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Spectroscopic Observations of roAp Pulsations

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Abstract. I summarize results of new spectroscopic time-resolved observations of several bright roAp stars. A series of very high resolution and high S/N spectra were obtained at the CFHT and ESO 3.6-m telescopes in which line profile variations due to stellar pulsations are seen. The pulsational behaviour of different spectral lines is very diverse, but in all roAp stars it is invariably dominated by the variation of doubly ionized rare-earth lines. Differences in the amplitudes and phases of the pulsational radial velocity curves of individual spectral lines are attributed to an inhomogeneous vertical distribution of chemical abundances in roAp atmospheres and a strong depth dependence of pulsational amplitude. The outstanding variability of the Pr III and Nd III spectral features opens unique possibilities for pulsational mode identification and investigation of the relationship between nonradial pulsations and 3D magnetic and abundance structures in the atmospheres of peculiar stars. A preliminary study of the the variation of the line profile moments of rare-earth lines indicates that the surface velocity field in at least some roAp stars is appreciably different from the commonly assumed oblique, axisymmetric dipole pulsation.

1. Introduction

Rapidly oscillating Ap stars belong to the group of cool magnetic chemically peculiar stars and pulsate in high-overtone p-modes with periods in the range of 4–16 min. Traditionally, roAp stars are discovered and studied using high-speed photometric techniques. A few roAp stars have been also investigated with low-resolution spectroscopic methods (e.g. Baldry et al. 1998). These studies resulted in a firm detection of short-period radial velocity (RV) variations and suggested a surprisingly strong dependence of the pulsational properties of roAp stars on the wavelength region considered. Subsequently, an important discovery was made by Savanov et al. (1999), who found that in γ Equ spectral lines of Pr III and Nd III show the highest RV amplitudes, reaching up to 1 $\mathrm{km\,s^{-1}}$.

Observations of the large diversity of pulsations in different spectral lines demonstrated that real progress in understanding the roAp pulsations can only be achieved with detailed, high-resolution and high S/N analyses of the behaviour of *individual spectral lines*. In particular, studies of the rapid variations in the lines of the rare-earth elements (REE) can potentially provide us with crucial information about the excitation of p-mode pulsations and allow spectro-

