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Indirect imaging of stellar nonradial pulsations

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Abstract. We present a novel method, based on the Doppler imaging inversion technique, which tries to construct a two-dimensional 'image' of the pulsation velocity field using time series observations of stellar spectra. This method is applied to study the geometry of nonradial oscillations in the roAp star HR 3831. The image of pulsational perturbations at the surface of this star is the first stellar pulsation map derived without assuming the spherical harmonic formalism. Our Doppler reconstruction directly demonstrates an alignment of the roAp pulsations with the stellar magnetic field axis. It also reveals a significant distortion of the dominant oblique $\ell = 1$ oscillation mode by the stellar magnetic field. This first detailed characterization of the magnetic and rotation effects on pulsations opens possibilities for the direct testing of recent theories of magnetoacoustic oscillations in roAp stars.

Keywords. Methods: data analysis, line: profiles, stars: chemically peculiar, stars: oscillations, stars: individual: (HR 3831)

1. Introduction

Many types of stars show periodic pulsational variation of radius and brightness. Observed pulsational characteristics are determined by the fundamental stellar parameters. Consequently, investigations of stellar pulsations provide a unique opportunity to verify and refine our understanding of the evolution and the internal structure of stars. However, a key boundary condition for this analysis, precise information about the geometry of pulsations in the outer stellar envelopes, has been notoriously difficult to secure, especially for the stars (rapid rotators, roAp stars) in which the pulsation modes are distorted and cannot be described with a single spherical harmonic function.

Here we demonstrate that it is possible to solve this problem by constructing a 2-D image of the pulsation velocity field from time series high-dispersion observations of stellar spectra. This novel *Pulsation Doppler Imaging* technique is applied to study the geometry of nonradial pulsations in the prototype roAp star HR 3831. The pulsation map of HR 3831 provides a long-sought *solution of the problem of the pulsation geometry of roAp stars* and enables verification of the recent theories of stellar magnetoacoustic oscillations.

2. Pulsation Doppler imaging

Nonradial pulsations often have a dramatic influence on the shapes and variability of stellar spectral lines. Temporal evolution of the dips and bumps in the Doppler-broadened line profiles encodes information about the amplitude as well as the latitude and longitude position of the surface velocity fluctuations (see Fig. 1). Observations at sufficient number of pulsation phases can be used to reconstruct a 2-D surface pulsation map through a solution of the regularized spectral inversion problem (Kochukhov 2004).

