental resolution limit of Doppler imaging.

Fig. 4 shows some of the chemical maps reconstructed for HD 83368. Only a few elements show unambiguous correlation with the stellar magnetic field geometry. For instance, Li is accumulated in the surface areas around the poles of the dipolar field and O is enhanced at the magnetic equator. These simple symmetric chemical maps are exceptional. Many other elements, such as Fe (see Fig. 4), are distributed in a rather complex manner and do not follow the symmetry of the dominant dipolar magnetic field component of HD 83368. Some elements (Ba) tend to accumulate at the intersection of the magnetic and rotational equators. This geometry of the surface chemical patterns is similar to the Cr distribution found in α^2 CVn (Kochukhov et al. 2002).

A striking characteristic of the chemical maps reconstructed for HD 83368 is their extreme diversity. Even elements with similar atomic weights often show vastly dissimilar maps. It was commonly believed that all rare-earth elements are characterized by approximately similar surface distributions and are concentrated at the magnetic poles. Evidently, this is not the case for HD 83368. Eu shows small spots, which are noticeably displaced from the magnetic poles. On the other hand, Nd and Pr avoid the magnetic equator, but are present elsewhere at the stellar surface.

The Doppler imaging results obtained for HD 83368 demonstrate complexity of the diffusion in Ap stars and discard a simplified paradigm of the one-to-one correspondence between the global magnetic field geometry and the structure of chemical spots. It appears that abundance distributions are affected by some other phenomena, which are not directly related to the global magnetic field diagnosed through the longitudinal magnetic measurements. Perhaps, magnetic field in HD 83368 is considerably more complex than an axisymmetric dipole and, therefore, the observed complex chemical maps reflect the influence of unresolved small-scale magnetic topologies. One can also suspect that the magnetically-controlled mass loss (Babel 1992), modified further by the stellar rotation, alters the balance between radiative levitation and gravitational settling in different parts of the stellar surface. Moreover, possibility of the time-dependent modulation of the chemical transport processes by non-magnetic hydrodynamical instabilities cannot be ruled out.

A compelling evidence in favour of the presence of a non-magnetic modulation of the radiative diffusion has emerged with the recent discovery of surface inhomogeneities in mercury-manganese (Hg-Mn) stars. Adelman et al. (2002) reported convincing observation of the variability of the reso-

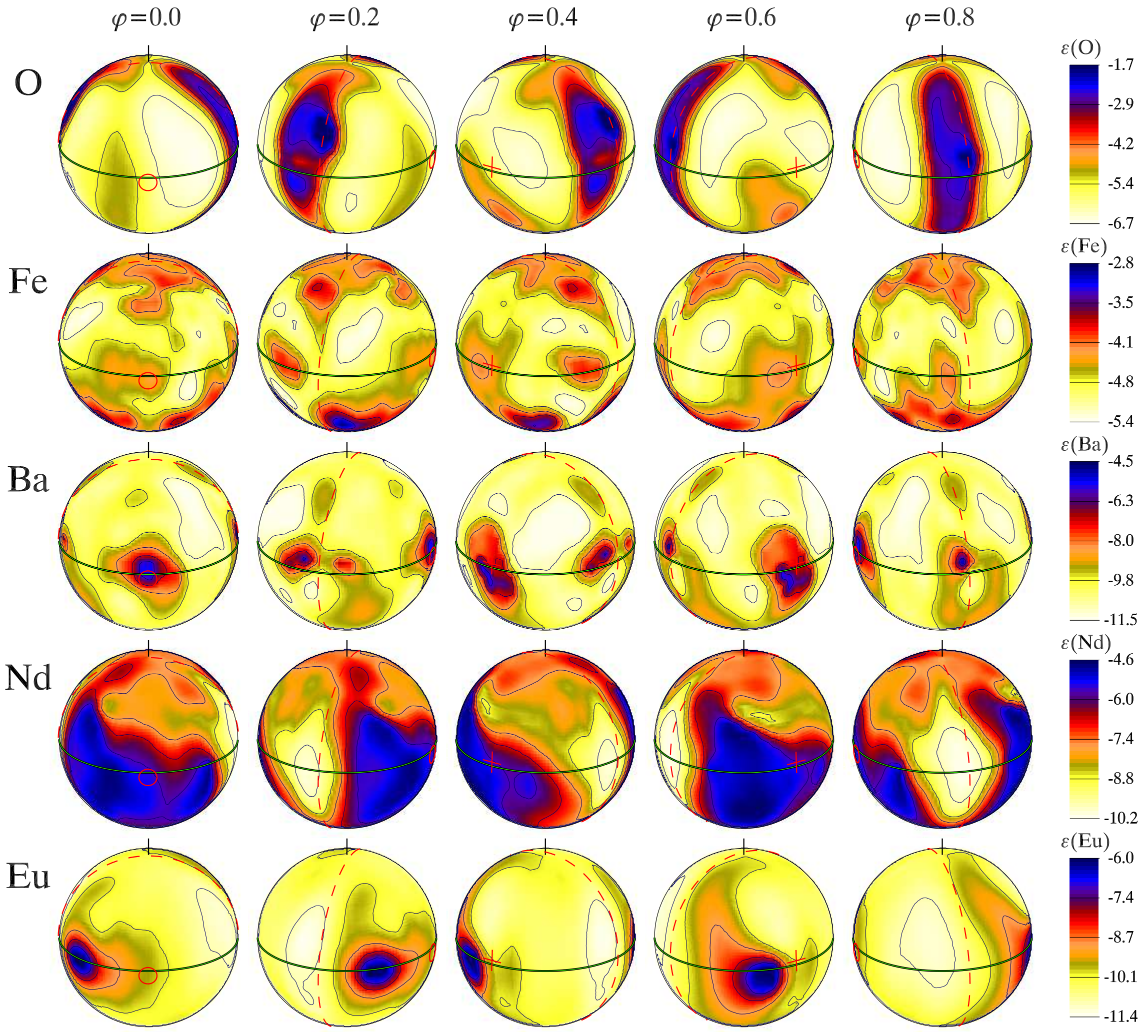

Figure 4: Distribution of O, Fe, Ba, Nd and Eu over the surface of the roAp star HD 83368. The star is shown at five equidistant rotation phases at the inclination angle $i = 68^\circ$ and vertically oriented axis of rotation. In the plots darker areas correspond to higher abundance. The thick solid line shows the location of the rotational equator, whereas the dashed line, plus sign and circle correspond, respectively, to the equator and poles of the dipolar magnetic field in HD 83368.

nance Hg II 3984 Å line for the brightest Hg-Mn star α And and reconstructed surface distribution of mercury. Concentration of this element was found to increase from the rotation poles towards the equator. A trend of the abundance versus latitude may be related to latitudinal modulation of the diffusion processes due to a fairly rapid rotation of α And. However, this does not explain the origin of the longitudinal abundance variation, which is observed as a series of spots of extreme Hg overabundance at or near the equator. Perhaps, appearance of the longitudinal structures is caused by the dynamic tides induced by the secondary star in the α And system, or it may be a signature of undetected weak magnetic field.