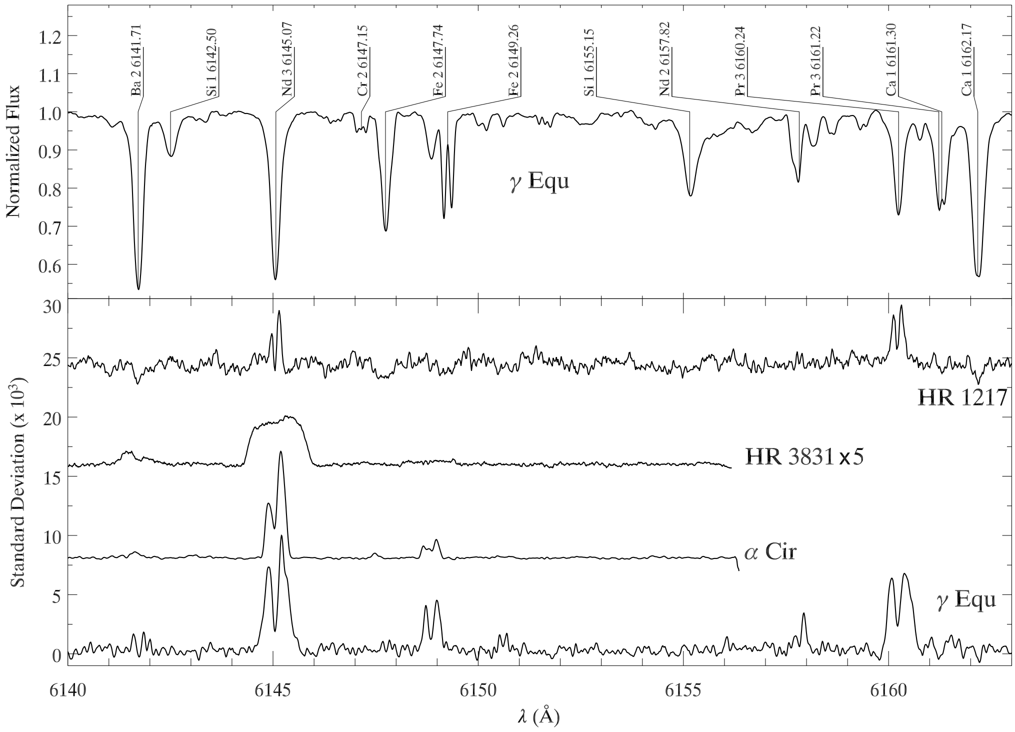

Figure 1. Comparison of the standard deviation spectra of γ Equ, α Cir, HR 3831 and HR 1217 with the average spectrum of γ Equ. In all four roAp stars, the maximum pulsational amplitude is detected in lines of doubly ionized Pr and Nd.

scopic mode identification. In order to utilize the information contained in the variations of REE lines, we performed very high resolution, high S/N time-series observations of several roAp stars.

Here I provide a summary of the first results of our observing campaign. A detailed discussion of the oscillations in γ Equ can be found in Kochukhov & Ryabchikova (2001a), while preliminary results on α Cir and HR 3831 have been reported by Kochukhov & Ryabchikova (2001b). In another recent paper (Kochukhov et al. 2002) we present the discovery of pulsational RV variations in 10 Aql and a time-resolved spectroscopic study of β CrB.

2. Time-resolved spectroscopic observations

Observations of roAp stars were obtained during several observing runs at the ESO 3.6-m telescope and the CFHT. Both telescopes are equipped with very high resolution spectrographs: `CES` at the 3.6-m telescope was used to observe roAp stars at a resolution of $R = 125\,000$–$170\,000$ and the `Gecko` spectrograph at the CFHT allowed us to record stellar spectra at $R = 115\,000$. This very high resolution is imperative for quantitative analyses of rapid line profile variations in slowly rotating roAp stars, and it enables us to detect pulsations with an amplitude of 20–30 $\mathrm{m\,s^{-1}}$ using only a dozen or so time-resolved spectra with sufficient quality ($S/N \geq 100$)

The `CES` and `Gecko` instruments have the drawback of being limited to a relatively small (50–100 Å) wavelength interval. Therefore, each spectral interval that we observe has to be carefully chosen to contain several strong lines of Pr III and Nd III, which proved to be the best indicators of p-mode pulsations in roAp stars. We typically obtained between 50 and 100 time-resolved spectra in each wavelength region every night. The most extensive dataset of about 1900 spectra was obtained for HR 3831 during an observing run which consisted of 6 nights spread over two weeks. Shorter monitoring was carried out in one or several spectral regions in γ Equ (HD 201601), α Cir (HD 128898), HR 1217 (HD 24712), 10 Aql (HD 176232), β CrB (HD 137909) and HD 217522.

Fig. 1 demonstrates that inspection of the standard deviation of the spectra is usually sufficient to detect high-amplitude pulsational variability in a few of the most prominent lines. The diversity of pulsations in different lines is striking: while rare-earth lines show amplitudes of up to 1 $\mathrm{km\,s^{-1}}$, the strong lines of light elements, for example neutral Ca, do not exhibit any RV shifts above $\approx$ 20 $\mathrm{m\,s^{-1}}$. Phases of pulsations also differ significantly, and we find absolutely no indication of any statistically significant correlation between the line strength and pulsational amplitude (see Kochukhov & Ryabchikova 2001a).

It is interesting that in *all* roAp stars we observe the strongest line profile variations in the same rare-earth spectral lines, such as the Nd III 6145 Å. Lines of doubly ionized REEs dominate the spectroscopic variations over the whole optical region (Balona 2002). The similarity in pulsational behaviour of different roAp stars contrasts with the line-to-line differences and appears somewhat surprising. The stars that we study have widely different pulsational and rotational periods. The magnetic field strengths and effective temperatures are also different, yet we see basically the same pulsational signature. In all stars the rare-earth lines somehow sample the pulsational areas more efficiently compared to lines of other elements. This probably provides us with fundamental information about the nature of the pulsational cavity in roAp stars.