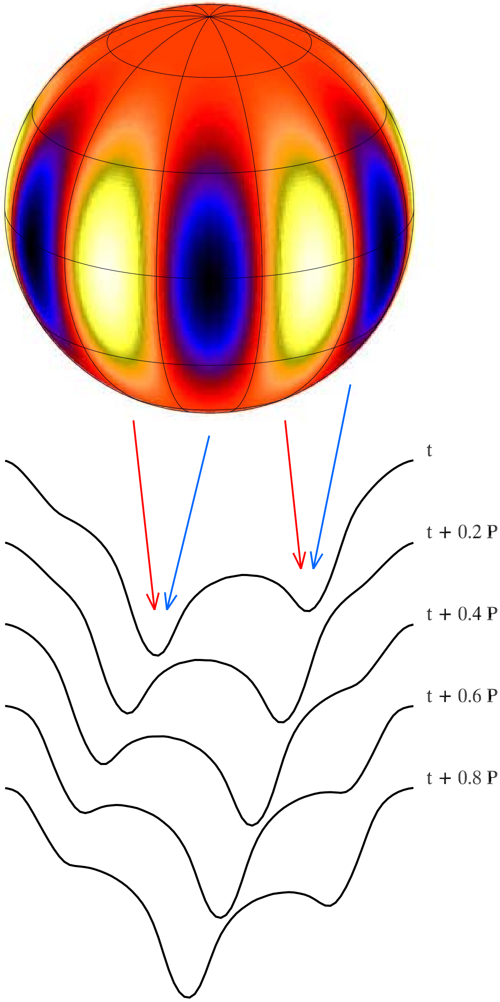

Figure 1. Illustration of the mapping between position across the stellar disk and distortions in the spectral line profiles of a rapidly rotating oscillating star. The spherical image shows the vertical component of the surface velocity field due to $\ell = m = 6$ nonradial pulsation mode. The uppermost curve shows the resultant theoretical disk-averaged line profile (with wavelength increasing from left to right), scaled to match the stellar diameter. The lighter areas in the velocity map show surface zones receding from the observer. The corresponding contribution of a local absorption profile is shifted redward. On the other hand, the darker areas correspond to material moving toward the observer and their contribution is shifted blueward. The temporal evolution of profile distortions is illustrated with other curves. They are shifted in vertical direction and correspond to 4 moments of time with a step of 20% of pulsation period P relative to the first profile.

In the modelling approach pioneered by Kochukhov (2004) the principle of Doppler imaging is extended to the reconstruction of the time-dependent velocity field. 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

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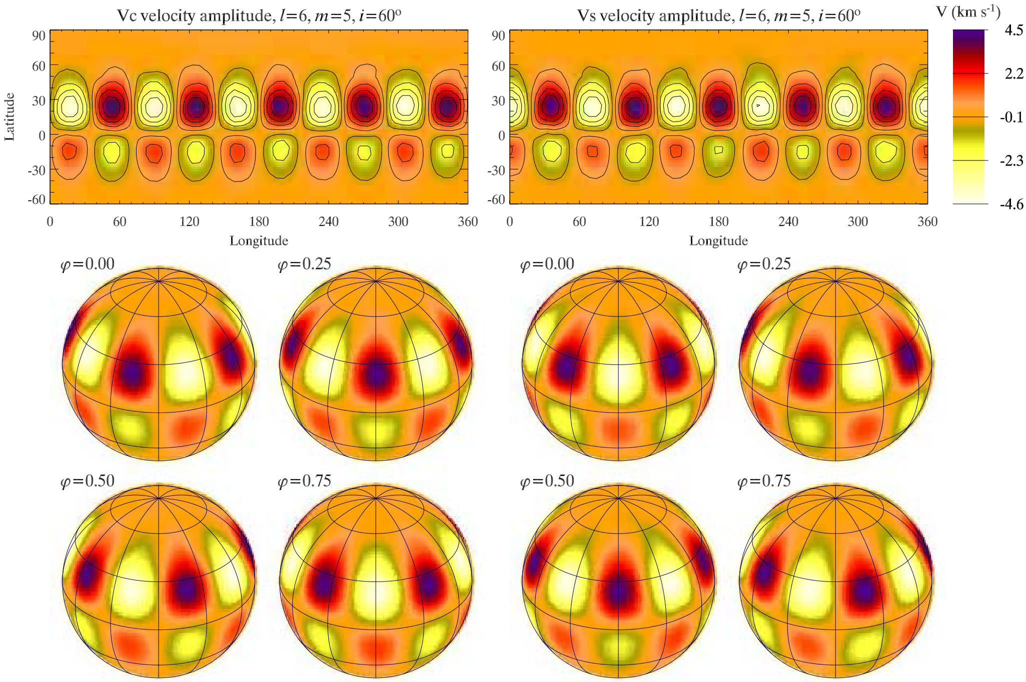

Figure 2. Test of the pulsation Doppler imaging reconstruction of the velocity field for the sectoral $\ell = m = 6$ mode and inclination angle $i = 60°$. Rectangular projections of the vertical pulsation velocity amplitudes, V_r^c and V_r^s, are shown as colour images in the upper panels. The contours of equal velocity amplitude are plotted with a step of 1.0 km s^{-1}. The spherical projections of the respective pulsational amplitude maps are plotted below. In the spherical plots the star is shown at four different aspect angles, corresponding to the rotation phases $\varphi = 0.00$, 0.25, 0.50 and 0.75, and $i = 60°$. The grid at the stellar surface is plotted with a 30° step in longitude and latitude.