The latter hypothesis has been recently tested by Wade et al. (2006), who obtained high-quality spectropolarimetric observations of α And. These authors find no magnetic field signatures in the Stokes V spectra and assert that the line of sight component of the stellar magnetic field does not exceed 10 G. The corresponding large-scale field in α And is thus constrained to be below the equipartition strength of ≈ 250 G. Results of Wade et al. (2006) confirm the common understanding that Hg-Mn stars as a class lack strong magnetic fields (Shorlin et al. 2002).

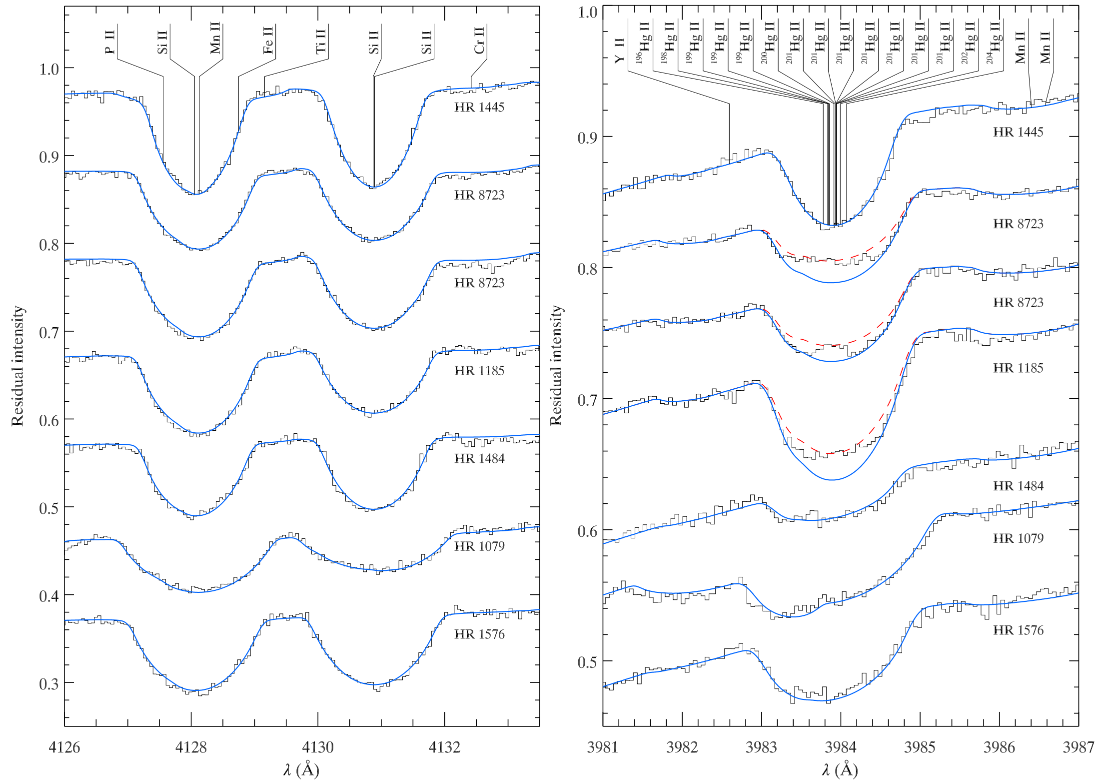

Figure 5: Comparison of the observed (histogram) and theoretical spectra of several Hg-Mn stars in the vicinity of the Si II lines at $\lambda = 4130$ Å (left panel) and the Hg II 3984 Å line (right panel). The Si II lines can be well fitted with the rotationally broadened synthetic spectra, whereas different abundances are required to fit the wings (solid curve) and the core (dashed curve) of the Hg line in HR 1185 and HR 8723. Spectra of the latter star obtained at two different nights show temporal evolution indicative of the variation of Hg abundance over the stellar surface.

Kochukhov et al. (2005) suggested Doppler effect to be used to detect signatures of inhomogeneous chemical distribution in Hg-Mn stars other than α And. They have conducted a survey of the Hg II 3984 Å line in the spectra of a small group of rapidly rotating Hg-Mn stars using spectroscopic observations with the SAO 6-m telescope. Analysis of the data (see Fig. 5) revealed signatures of mercury spots in two stars, HR 1185 and HR 8723, with $T_{\rm eff}$ similar to that of α And. It seems that previously unrecognized class of the spectrum variable spotted stars exists among the late-B non-magnetic chemically peculiar stars.

New observations of α And (Kochukhov et al., in preparation), covering the period from 1998 to 2004, suggest a long-term evolution of the Hg spot distribution in this star. This is the first ever evidence of the variation in the structure of chemical clouds in the atmospheres of CP stars. It is feasible that the physical effects responsible for the modulation in the mercury cloud cover in α And are active in other CP stars and can contribute to the scatter of abundances for stars with the same atmospheric parameters. The surprising discovery of spotted Hg-Mn stars shows how incomplete is our observational and theoretical understanding of the radiative diffusion processes even when we deal with bright non-magnetic stars.

3.2 Chemical stratification

Diffusion processes, invoked to explain the observed average atmospheric abundance anomalies of CP stars, also lead to an inhomogeneous abundance distribution through the stellar atmosphere