In general, spectroscopic detection of roAp pulsations using doubly ionized REE lines is relatively straightforward. Typical maximum amplitudes reach a few hundred $\mathrm{m\,s^{-1}}$ or up to 1 $\mathrm{km\,s^{-1}}$ in ideal cases. Such precision is readily available with all high-resolution spectrographs on large telescopes. Therefore, compared to photometric techniques, time-resolved spectroscopy may be more efficient in finding new members of the roAp group and detecting low-amplitude pulsations in bright magnetic chemically peculiar stars. This advantage of time-resolved spectroscopy was clearly demonstrated by our search for pulsations in 10 Aql and β CrB (Kochukhov et al. 2002). The first star shows very low-amplitude pulsations in the photometry and is often considered to be a questionable member of the roAp group. Nevertheless, 10 Aql shows a convincing pulsational signal in the Nd III lines. Intriguingly, we also found evidence of possible short-period RV variations in weak Fe I lines in β CrB, for which no previous detection of photometric oscillations has been reported.

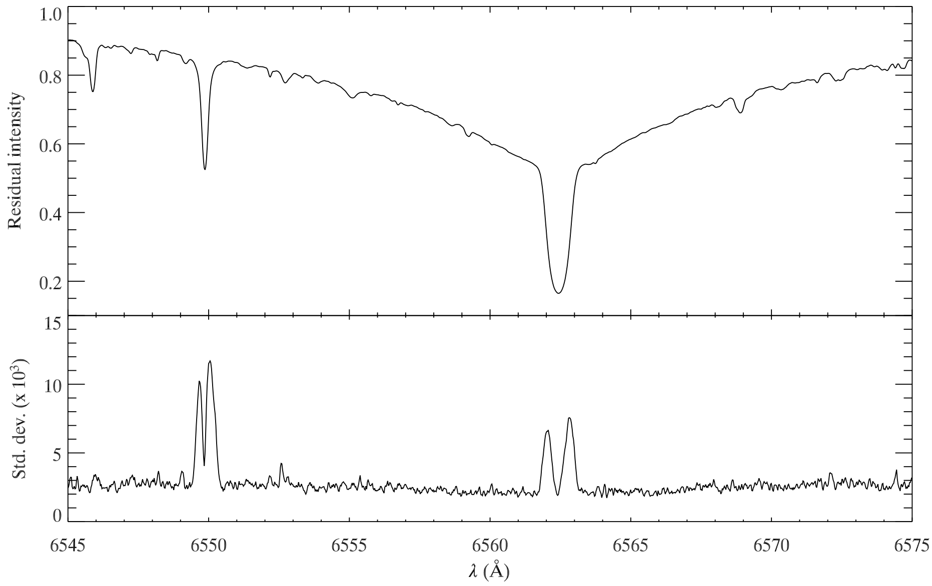

Figure 2. Comparison of the standard deviation and the average spectra of γ Equ in the Hα region. The maximum pulsational amplitudes are observed in the Nd III 6550 Å and in the core of Hα.

3. Nonradial pulsations and vertical abundance stratification

Why do lines of different chemical elements behave so differently in roAp stars? This cannot be due to surface chemical inhomogeneities, since these have to be enormous to account for the two orders of magnitude difference in the radial velocity amplitudes. We certainly do not observe the enormous rotational modulation of the profiles of, for example, the Ca and Fe lines in roAp spectra which would arise from such an extreme abundance inhomogeneity. However, it turns out that another type of abundance inhomogeneity, namely vertical abundance stratification, helps to explain the observed pulsational behaviour.

We suggested that the large pulsational amplitudes of the Pr III and Nd III lines are closely related to the anomalous strength of these lines in spectra of roAp stars. Ryabchikova et al. (2001) showed that abundances derived for roAp stars using Nd III and Pr III spectral lines are 1–2 dex higher than abundances obtained from lines of the first rare-earth ions. This spectroscopic anomaly, which is absent in non-pulsating Ap stars, points to inhomogeneous vertical distribution of rare-earths in the atmospheres of roAp stars.