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.

The foundations of the pulsational Doppler mapping and description of its computer implementation were presented by Kochukhov (2004). 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.

Figure 2 presents an example of the numerical test of the pulsation DI reconstruction. Velocity maps for the sectoral $\ell = 6$, $m = 6$ pulsation mode were recovered from the spectra simulated for $i = 60°$ neglecting horizontal pulsation motions. The quality of reconstruction is good over most of the visible stellar surface. The sectoral $\ell = m = 6$ structure is easily recognizable in both the vertical pulsation maps V_r^c and V_r^s and finds a satisfactory agreement with the input velocity distribution. This success of the inversion procedure is representative for all types of pulsation geometries accompanied by significant line profile variations and dominated by the vertical pulsation motions.

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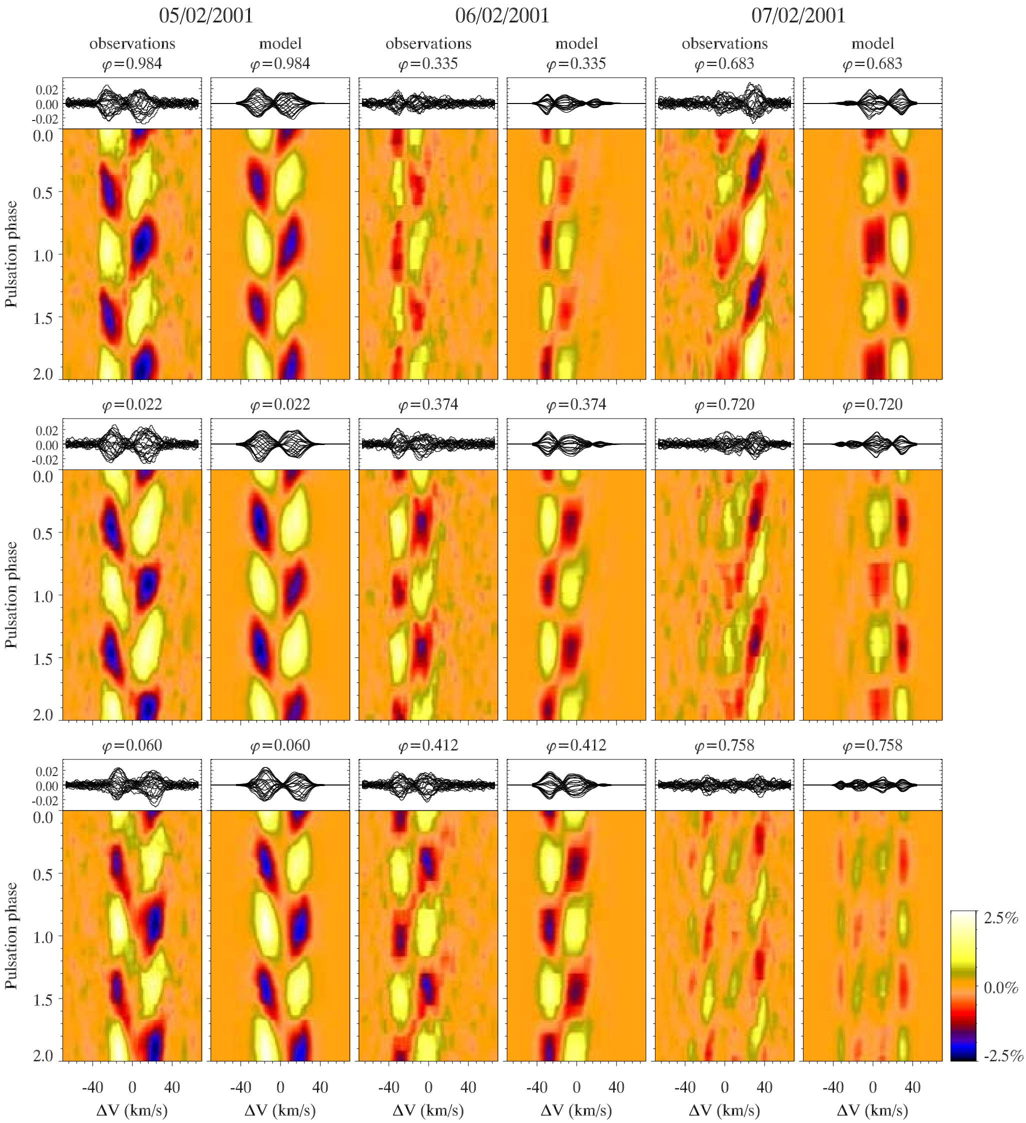