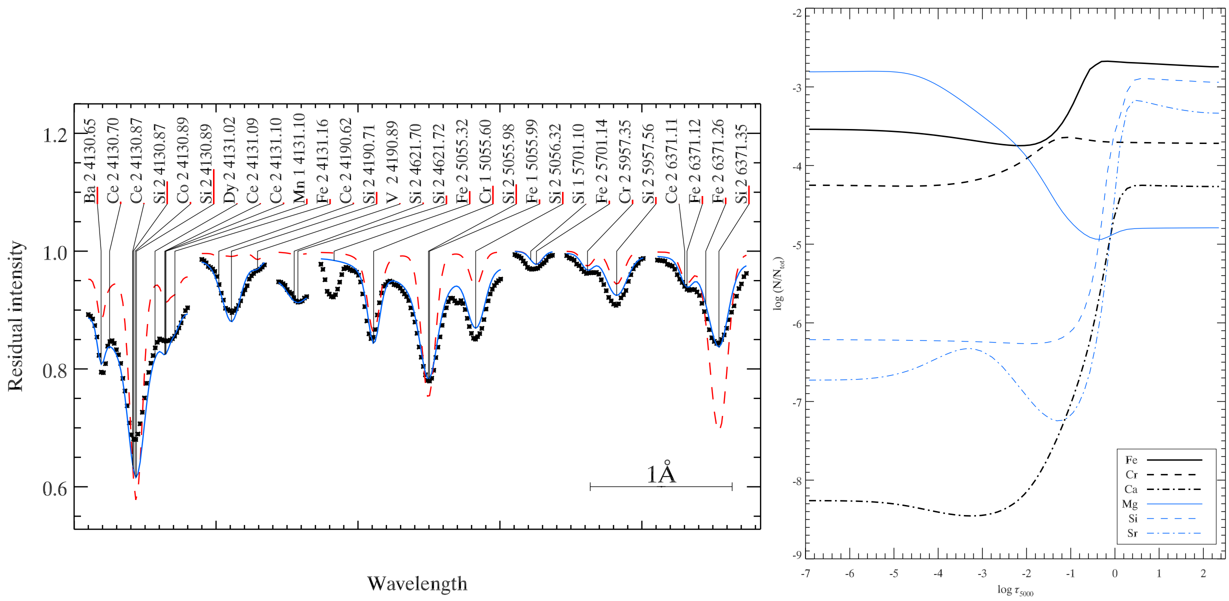

Figure 6: Chemical stratification analysis for the atmosphere of Ap star HD 133792. The left panel shows comparison of the observed Si line profiles (symbols) and calculations for the stratified abundance distribution (full line) and for the best-fit homogeneous abundance (dashed line) of Si. The right panel summarizes the chemical stratification profiles obtained for HD 133792 with the help of regularized vertical inversion technique of Kochukhov et al. (2006).

depending on the balance between radiative acceleration and surface gravity. The absence of significant convective mixing in the atmospheres of A-type stars and additional stabilization effect of magnetic fields may facilitate diffusive separation of elements and can create large abundance gradients in the line-forming photospheric regions. This theoretical prediction has been put forward long time ago (e.g., Borsenberger et al. 1981), but limited quality of observations did not permit recognizing stratification signatures for all but the strongest lines with the most extreme anomalies, like the Ca II 3933 Å absorption feature (Babel 1994).

Recently modern spectrographs at large telescopes have reached remarkable precision and spectral coverage, and now allow us to record very high signal-to-noise ratio data covering the whole optical region spectra of moderately faint Ap stars. This dramatic improvement in the quality and quantity of the available observational material suggests that unprecedented details of the stellar atmospheric properties, and, in particular, the vertical abundance distributions, can be deduced with the help of detailed modelling of the spectral line profiles. This stimulated a recent surge of interest in the observational analysis of chemical stratification. In fact, magnetic chemically peculiar stars represent the only type of non-degenerate stellar objects where direct observations and diagnosis of the chemical diffusion signatures becomes possible. Observational study of the chemical stratification in Ap stars is able to provide crucial and unique constraints for the theoretical modelling of chemical diffusion in stellar atmospheres (Babel 1992; LeBlanc & Monin 2004) and also helps to understand the relation between diffusion and hydrodynamic mixing processes.

A series of studies of cool Ap stars (Bagnulo et al. 2001; Wade et al. 2003; Ryabchikova et al. 2002, 2005; Kochukhov et al. 2006) showed the presence of ubiquitous signatures of chemical stratification in stellar spectra. For the light and iron-peak elements broad wings of strong spectral lines often indicate a far larger abundance than the cores. In addition, one finds significant discrepancy (sometimes reaching 0.5–1.0 dex) of abundances derived from the lines of different equivalent width, excitation potential and different ionization stages of the same element. It turns out that a relatively simple vertical chemical stratification profile, consisting of different constant abundances above and below certain level in the stellar atmosphere, is sufficient to reduce the disagreement between calculated and observed line profile shapes and strengths. Thus, many puzzling features in the Ap-star spectra originate from an inhomogeneous vertical distribution of chemical elements.

Vertical distribution derived for various light and iron-peak elements in cool Ap stars is remarkably similar: element concentrations are enhanced in deep atmospheric layers, whereas the upper atmosphere is characterized by the solar or subsolar composition. The transition region between the two zones is usually narrow and is located between $\log \tau_{5000} = 0.0$ and $\log \tau_{5000} = -1.0$ for the majority of elements. The amplitude of the abundance jump typically ranges from 0.5 dex up to 2–3 dex. This vertical abundance variation is sufficiently large to induce non-negligible modification of the atmospheric structure, energy distribution, colours and other observable characteristics of CP stars. This calls for inclusion of the depth-dependent chemistry in the model atmosphere calculations for peculiar A and B-type stars (Shulyak et al. 2004).

Until now observational analyses of stratification in peculiar stars have been limited to fitting simple parametrized vertical chemical profiles to a small number of diagnostic lines. Chemical distributions were approximated with a step function, whose shape is described by two abundance values and the position of the transition zone. A different approach, significantly improving stratification modelling techniques, was recently presented by Kochukhov et al. (2006). These authors developed the first assumption-free method of reconstruction of chemical stratification in stellar atmospheres. In this technique, the individual chemical composition is derived for all atmospheric layers contributing to the line absorption. Uniqueness and stability of the chemical inversion is achieved by applying the Tikhonov regularization function. This means that the vertical inversion code finds the simplest elemental distribution sufficient to fit observations.

Kochukhov et al. (2006) applied the vertical inversion procedure to the weakly magnetic Ap star HD 133792, reconstructing vertical distributions of six elements (see Fig. 6). Investigation of the diffusion signatures in HD 133792 confirmed the validity of the step-like, parametrized stratification models applied in previous studies of Ap stars. However, for some species the transition region can be rather extended (Mg), or the vertical distribution is more complex than a simple one-step function (Sr). Thus, the applicability of the latter approximation is wide, but not universal. In this context, automatic regularized inversion approach of Kochukhov et al. (2006) appears to be more robust and should be preferred whenever possible.

4 Non-radial pulsations in roAp stars

In addition to the remarkable magnetic and chemical surface characteristics of chemically peculiar stars, many cooler Ap stars also exhibit high-overtone non-radial acoustic p-modes. There are more than 30 such rapidly oscillating Ap (roAp) stars known at the present time (Kurtz & Martinez 2000; Kurtz et al. 2006). These objects oscillate with periods in the range of 6–21 min, while their light variation amplitudes rarely exceed 10 mmag in Johnson B. Pulsations in roAp stars bear a certain resemblance to the solar acoustic p-mode oscillations, but are characterized by a smaller number of excited modes and have amplitudes that are three orders of magnitude larger than the p-mode oscillations in the Sun. Photometric investigations of roAp stars were carried out during the last 25 years and have yielded unique asteroseismic information on the internal structure and fundamental parameters of roAp pulsators (e.g., Matthews et al. 1999; Cunha et al. 2003).

The observed pulsation amplitudes of roAp stars are modulated according to the visible magnetic field structure, pointing to a defining role played by magnetic fields in exciting the oscillations and shaping the main pulsation properties. Observation of the coincidence of the magnetic field and pulsation amplitude extrema gave rise to the *oblique pulsator model* (OPM, Kurtz 1982). According to this phenomenological framework, the main characteristics of non-radial pulsations in roAp stars can be attributed to an oblique axisymmetric ($\ell = 1$, $m = 0$) mode, aligned with the axis of a nearly axisymmetric quasi-dipolar magnetic field.