One of the clearest manifestations of abundance stratification and its impact on the pulsational behaviour is provided by time-resolved spectroscopy of γ Equ in Hα region (Fig. 2). Comparison of the standard deviation and the average spectra allows us to unambiguously identify strong pulsations in the core of Hα and in the Nd III 6550 Å line. Hydrogen is, of course, distributed homogeneously in atmospheres of roAp stars. In addition, we know that the Hα core is formed in the upper part of stellar atmosphere. Thus, observation of similar pulsation patterns in the Hα core and the Nd III line tells us that these two spectral features originate from similar atmospheric layers, which in

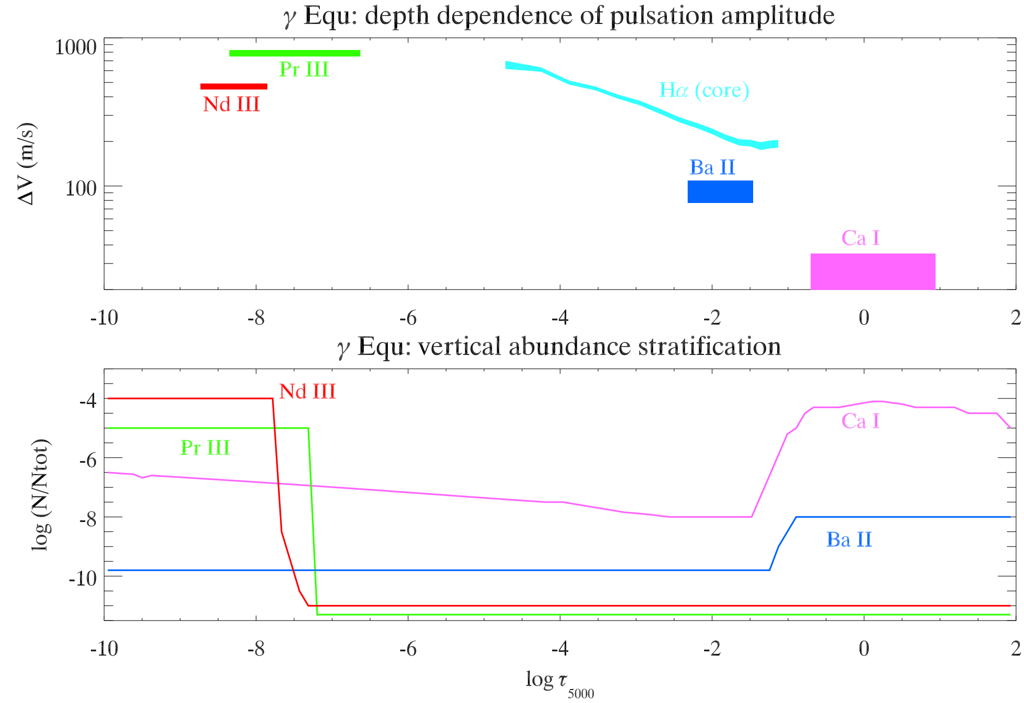

Figure 3. Reconstruction of the vertical abundance stratification and variation of the pulsational amplitude with depth in the atmosphere of γ Equ.

turn implies strong stratification of the Nd abundance and suggests a dramatic increase of pulsational amplitude with height in roAp atmospheres.

These conclusions have been verified by a combined quantitative analysis of abundance stratification and pulsations in γ Equ (Ryabchikova et al. 2002). A summary of our findings is presented in Fig. 3, which shows the depth dependence of the chemical abundance and the corresponding pulsational amplitudes in different layers in the atmosphere of γ Equ. It turns out that all light and iron-peak elements are overabundant deep in the atmosphere, below $\log \tau_{5000} \approx -1$ or -2, while rare-earth elements are concentrated in a very high cloud above $\log \tau_{5000} \approx -8$. In such a chemically stratified atmosphere, the depths of formation of rare-earth lines are sufficiently different from those of light and iron-peak elements. Pr III and Nd III lines sample higher layers where the pulsational amplitude increases due to the exponential drop of density or, perhaps, because of the intrinsic radial dependence of the amplitudes of the high-overtone p-modes. The phase shifts observed in the radial velocity curves of different elements can then be interpreted as a *running pulsational wave* propagating outwards through the chemically inhomogeneous atmosphere.