Figure 3. Comparison of the computed and observed rapid variation of the Nd III λ6145 line profile at different rotation phases of HR 3831. Each colour image is based on a group of 23 time-resolved spectra covering roughly 3 oscillation cycles of HR 3831. The upper plot in each panel shows residuals from the mean line profile. The colour plots show time evolution of the residuals, phased with the main pulsation frequency $\nu_0 = 1428.0091\,\mu$Hz (Kurtz *et al.* 1997) and using the scale of ±2.5% of the continuum intensity. The three pairs of columns show the profile variability recorded on the observing nights 5–7 February, 2001 (first column in each pair) and the corresponding model residuals (second column in each pair). The three subpanels in each column display changes in the residuals for the beginning, middle and end of continuous monitoring, illustrating an evolution of the variability pattern during the night.

3. Pulsation Doppler mapping of the roAp star HR 3831

The pulsation Doppler inversion is applied to time-resolved observations of Nd III λ6145 in the spectrum of the well-known roAp star HR 3831 (HD 83368). A total of 1860 spectra of this object were obtained in 2001 over the period of 11 nights using the

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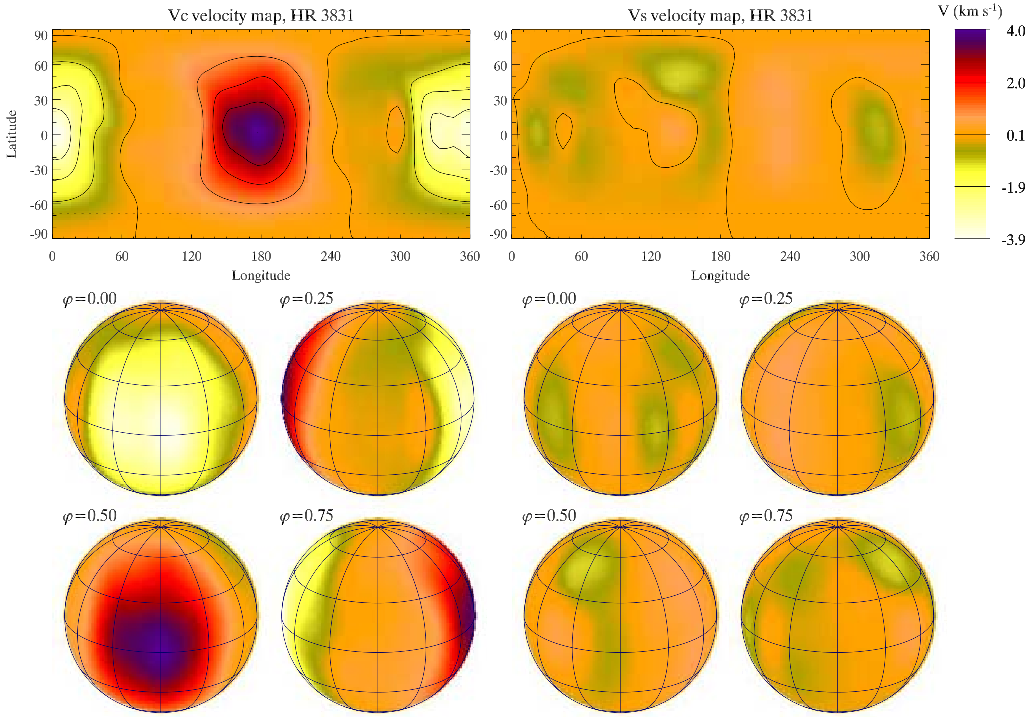

Figure 4. The first Doppler image of the stellar pulsational velocity field. This figure shows the V_r^c and V_r^s pulsation velocity amplitude maps obtained for the roAp star HR 3831. The format of the plots is similar to Fig. 2.