The OPM gave rather successful and straightforward geometrical explanation of the main features in the roAp frequency spectra found by time-resolved photometric monitoring of these stars. However, subsequent detailed studies of roAp pulsations have revealed that the mode geometry in some stars defies a simple interpretation in terms of a single spherical harmonic (e.g., Kurtz et al. 1989). Moreover, gradual accumulation of the photometric information about pulsations in some of the best-studied monoperiodic roAp stars with oblique dipole modes has provided evidence of significant deviations in the mode geometry from the expected axisymmetric dipole shape – an effect loosely called "distorted dipole modes" (Kurtz et al. 1997).

Several theoretical investigations (Bigot & Dziembowski 2002; Saio & Gautschy 2004; Saio 2005) studied the effects of the distortion of oblique pulsation mode geometry by the global magnetic field and stellar rotation. Bigot & Dziembowski (2002) predicted that the rotational distortion of pulsation eigenmodes is represented by a superposition of spherical harmonic functions, containing substantial non-axisymmetric components, and that there is no alignment of the pulsation axis and the dipolar magnetic field. On the other hand, Saio & Gautschy (2004) and Saio (2005) disregarded effects of rotation, focusing on the detailed treatment of the interaction between p-modes and a strong magnetic field. As a consequence, these authors find an axisymmetric pulsation structure and alignment between the magnetic field and the pulsation modes. At the same time, Saio & Gautschy (2004) predicted substantial deviation of the surface structure of pulsational fluctuations from a single spherical harmonic. In particular, the $\ell = 1$ mode is distorted by a dipolar magnetic field in such a way that pulsations are described by superposition of the spherical harmonics with odd angular degree ℓ, and pulsation amplitude is strongly confined to the magnetic axis in the outer stellar layers.

Sophistication of the theoretical speculations about the geometry and physics of roAp oscillations notwithstanding, it became clear that modelling of the photometric light curves of roAp stars is generally insufficient for accurate determination of the structure of pulsation modes and that these observations are unable to provide useful tests of theoretical predictions. The information content of the high-speed photometric observations is small due to averaging of the pulsational disturbances over the whole visible stellar hemisphere (see Saio & Gautschy 2004) and highly uncertain because rapid light variation in roAp stars involves non-linear and non-adiabatic effects that are strongly wavelength dependent and are not at all understood (Medupe & Kurtz 1998). The latter problem explains why no consistent physical picture of the broad-band photometric variability of roAp has ever been developed. Instead of deducing the structure of the luminosity perturbations from the fundamental pulsation quantities, all theoretical works and phenomenological attempts to interpret photometric observations of roAp stars have *assumed* that luminosity perturbations are proportional to pulsational displacement. Therefore, constraints on the pulsation mode geometry obtained from the photometry of roAp stars are inherently indirect, which arguably makes any subsequent inferences about the physics of magnetoacoustic oscillations questionable.

Investigations of pulsational variation in the spectral line profiles of roAp stars observed at high time and spectral resolution can potentially provide much more direct and unprecedentedly complete information about the vertical and horizontal structure of p-modes and about its relation to the magnetic field topology, chemical inhomogeneities and anomalous atmospheric structure of Ap stars. Such spectroscopic studies may eventually allow us to address the underlying questions about the physics of pulsating peculiar stars, for instance, the problem of excitation of the magnetoacoustic oscillations or the nature of the mode selection mechanism.

Recently major progress in the observational study of roAp stars was achieved by employing time-series spectroscopy in addition to the classical high-speed photometric measurements. Time-resolved spectroscopy of magnetic pulsators revealed a surprising diversity, not observed in any other type of pulsating stars, in the pulsational behaviour of different lines (e.g., Kanaan & Hatzes 1998).

Detailed analysis of the bright roAp star γ Equ (Kochukhov & Ryabchikova 2001a) demonstrated that spectroscopic pulsational variability is dominated by the lines of rare-earth ions, especially those of Pr and Nd, which are strong and numerous in the roAp spectra. On the other hand, light and iron-peak elements do not pulsate with amplitudes above 50–100 $\mathrm{m\,s^{-1}}$. This is at least an order of magnitude lower than the 1–5 $\mathrm{km\,s^{-1}}$ variability observed in the lines of rare-earth elements (REE). Many other roAp stars have been found to show a very similar overall pulsational behaviour (Kochukhov & Ryabchikova 2001b; Balona 2002; Mkrtichian et al. 2003; Ryabchikova et al. 2007a).

4.1 Magnetoacoustic tomography

The peculiar characteristics of the p-mode pulsations in roAp stars were clarified by Ryabchikova et al. (2002), who were the first to relate pulsational variability to vertical stratification of chemical elements. In this study of the atmospheric properties of γ Equ we showed that the light and iron-peak elements are enhanced in the lower atmospheric layers ($\log\tau_{5000} \geq -0.5$), whereas REE ions are concentrated in a cloud with a lower boundary at $\log\tau_{5000} \leq -4$ (Mashonkina et al. 2005). Thus, high-amplitude pulsations observed in REE lines occur in the upper atmosphere, while lines of elements showing no significant variability form in the lower atmosphere. This leads to the following general picture of roAp pulsations: we observe a signature of a magnetoacoustic wave, propagating outwards with increasing amplitude through the chemically stratified atmosphere.

The presence of significant phase shifts between the pulsation radial velocity curves of REEs (Kochukhov & Ryabchikova 2001a), or even between lines of the same element (Mkrtichian et al. 2003), can be attributed to the chemical stratification effects and, possibly, to the short vertical wavelength of the running magnetoacoustic wave. These unique properties of roAp pulsations, combined with a presence of large vertical abundance gradients in the line-forming region, make it possible to resolve the vertical structure of p-modes and to study propagation of pulsation waves at the level of detail previously possible only for the Sun.

The study by Ryabchikova et al. (2002) represents the first attempt to use the vertical chemical inhomogeneities as spatial filters which resolve the vertical p-mode structure. The basic idea of this *pulsation tomography* approach consists of characterizing pulsational behaviour of a carefully chosen, but extensive, sample of spectral lines and subsequently interpreting these observations in terms of pulsation wave propagation. Chemical stratification analysis of REE lines constrains formation depths of pulsating lines, thus allowing one to associate geometrical height with the amplitude and phase of RV pulsations.

In Fig. 7 we illustrate results of the pulsation tomography analysis of the roAp star HD 24712. This star was observed simultaneously by the MOST satellite and from the ground, using high-resolution spectrographs at several large telescopes, including the ESO VLT. Using these time-series spectra, Ryabchikova et al. (2007a) studied pulsational variation of more than 600 lines. Pulsation amplitudes and phases for several characteristic lines of light elements, the core of Hα, Pr III, Nd II and Nd III lines are plotted in Fig. 7 as a function of optical depth. Observations are compared with the pulsational wave depth dependence expected for the non-adiabatic model calculated by Saio (2005 and private communication). NLTE line formation was taken into account in chemical stratification analysis of REE ions. This modelling reveals a rapid increase of the pulsation amplitude with height and the respective changes of the pulsation phase. Oscillation amplitude reaches maximum at $\log\tau_{5000} \approx -4.5$ and decreases in the higher layers. Preliminary NLTE stratification analysis of Pr (Ryabchikova et al. 2006) suggests that formation heights of the Pr III absorption features are not too different from Nd III, despite a clear phase offset between the two groups of lines. This phase difference, as well as the amplitude and phase jump between the uppermost layers probed by the Hα core and the location of the REE cloud, may reflect shortcomings of the complicated NLTE analysis. Alternatively, it is possible that we are seeing effects of the inhomogeneous surface distribution of different REEs in HD 24712. Magnetic Doppler images obtained by Lüftinger et al.