Thus, the phenomenon of chemical stratification gives us a satisfactory explanation for the observed spectroscopic pulsational behaviour of roAp stars. Furthermore, the similarity of the line-strength anomaly of REEs and spectroscopic pulsational properties of γ Equ, HR 3831 and α Cir allows us to speculate

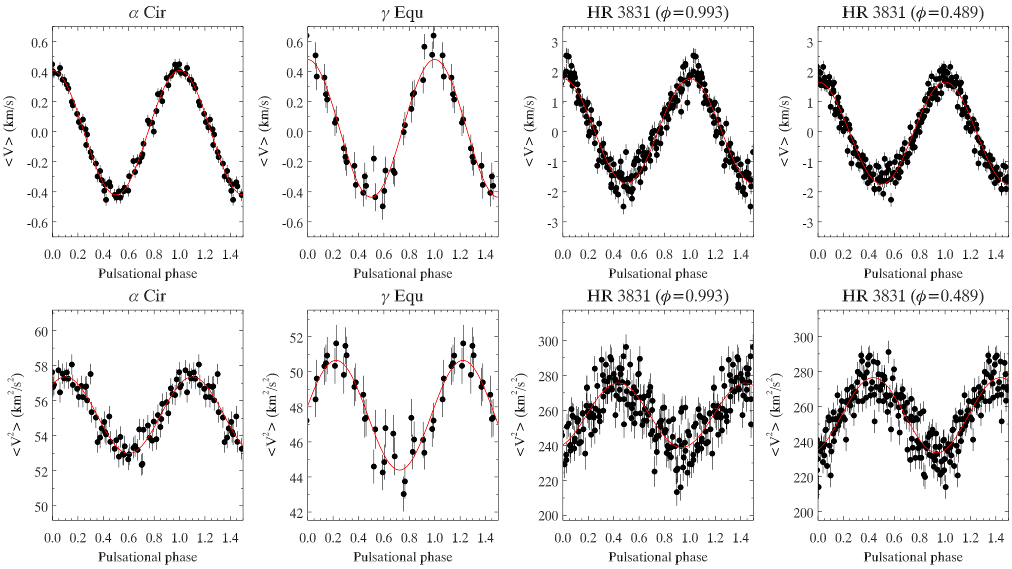

Figure 4. Variation of the first moment (upper panels) and the second moment (lower panels) of the Nd III 6145 Å line profile in the spectra of α Cir, γ Equ and HR 3831.

that all members of the class of roAp pulsators feature similar vertical distributions of rare-earth elements and pulsational amplitudes.

4. Mode identification

The discovery of large amplitude variations in doubly ionized REE lines opened the possibility to go beyond trivial time-series analysis of the RV shifts and study, in detail, the line profile variability in order to identify pulsation modes and deduce other physical characteristics of nonradial pulsations in roAp stars. As a starting point, we can use mode identification methods developed for other types of nonradially pulsating stars. This includes the calculation of the moments of the line profiles, assuming simple analytical formulas for the intrinsic line profiles (Aerts et al. 1992). Alternatively, one can determine the change of pulsation phase across the line profile and relate this information to the degree, ℓ, of the pulsation (Telting & Schrijvers 1997). Using a variety of these simple mode identification techniques, we estimated $\ell = 2$ or 3, $m = -\ell$ or $-\ell + 1$ and a pulsational velocity amplitude $v_p \approx 10$ km s^{-1} from the Nd III and Pr III lines in the spectrum of γ Equ (Kochukhov & Ryabchikova 2001a).