Coudé Echelle Spectrograph fiber-linked to the Cassegrain focus of the 3.6-m telescope at the European Southern Observatory. A preliminary discovery report of the pulsational variations in individual spectral lines in HR 3831 using these observational data was published by Kochukhov & Ryabchikova (2001). Our observations evenly sample the 2.851976 day (Kurtz *et al.* 1997) rotation period of the star and are characterized by the resolving power of $\lambda/\Delta\lambda = 123\,000$ and the signal-to-noise ratio of 110–160 pixel^{-1}. A 70^{s} exposure time was chosen to ensure an appropriate sampling of the 11.67 min oscillation period.

Reconstruction of the pulsation velocity field of HR 3831 took into account an inhomogeneous surface distribution of neodymium which significantly distorts the mean Nd III line shapes. The maps of chemical abundance and pulsational fluctuations were recovered simultaneously in a self-consistent manner. The resulting Nd abundance map agrees very well with the distribution derived by Kochukhov *et al.* (2004) using a different DI code.

Horizontal pulsation displacement is expected (e.g., Saio & Gautschy 2004) to be small for high-overtone p-modes in the upper atmosphere of roAp stars where Nd III λ6145 forms. Hence, pulsation imaging of HR 3831 was carried out assuming the dominance of the vertical pulsation motions. Figure 3 shows an example of the rapid line profile variation of HR 3831 and presents a comparison between the observed and calculated residuals from the mean profile.

The Doppler maps of the pulsation velocity field of HR 3831 revealed with our technique are illustrated in Fig. 4. The V_r^c velocity amplitude map shows a clear dipolar-like structure with the local pulsation amplitude reaching up to 4.0 km s^{-1}. The second map does not contain significant global velocity structures, indicating that the pulsation ge-