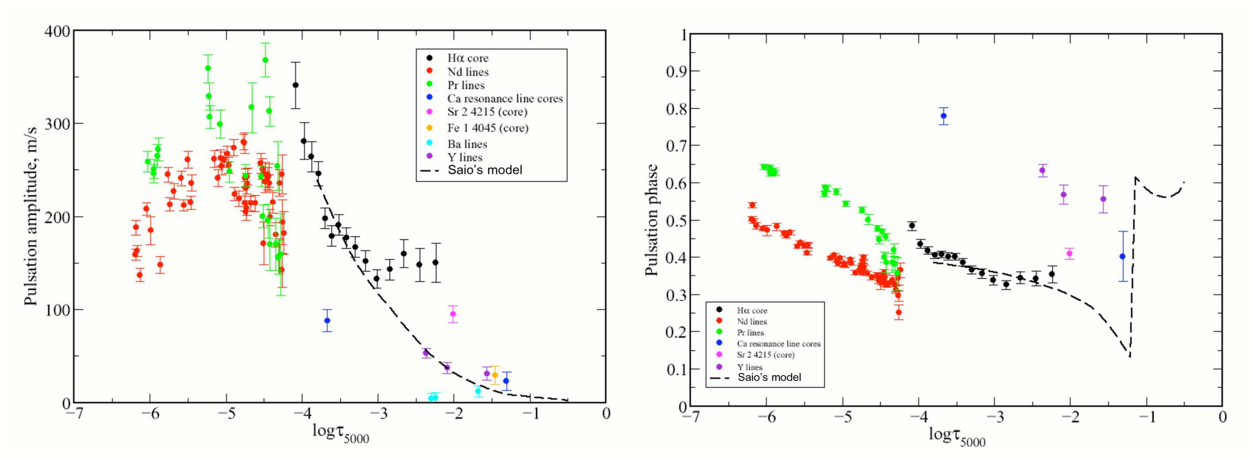

Figure 7: Reconstruction of the vertical cross-section of pulsation mode in the roAp star HD 24712. Symbols show the observed amplitude (left panel) and phase (right panel) of the radial velocity variation for different spectral lines. These measurements are plotted as a function of the continuum optical depth at $\lambda = 5000$ Å. The dashed line illustrates theoretical depth dependence of the pulsation wave properties (H. Saio, private communication).

(this conference) show that the horizontal geometry of the Pr and Nd distribution is not the same. This may lead to different pulsational behaviour because the vertical structure of magnetoacoustic modes depends on the field strength and orientation (Cunha 2006) and, therefore, may be different at the locations of the Pr and Nd spots in HD 24712.

The detailed pulsation tomography analysis based on the NLTE chemical stratification modelling is very demanding in terms of the quality of observations, required computer resources and physical input data. This is why only two roAp stars, γ Equ and HD 24712, were studied with this method. A different approach to the pulsation tomography problem was recently proposed by Ryabchikova et al. (2007b). They noted that, in the framework of the outward propagating running magnetoacoustic wave, one expects a smooth, continuous amplitude vs. phase trend of the pulsational characteristics. Investigation of the amplitude-phase diagrams thus offers a possibility to trace the vertical variation in the mode structure without assigning physical depth to pulsation measurements. Ryabchikova et al. (2007b) analysed a sample of ten roAp stars, measuring variation of several hundred lines for each object. The amplitude-phase diagrams were constructed for each star and the resultant vertical mode cross-sections were compared with other pulsational characteristics and with the fundamental stellar parameters. As an outcome of this analysis, it was discovered that the form of pulsational perturbation changes from predominantly standing to mainly running wave within the REE line-forming region. In other words, one group of REE lines shows a large scatter in the pulsation amplitude, but possesses nearly the same pulsation phase. In contrast, a group of lines probing higher layers shows substantial variation of both characteristics of their RV curves. It appears that the location of this interesting modification of the pulsation wave properties shifts towards higher layers for cooler roAp stars.

4.2 Pulsation Doppler imaging

The outstanding pulsational variability of REE lines in the spectra of rapidly rotating roAp stars permitted detailed mapping of the horizontal pulsation structure. In fact, the short rotation periods of some roAp stars and the oblique nature of their non-radial oscillations allow pulsational monitoring from different aspect angles, thus facilitating reconstruction of the horizontal pulsation