Mode identification based on the analyses of moment variations is probably the most promising tool for an initial attempt to derive the horizontal velocity field in roAp stars. Fig. 4 illustrates the rapid periodic variations of the radial velocity and the line width (i.e. the first and second moments) of the Nd III 6145 Å line in α Cir, γ Equ and HR 3831. The data for the last star is shown for two different rotational phases, both roughly corresponding to the maximum

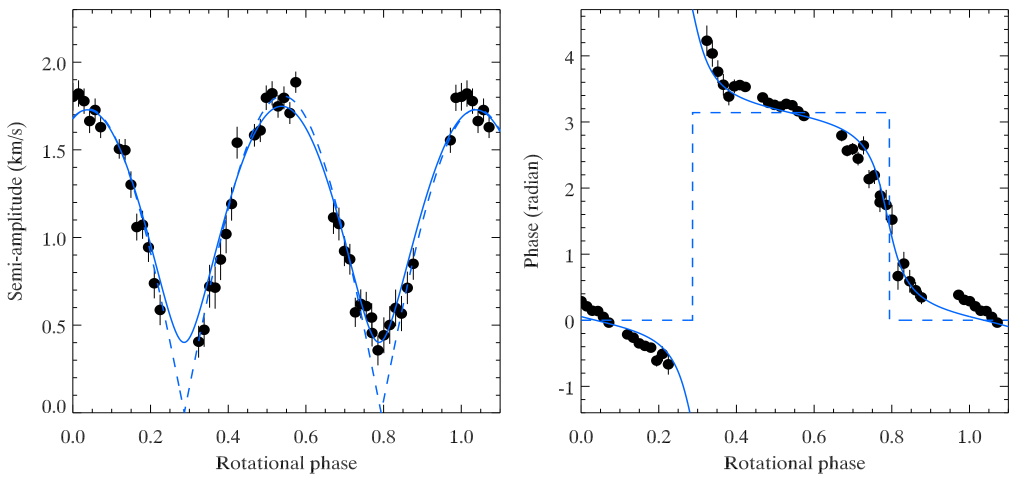

Figure 5. Rotational modulation of the amplitude and phase of the pulsational RV shifts of the Nd III 6145 Å line in the spectrum of HR 3831. The points have been calculated by fitting the main pulsation frequency ($\nu = 1428.009$ μHz) to short sequences of time-resolved spectra. The dashed line shows predictions of a pure axisymmetric oblique dipole pulsator model and the solid line corresponds to a best-fit superposition of the $\ell = 1$, $m = -1, 0, 1$ pulsations.

amplitude of the RV and photometric oscillations. The RV curves of all stars are very close to pure sinusoids, which suggests that we observe monoperiodic linear pulsations. On the other hand, appreciable non-sinusoidal photometric variations have been observed in several roAp stars (Kurtz 1982). Thus, the temperature variation, which is responsible for the light variation, is probably related to the pulsational displacement in a complex non-linear manner (Balona 2002). Therefore, compared to studies of spectroscopic variability, photometric analyses of roAp stars may be less suitable for quantitative mode identification.

Returning to the variation of moments of the Nd III line (Fig. 4), we note that the line width shows a single-wave variation, rather than a double-wave variation. This seems to be a universal feature of the spectroscopic variability in all roAp stars studied so far. In none of the stars were we able to detect a significant contribution from the first harmonic to the variation of the second moment (although different stars often exhibit different phase shifts between the curves of the first and the second moments). In classical nonradially pulsating stars, this behaviour is interpreted as the unambiguous signature of *non-axisymmetric* pulsational modes (e.g. Aerts et al. 1992). This conclusion can be safely extended to very slowly rotating roAp stars, like γ Equ, which have $v_p >> v_{\rm e} \sin i$. However, in the more rapidly rotating objects, for instance HR 3831, the velocity field due to stellar rotation is dominant, and therefore the observed variation of the second moment may be simply a consequence of an assymetric co-addition of the rotational Doppler shifts and an axisymmetric pulsational mode inclined to the rotational axis. Careful theoretical analysis of the variation of the line profile moments expected for oblique nonradial pulsations would be very useful for distinguishing these different scenarios.