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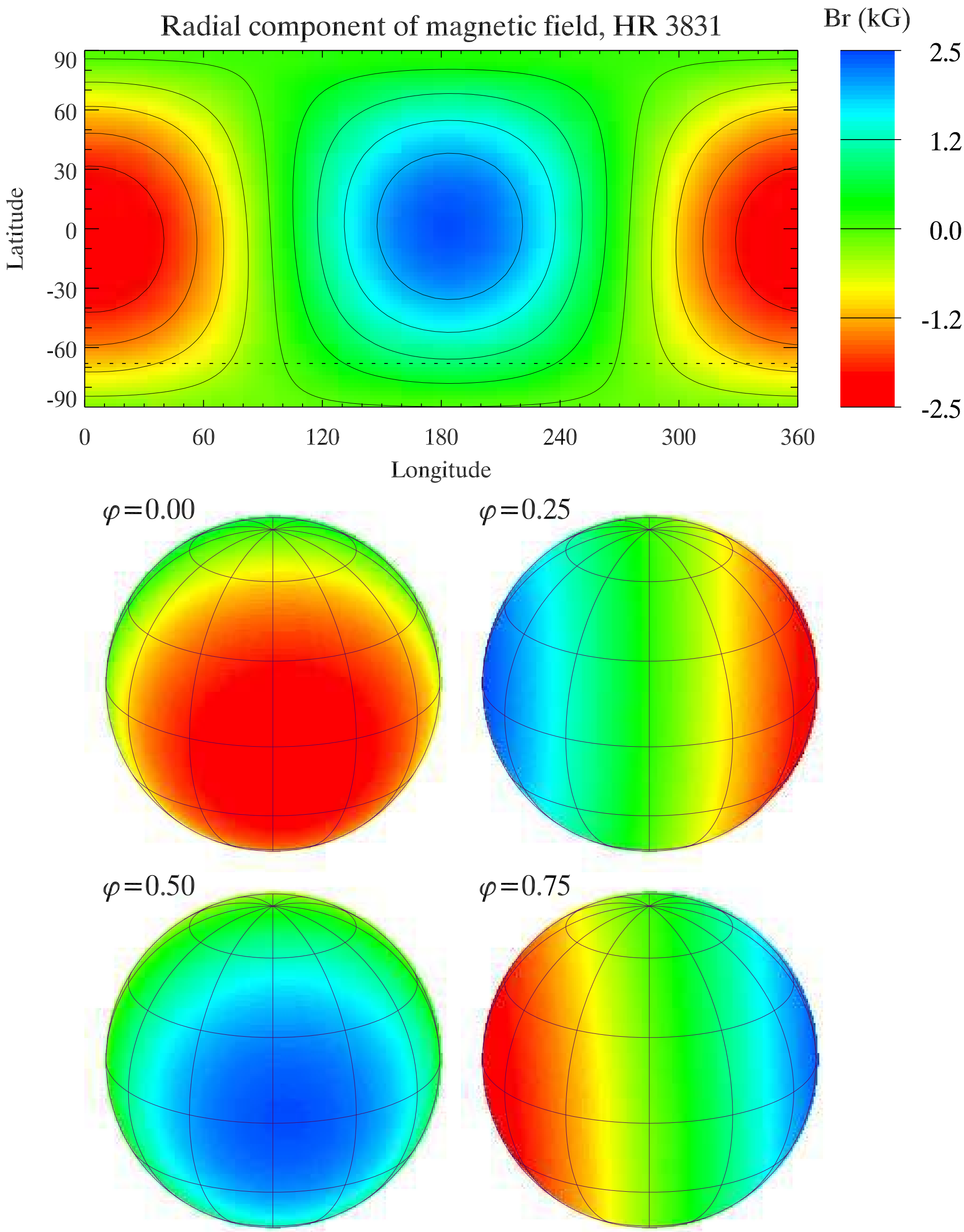

Figure 5. Surface distribution of the radial component of the magnetic field in HR 3831 according to the dipolar model derived for this star by Kochukhov *et al.* (2004). The upper panel shows rectangular projection of the magnetic map. The contours of equal field strength are plotted with a step of 500 G. The lower panel displays the spherical projection of the same map.

ometry of HR 3831 is fairly close to an oblique axisymmetric topology (see Sect. 5.5 of Kochukhov 2004).