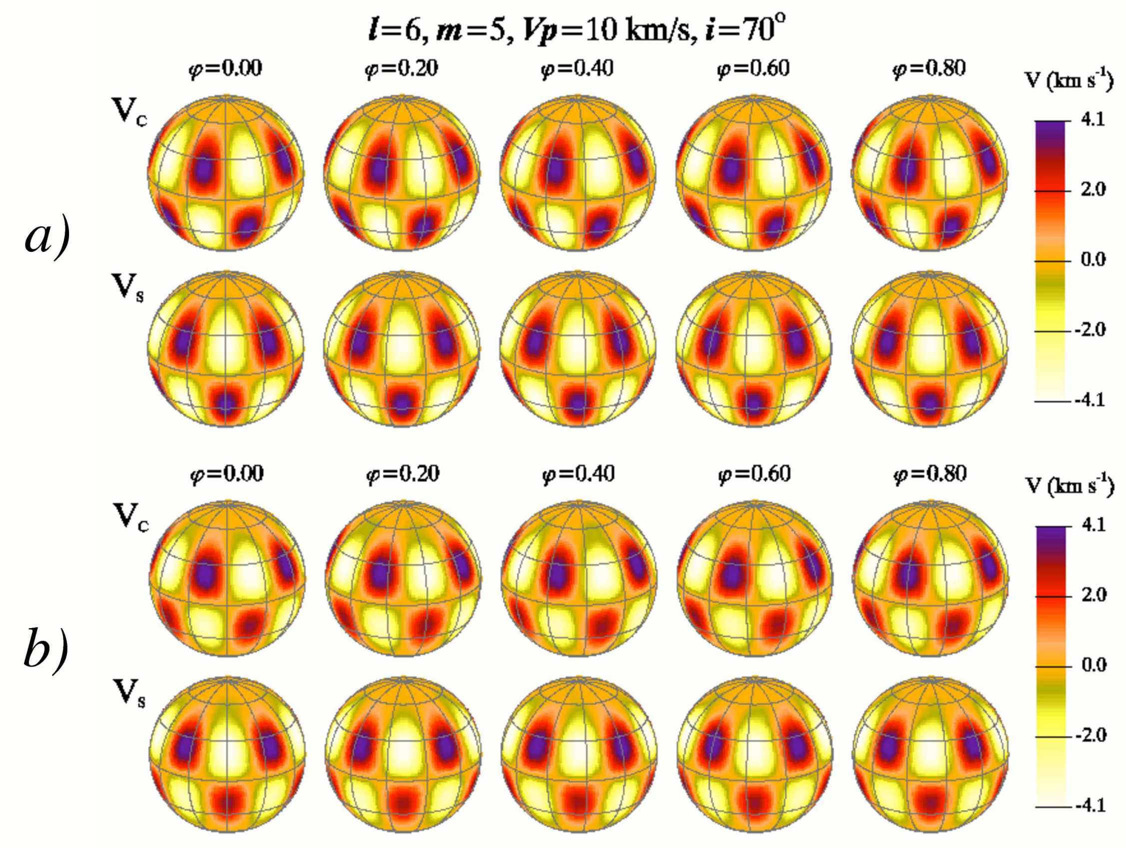

Figure 8: Numerical experiment illustrating capabilities of pulsation Doppler imaging. **a)** Spherical maps show surface distribution of the V^c and V^s velocity amplitudes, corresponding to the $\ell = 6$, $m = 5$ non-radial mode viewed at $i = 70°$. **b)** Velocity maps reconstructed by the pulsation Doppler imaging code from the simulated line profile time series.

pattern. Using this unique geometrical property of roAp pulsations, Kochukhov (2006) has carried out a high-resolution spectroscopic monitoring of the prototype roAp star HD 83368 (HR 3831). This star was observed at the ESO 3.6-m telescope during 6 nights over the period of two weeks. Full rotational phase coverage with the time-resolved spectra was obtained, supplying observational material for the first investigation of the rotational modulation of the pulsational line profile variability (LPV) in a roAp star.

The moderately rapid ($v_{\rm e} \sin i = 33$ km s^{-1}) rotation of HD 83368 makes it possible to use Doppler effect in spectral lines to resolve the horizontal topology of chemical inhomogeneities and velocity perturbations due to non-radial oscillations. Kochukhov (2004a) extended the principles of Doppler imaging to the reconstruction of the time-dependent velocity field. In this approach the temporal and surface variation of the velocity vector are represented with a superposition of the two constant surface distributions:

$$\boldsymbol{V}(t,\theta,\phi) = \boldsymbol{V}^c(\theta,\phi)\cos(\omega t) + \boldsymbol{V}^s(\theta,\phi)\sin(\omega t),$$

where ω is the pulsation frequency and θ, ϕ are usual spherical coordinates on the stellar surface. The $\boldsymbol{V}^c$ and $\boldsymbol{V}^s$ vector maps are recovered directly from the observed line profile variability without imposing any specific global constraints on the pulsation geometry. This is equivalent to mapping a two-dimensional surface distribution of the pulsation amplitude and phase for each velocity component.

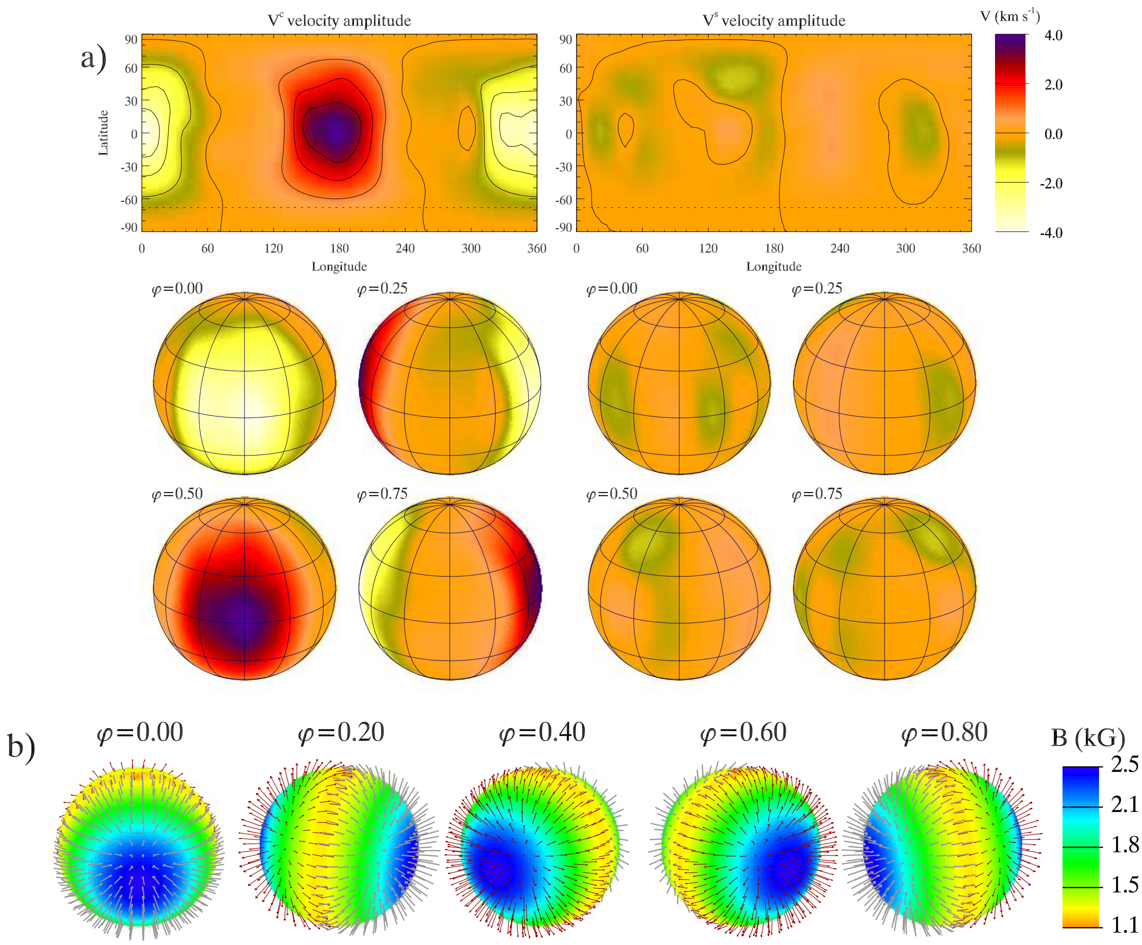

Figure 9: The interplay of the pulsation geometry and magnetic field found for the roAp star HD 83368. **a)** Rectangular and spherical projections of the vertical V^c and V^s pulsation velocity maps reconstructed by the pulsation Doppler imaging method; **b)** dipolar magnetic field geometry of HD 83368. In all spherical plots the star is shown at the specified set of rotation phases and for the inclination angle $i = 68°$.

