Indirect Imaging of Stellar

Nonradial Pulsations

Oleg Kochukhov

Institut für Astronomie, Universität Wien, Austria

kochukhov@astro.univie.ac.at

Introduction

Many types of stars show periodic pulsational variation of radius and brightness. Observed pulsational characteristics are determined by fundamental stellar parameters. Consequently, investigations of stellar pulsations provide a unique opportunity to verify and refine our understanding of the evolution and 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 pulsation modes are distorted and cannot be described with a single spherical harmonic function.

Here I 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 a 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 very stringent tests of the recent theories of stellar magneto-acoustic oscillations.

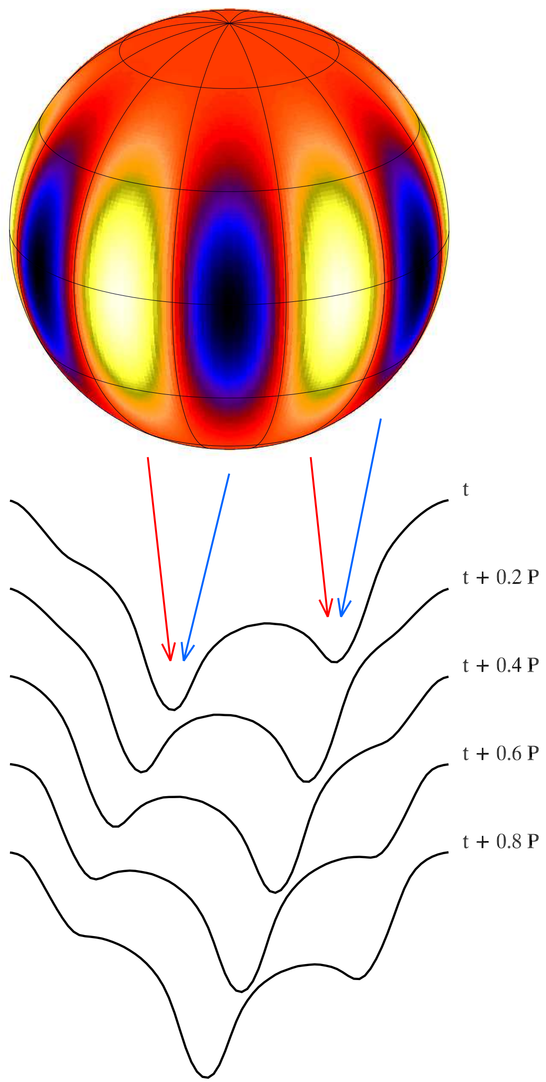
Pulsation Doppler Imaging

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 (*right figure*). 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).

The time-dependent vector velocity field is represented with a superposition of the two constant surface distributions:

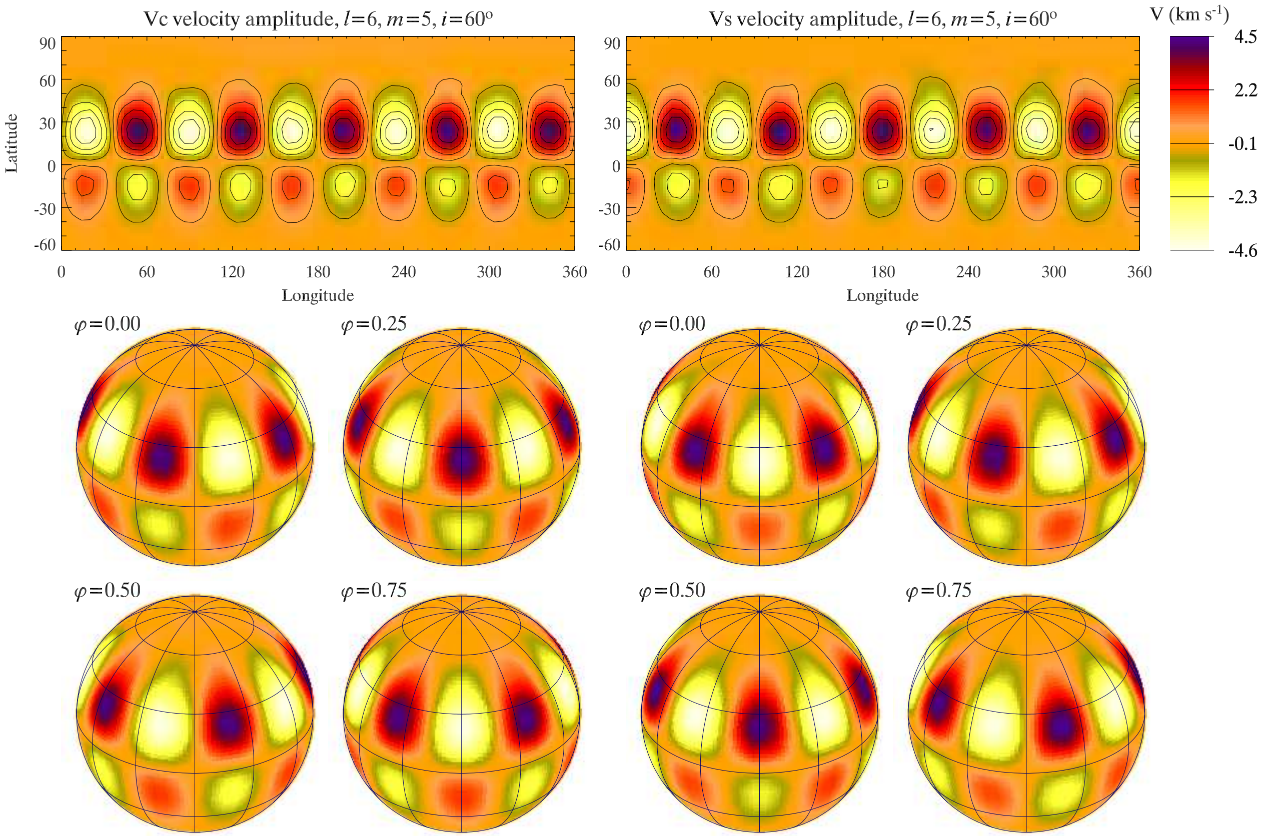
$$\boldsymbol{V}(t,\theta,\phi) = \boldsymbol{V}^c(\theta,\phi)\cos(\omega t) + \boldsymbol{V}^s(\theta,\phi)\sin(\omega t).$$

The $\boldsymbol{V}^c$ and $\boldsymbol{V}^s$ vector