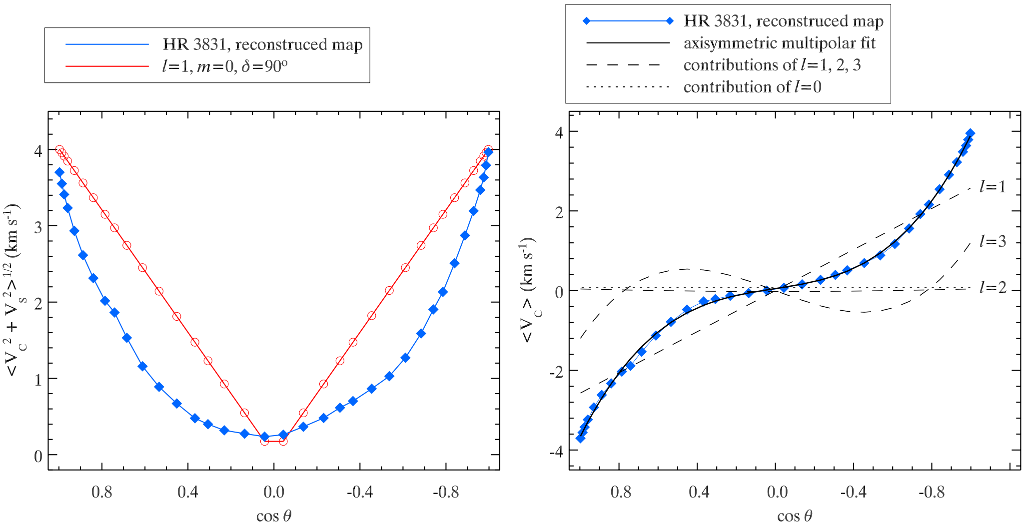

Figure 6. Analysis of the co-latitude dependence of the dominant axisymmetric component of the HR 3831 pulsation geometry in the coordinate system inclined by 90° with respect to the stellar axis of rotation. The left panel compares the total velocity amplitude $\langle (V_r^c)^2 + (V_r^s)^2 \rangle^{1/2}$ obtained for HR 3831 (blue) with the picture expected for the pure $\ell = 1$, $m = 0$ oblique mode (red). The right panel illustrates an axisymmetric multipolar expansion of the latitudinal dependence of the V_r^c velocity amplitude. The fit with a superposition of $\ell = 0$–3 components is shown with the solid line. Contributions of the individual multipolar components are indicated with the dashed lines for $\ell = 1$–3 and by dotted line for $\ell = 0$.

4. Analysis of the HR 3831 pulsation geometry

The pulsation map (Fig. 4) reconstructed here for the prototype roAp star HR 3831 displays an obvious correlation with the stellar magnetic field geometry. Kochukhov *et al.* (2004) found that the dominant $B_{\rm p} = 2.5$ kG dipolar component of the global field in HR 3831 is inclined by about 90° relative to the stellar rotation axis and is oriented at $\approx$ 180° in longitude. At the same time, the V_r^c velocity map presented in Fig. 4 indicates that pulsation geometry of HR 3831 is dominated by an axisymmetric structure. Furthermore, it is clear that the two maxima of the pulsation amplitude coincide with the magnetic poles. This is the first independent verification of the alignment of pulsations and magnetic field in oscillating magnetized stars.

Figure 5 illustrates an analysis of the latitudinal dependence of the V_r^c pulsation amplitude in the reference frame of the stellar magnetic field. The inferred trend is clearly different from the one expected for a pure oblique $\ell = 1$ pulsation. Axisymmetric multipolar decomposition of the observed latitudinal dependence suggests that oscillations in HR 3831 can be roughly described with a superposition of $\ell = 1$ and $\ell = 3$ harmonic components. The octupolar component has the same sign as the dipolar contribution and an amplitude smaller by a factor of two. Thus, we discover that pulsations in HR 3831 are strongly confined to the magnetic field axis. This pulsation geometry is in remarkable agreement with the predictions obtained in recent calculations assuming the dominant role of the magnetic field (Saio & Gautschy 2004).

5. Conclusions

• Pulsation Doppler imaging is demonstrated to be a powerful technique to study the geometry of stellar nonradial oscillations.

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- The first stellar pulsation velocity DI map is successfully derived for the roAp star HR 3831 making no *a priori* assumptions about the stellar pulsation geometry and taking into account chemical inhomogeneities.
- The pulsation Doppler map of HR 3831 for the first time directly demonstrates an alignment of the roAp pulsations with the symmetry axis of the stellar magnetic field.
- Significant magnetically induced distortion of the oblique dipolar oscillation is discovered. The pulsation amplitude is enhanced at the magnetic poles which is equivalent to a pulsation geometry dominated by a superposition of the axisymmetric $\ell = 1$ and $\ell = 3$ components.
- The pulsation geometry of HR 3831 is in excellent agreement with the axisymmetric theoretical model of Saio & Gautschy (2004). In contrast, no important nonaxisymmetric $\ell = 1$ components are needed for the description of the velocity field. This demonstrates that the nonaxisymmetric "revised oblique pulsator model" proposed by Bigot & Dziembowski (2002) is not able to describe the pulsations in HR 3831 which can be taken as an indication that the influence of the stellar rotation on oblique pulsations is considerably less important in comparison with the magnetic perturbation of p-modes.

Acknowledgements

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