The foundations of the pulsational Doppler mapping and description of its computer implementation were presented by Kochukhov (2004a). We refer the reader to this paper for a detailed explanation of the technique and discussion of the numerical simulations which were used to evaluate performance and intrinsic limitations of the new surface mapping method.

Fig. 8 illustrates representative pulsation Doppler imaging inversion with simulated time-resolved observations of $\ell = 6$, $m = 5$ non-radial pulsator. Comparison of the true and reconstructed velocity distribution shows good correspondence of the main features of the velocity maps. Unlike many other attempts to use LPV for the purpose of mode identification in non-radially pulsating stars, pulsation Doppler imaging does not assume that the surface mode geometry is described by the spherical harmonic functions. Instead, the spherical harmonic pattern emerges naturally when the inversion procedure recovers surface maps directly from observations. The absence of *a priori* constraints on the functional form of pulsation maps makes pulsation Doppler imaging method uniquely suited to the problem of inferring pulsation geometry of stars with non-radial modes strongly distorted by magnetic field or rapid stellar rotation.

Applying pulsation mapping technique to the roAp star HD 83368, Kochukhov (2004b) obtained the first stellar Doppler image of the velocity field in a non-radial pulsator. Velocity maps derived

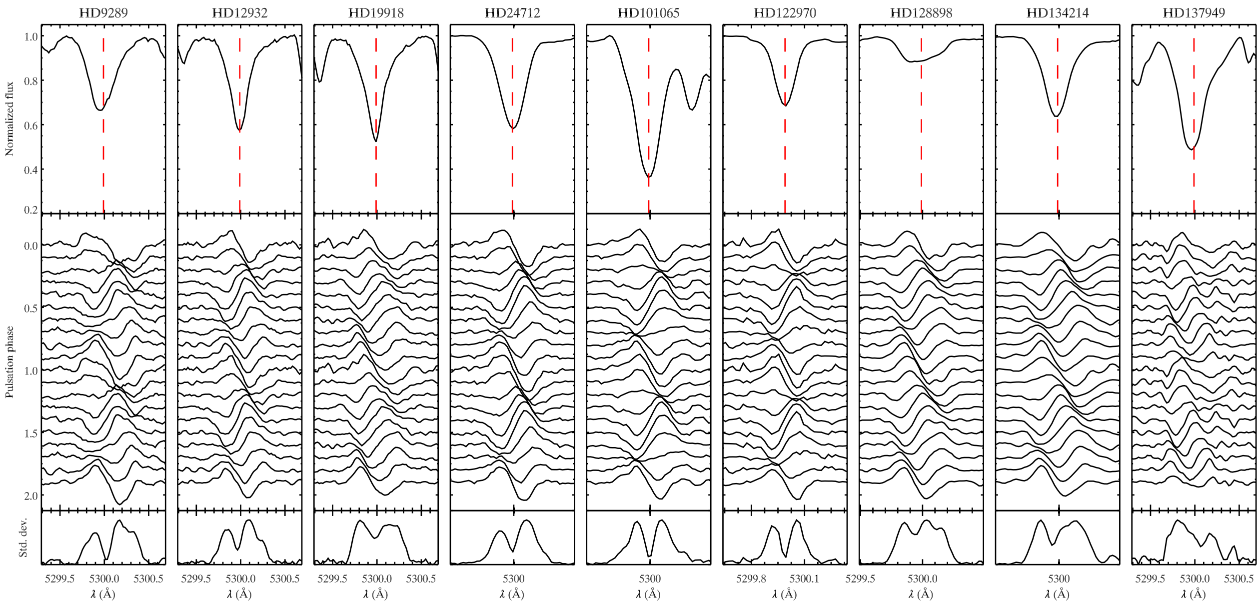

Figure 10: Profile variations of the Pr III 5300 Å line in the spectra of sharp-lined roAp stars. The average spectrum is plotted in the upper part of each panel. The difference spectra (arbitrary scale) as a function of pulsation phase are presented in the middle part. Observations for consecutive pulsation phases are shifted in the vertical direction, and each phase is shown twice. The bottom curve presents the wavelength dependence of the the standard deviation. The blue-to-red moving features in the difference spectra are clearly seen for all roAp stars, except for the two pulsators, HD 101065 and HD 122970, with $T_{\rm eff} < 7000$ K.

from the variation of the Nd III 6145 Å line are presented in Fig. 9. This plot also compares pulsation structure with the magnetic field topology of HD 83368 (Kochukhov et al. 2004b). Doppler imaging analysis reveals nearly axisymmetric pulsation geometry and for the first time allows to obtain an independent confirmation of the alignment of non-radial pulsations and magnetic field. Pulsation mapping finds the oblique pulsator geometry as a result of the assumption-free analysis, in contrast to all previous studies of roAp stars which started from the *assumption* that OPM is valid.

High-resolution surface map of pulsations in HD 83368 were used by Kochukhov (2004b) to disentangle different harmonic contributions to the pulsation geometry. It was shown that the magnetoacoustic pulsations in HD 83368 are shaped as suggested by Saio & Gautschy (2004), whereas the non-axisymmetric pulsation components predicted by the theory of Bigot & Dziembowski (2002) cannot be detected. This demonstrates a dominant role of the magnetic perturbation of the p-modes and considerably less important influence of the stellar rotation.

4.3 Rapid line profile variation in sharp-lined roAp stars

As for the slowly rotating roAp stars, despite dramatic recent progress in understanding the vertical structure of their pulsation modes, relatively little attention has been paid to the problem of inferring the horizontal geometry of pulsations. Typically, it is assumed that a horizontal cross-section of non-radial pulsations is given by an oblique axisymmetric mode of low degree, similar to the pulsation geometries inferred for rapidly rotating roAp stars, where periodic modulation of the geometrical aspect supplies additional information that helps to constrain the pulsation geometry. Thus, 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 sharp-lined magnetic pulsators, which represent the majority of roAp stars.