maps are recovered directly from the stellar spectra without imposing any specific global constraints on the pulsation geometry.



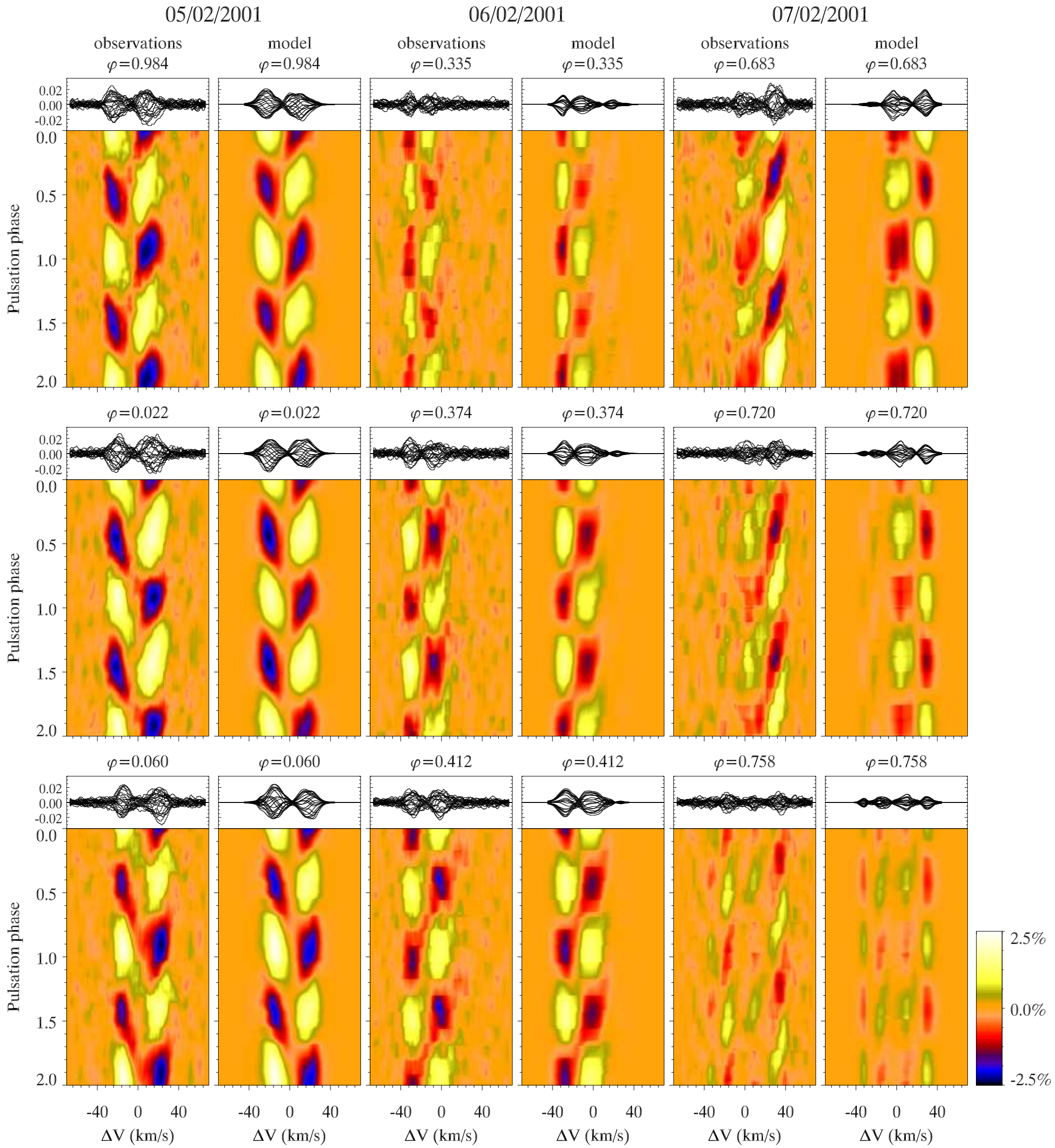
Numerical Tests of the Pulsation Velocity Inversion