According to the very successful oblique pulsator model (Kurtz 1982), the pulsation axes of roAp stars are generally inclined to the rotational axes. This makes it possible to examine roAp oscillations from varying aspecta, as can be done for no other type of pulsating star. Thus, another way to reconstruct the surface map of stellar pulsations is to follow the rotational modulation of the amplitude and the phase of the moment variation. Fig. 5 shows the amplitude and phase of the RV shifts of the Nd III 6145 Å line as a function of rotational phase of HR 3831. We found that the semi-amplitude of the RV variations changes between 0.4 and 1.8 $\mathrm{km\,s^{-1}}$, while the phase shows a typical jump of $\approx \pi$ radian expected for a nonradial mode dominated by an axisymmetric dipolar component. However, details of the shape of the phase modulation can only be fitted by a superposition of axisymmetric and non-axisymmetric $\ell = 1$ pulsations. In particular, the optimal description of the variations illustrated in Fig. 5 is achieved with the following non-axisymmetric oblique pulsator model: inclination angle $i = 74^{\circ}$ (fixed), obliquity of pulsation axis $\beta = 89^{\circ} \pm 2^{\circ}$ and pulsational amplitudes $v_0 = 2.73 \pm 0.03$ $\mathrm{km\,s^{-1}}$, $v_1 = v_{-1} = 0.32 \pm 0.03$ $\mathrm{km\,s^{-1}}$. The resulting pulsational velocity field is already fairly complex, but it provides an inadequate fit to the rotational modulation of the second moment. The Fourier transform of the latter clearly shows strong peaks shifted by $\pm 3\nu_{rot}$ from the main pulsational frequency. This implies an important contribution of octupolar ($\ell = 3$) components to the pulsational velocity field.

5. Conclusions

Spectroscopic studies of pulsations in roAp stars have provided a wealth of new information about p-mode oscillations. We have learnt that abundance stratification is responsible for the observed differences in pulsational amplitudes and phases of individual spectral lines. Chemical stratification plays the role of a very efficient vertical spatial filter and can be used to deduce the radial dependence of the pulsational amplitude and phase. Spectacular spectroscopic observations of running pulsational waves will lead to empirical mapping of the radial dependence of the p-mode characteristics and must be eventually complemented by MHD modelling of dynamical effects in the roAp atmospheres.

Observations of profile variations in strong REE lines are very useful for mode identification. An initial application of the moment method reveals the presence of non-axisymmetric pulsations in several roAp stars. However, the actual surface distribution of the pulsational velocity may be very different from pure spherical harmonic eigenfunctions because the stellar rotation and magnetic field are likely to distort the velocity field significantly, even in the simplest mono-periodic roAp pulsators. This suggests that it may be advantageous to abandon the spherical harmonic description and attempt to recover the velocity field directly from the observed line profile variations using an inversion procedure similar to the highly successful Doppler imaging technique.

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Discussion

Stępień: Can you see changes in the pulsational characteristics of γ Equ due to the changing geometrical aspect of the star caused by rotation?

Kochukhov: γ Equ rotates very slowly ($P_{rot} > 70$ years) and our spectroscopic observations span only a few years. We do not expect to see any rotational modulation of the pulsations in γ Equ on such a short timescale.

Gough: You conclude that maximal RV variations in roAp stars *always* occur in spectral lines of rare-earth elements. Yet, in β CrB you observe sinusoidal oscillations in Fe I, yet none in rare-earth elements. Even if no intensity oscillations are seen, the star is clearly oscillating. So, how do you reconcile this with the first of your conclusions?

Kochukhov: β CrB is not a "classical" roAp star in the sense that its variability was not detected photometrically and it lacks certain spectroscopic characteristics which distinguish roAp stars. Furthermore, we do not claim definite detection of the pulsations in β CrB. More observations are required to confirm the variations in Fe I lines. Until this is done, it is probably premature to discuss the pulsational behaviour of β CrB in comparison with other roAp stars.

Baade: The standard deviation spectra of all lines in all stars seem to be asymmetric in that the respective blue peak is weaker than the red one. If this is not due to uneven phase sampling, what is the reason?

Kochukhov: In time-resolved spectroscopy of roAp stars, the combination of stellar pulsation periods and data sampling frequencies is such that we rarely have problems with uneven phase sampling. The asymmetry of the pulsational signatures in standard deviation spectra is closely related to the single-wave variability of the second moment. In terms of the surface distribution of the pulsational velocity field, we can say that, compared to the half of the pulsational cycle where the RV shift is negative, positive velocity excursions correspond to a larger scatter of velocity (by absolute value) over the stellar surface. This can be attributed to non-axisymmetric pulsation modes with $\ell \geq 1$, or to an assymetric superposition of the pulsational and rotational velocity fields.