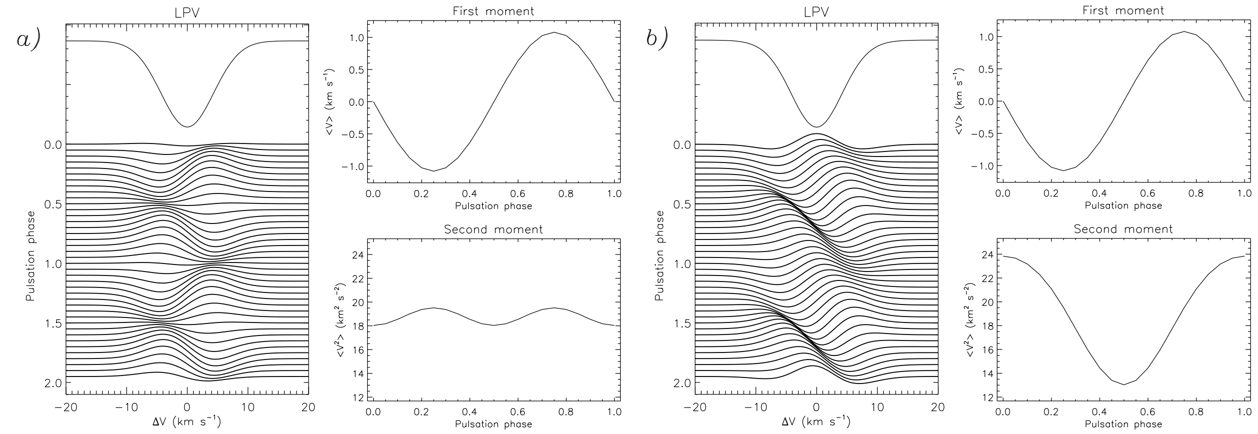

Figure 11: Line profile variation of a non-rotating non-radial pulsator. **a)** Spectrum variability for the $\ell = 1$, $m = 0$ mode viewed from the pulsation pole. The local profile is represented by a constant Gaussian with $FWHM = 10$ $\mathrm{km\,s^{-1}}$. **b)** Effect of adding harmonic variability of the line width with an amplitude of 1.5 $\mathrm{km\,s^{-1}}$ and a phase shift of 0.25 with respect to the pulsational velocity variation. In each panel the left plot shows the average line profile on top and time series of the difference spectra (covering two pulsation cycles) below. The right panels illustrates variation of the first (RV, upper plot) and second (line width, lower plot) line profile moments.

Understanding rapid LPV of the slowly rotating roAp stars turns out to be a challenging task. The first observation that achieved a signal-to-noise ratio sufficient to detect profile variability (Kochukhov & Ryabchikova 2001a) demonstrated the presence of unusual blue-to-red running features in the residual spectra of γ Equ. Moreover, observations of a single-wave variability of the REE line width in γ Equ is clearly inconsistent with *any* axisymmetric pulsation geometry described by spherical harmonics (Aerts et al. 1992; Kochukhov 2005). This led Kochukhov & Ryabchikova (2001a) to speculate about the possible presence of a non-axisymmetric non-radial mode in γ Equ – a suggestion equivalent to stating that the classical OPM is not applicable to this star. Later Shibahashi et al. (2004) drew attention to the blue-to-red running waves in our time-resolved spectra of γ Equ. These authors showed that the observed LPV is inconsistent with spectral variability expected for any, axisymmetric and non-axisymmetric alike, low-degree mode in a slowly rotating star and, in turn, suggested an exotic shock wave model to explain the observed rapid line profile changes.

The puzzle of the pulsational LPV in sharp-lined roAp stars has been finally solved by Kochukhov et al. (2007). In this study we have carried out the survey of profile variability in ten roAp stars using high-quality observations obtained with the VLT and CFHT telescopes. We investigated in detail the variations of Pr III, Nd II, Nd III and Tb III lines and discovered a prominent change of the profile variability pattern with height in the atmospheres of all roAp stars studied. It was shown that, in every investigated star, profile variability of at least one rare-earth ion is characterized by the blue-to-red moving features, previously discovered in the time-resolved spectra of the roAp star γ Equ. Fig. 10 shows example of this interesting profile behaviour, common in rapidly rotating non-radial pulsators but completely inexplicable in the framework of the standard OPM of slowly rotating roAp stars.

Analysis of the line profile moments and spectrum synthesis calculations presented by Kochukhov et al. (2007) demonstrates that unusual oscillations in spectral lines of roAp stars arise from the pulsational modulation of line widths. This variation occurs approximately in quadrature with the radial velocity changes, and its amplitude rapidly increases with height in stellar atmosphere. Kochukhov et al. (2007) proposed that the line width modulation is a consequence of the periodic expansion and compression of turbulent layers in the upper atmospheres of roAp stars. Thus, the line profile changes observed in slowly rotating magnetic pulsators should be interpreted as a superposition of two types of variability: the usual time-dependent velocity field due to an oblique low-order pulsation mode and an additional line width modulation, synchronized with the changes of stellar radius.

Fig. 11 shows that our new OPM is indeed capable of explaining the main features in the observed pulsational variability of line profiles and moments in roAp stars. On the other hand, our spectrum synthesis calculations pointed a number of important discrepancies between predictions of the shock wave model by Shibahashi et al. (2004) and actual observations. Thus, we concluded that the shock wave framework does not provide a viable explanation of the line profile variability in roAp stars.

5 Conclusions and outlook

The present overview of recent investigations of the magnetic, chemical and pulsation velocity structures in the atmospheres of CP stars paints an interesting and complex picture. It becomes increasingly clear that a traditional separate analysis of one type of structures ignoring other effects is often unable to capture the essence of the stellar variability phenomena and may even lead to misleading results. For instance, reconstruction of the magnetic field topology has to take into account both vertical and horizontal distribution of chemical elements. Conversely, abundance mapping of strongly magnetic stars is impossible without inclusion of the Zeeman effect in theoretical computation of stellar spectra. A similar close interrelation exists for the chemical stratification and pulsational variability: magnetoacoustic waves pass through distinct chemical clouds in the upper atmospheric layers, giving rise to depth-dependent amplitude and phase shifts in the radial velocity variation of different elements.

The quality of observational material and available computing resources have reached the stage when it becomes feasible to address the intricate problem of the structure formation in CP-star atmospheres with advanced, assumption-free spectral inversion procedures. In this way magnetic Doppler imaging was used to uncover remarkably complex and diverse fields in Ap stars and Doppler mapping of pulsations has yielded the first stellar maps of non-radial pulsation. We suggest that these techniques should be eventually combined in a self-consistent remote sensing procedure aiming at recovery of the 3-D geometry of all relevant atmospheric formations. It is foreseen that in the near future the new modelling techniques will allow us to address the following scientific problems:

- Reconstruction and interpretation of the 3-D structure of non-radial oscillations in roAp stars. This can be achieved by applying the pulsation Doppler imaging method to the time-series observations of spectral lines formed at different heights.

- Correlation between chemical stratification and horizontal abundance inhomogeneities may be studied with the help of 3-D imaging of abundance variations in CP stars. This, again, requires constructing a set of two-dimensional chemical maps from the line profile variation exhibited by different lines of the same element.

- Four Stokes parameter magnetic mapping of the representative sample of magnetic stars will answer the question of typical magnetic topology and relation between magnetic field and chemical spots.

Construction of the empirical maps should be supported by the advanced theoretical model atmosphere and radiative diffusion calculations, which will study feedback of non-solar abundances, chemical inhomogeneities and magnetic field effects on the outer stellar layers.

A special emphasis should be given to investigation of the possible long-term changes in the geometry of atmospheric structures in CP stars. Is it possible to detect variation in the small-scale magnetic features present at the surface of 53 Cam? Can we find changes of the chemical spot geometry in magnetic CP stars or the cyclic Hg spot behaviour of α And belongs to a separate and unique class of phenomena?

We can be sure that these and other questions will be addressed by forthcoming studies of CP stars and that many more surprising revelations about the physics of these objects will be made in the near future.

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