Performance of the new Doppler Imaging procedure was studied with inversions of simulated data. These tests showed that a reliable recovery of the surface pulsation velocity structures can be achieved for all types of pulsation geometries accompanied by significant line profile variations and dominated by the vertical pulsation motions.



Test of the Pulsation Doppler Imaging reconstruction for $\ell = 6$, $m = 5$, $i = 60^{\circ}$. The figure shows rectangular and spherical projections of the reconstructed vertical velocity amplitudes, V_r^c (*left*) and V_r^s (*right*). In the spherical plots the star is shown at four aspect angles, corresponding to the rotation phases $\varphi = 0.00$, 0.25, 0.50 and 0.75.

Pulsation Doppler Mapping of the RoAp Star HR 3831



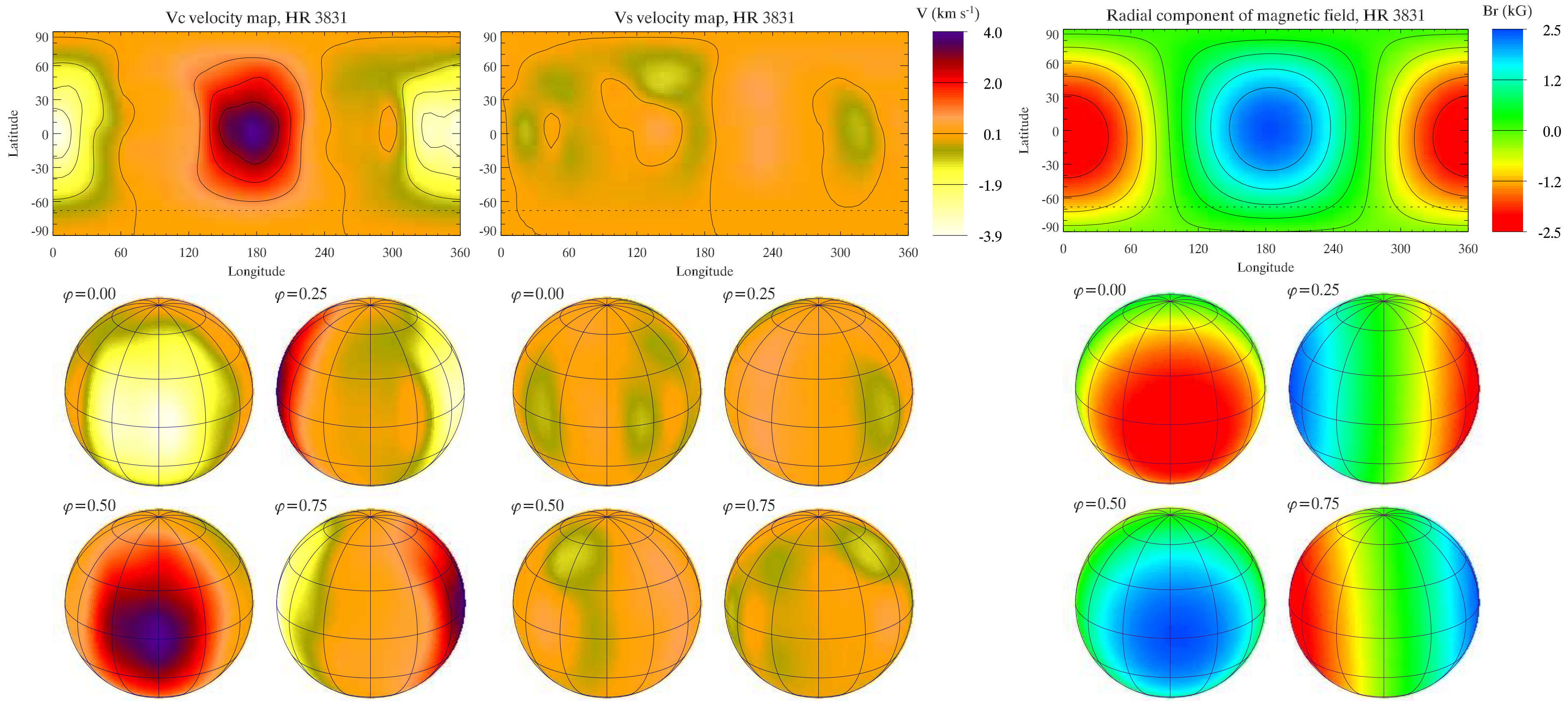
The pulsation Doppler inversion is applied to the time-resolved observations of the Nd III λ 6145 Å line in the spectrum of the roAp star HR 3831. We obtained 1860 $R = 123\,000$ spectra of this star over the period of 6 nights, evenly sampling the 2.85 day rotation period (Kochukhov & Ryabchikova 2001).

The upper plot in each panel shows residuals from the mean line profile. The color plots present pulsational variation of the residuals at specified rotation phases. Columns 1, 3, 5: observations; columns 2, 4, 6: predictions of the best-fit model derived with the Pulsation Doppler Imaging.

Revealing the RoAp Pulsation Geometry

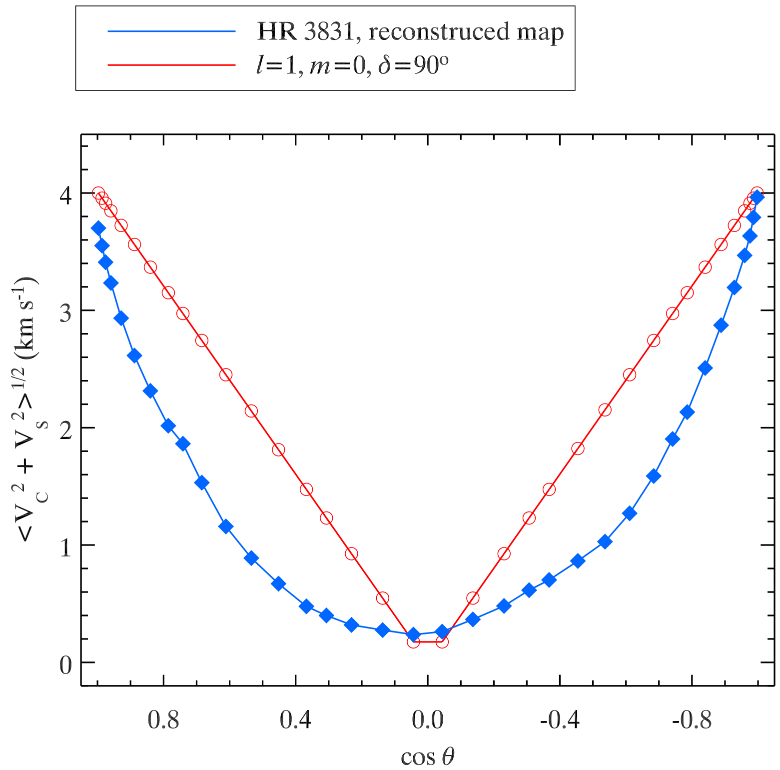
The first Doppler image of the stellar nonradial pulsation velocity field.

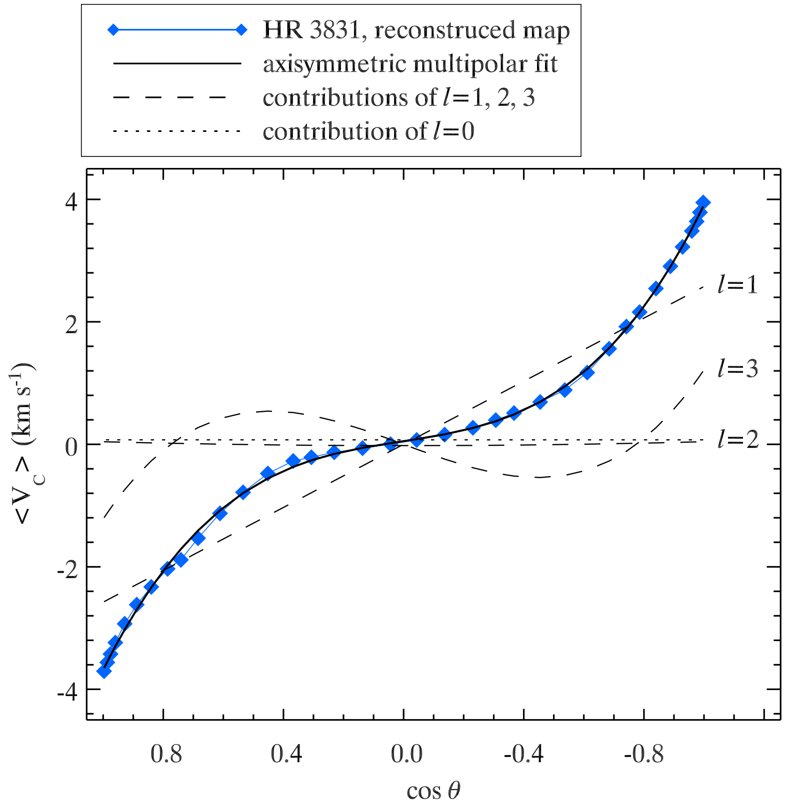
Left and center: rectangular and spherical projections of the V_r^c and V_r^s pulsation amplitude maps derived for HR 3831. *Right:* the surface distribution of the vertical component of the magnetic field in HR 3831 (Kochukhov et al. 2004).



Multipolar Analysis of the HR 3831 Pulsation Geometry

Analysis of the co-latitude dependence of the dominant axisymmetric component of the HR 3831 pulsation geometry. *Left:* co-latitude dependence of $\langle (V_r^c)^2 + (V_r^s)^2 \rangle^{1/2}$ is compared with the picture expected for the pure $\ell = 1$, $m = 0$ oblique mode. *Right:* axisymmetric multipolar fit of a superposition of $\ell = 0$–3 harmonics to the co-latitude trend in the V_r^c pulsation map.





Conclusions

- Pulsation Doppler Imaging is a powerful technique to study geometry of stellar nonradial oscillations.
- The first stellar pulsation 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: 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 non-axisymmetric $\ell = 1$ components are needed for the description of the velocity field. This demonstrates that the non-axisymmetric "revised oblique pulsator model" proposed by Bigot & Dziembowski (2002) is not able to describe pulsations in HR 3831.

References

Bigot, L., Dziembowski, W. A. *The oblique pulsator model revisited*, 2002, A&A, 391, 235

Kochukhov, O., Ryabchikova, T. *Pulsational and rotational line profile variations of the roAp stars α Cir and HR 3831*, 2001, A&A, 377, L22

Kochukhov, O. *Doppler imaging of stellar non-radial pulsations. I. Techniques and numerical experiments*, 2004, A&A, in press

Kochukhov, O., Drake, N. A., Piskunov, N., de la Reza, M. *Multi-element abundance Doppler imaging of the rapidly oscillating Ap star HR 3831*, 2004, A&A, in press

Saio, H. Gaustchy, A. *Axisymmetric p-mode pulsations of stars with dipole magnetic fields*, 2004, MNRAS, 350, 485