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HD 101065, the Most Peculiar Star: First Results from Precise Radial Velocity Study

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Abstract. In this paper we discuss the prospects for asteroseismology with spatial resolution and motivate studies of the most chemically peculiar roAp star HD 101065. We present the first results from a high-precision radial velocity (RV) study of HD 101065 based on data spanning four nights that were acquired using the HARPS echelle-spectrometer at the ESO 3.6 m telescope. The analysis of individual nights showed the amplitude and phase modulation of the dominant mode. The analysis of the whole data set showed the presence of multi-periodic oscillations with two groups of equally-spaced modes. We find $\Delta\nu = 65.2\,\mu$Hz and $\delta\nu = 7.3\,\mu$Hz for the large and the small spacing, respectively. HD 101065 is the only roAp star to show the existence of two groups of $l = 0, 2$ and $l = 1, 3$ excited modes.

Key words. Stars: oscillations, roAp stars.

1. Prospects for asteroseismology with spatial resolution of roAp stars

The main difference in observations in asteroseismology and helioseismology is that we cannot resolve the disks of most stars. As a consequence, cancellation effects reduce the integrated light and velocity amplitudes of pulsations causing only the lowest degree non-radial pulsation (NRP) modes ($l = 1$–4) to be detected in slowly rotating stars. In rapidly rotating stars higher degree modes ($l \approx 4$–20) can be detected by the spectral distortions in the rotationally broadened spectral lines (see Vogt & Penrod 1983). By comparison, resolved disk observations of the sun allow the detection of pulsation modes up to $l \approx 600$. The narrow l-range of modes visible in stellar disk-integrated studies decreases the diagnostic potential of asteroseismology. Furthermore, mode identification methods based on disk-integrated photometric or spectroscopic measurements do not work well. This is the most severe problem in asteroseismology.

The roAp stars are a unique group of pulsators that present us with advantages for asteroseismic studies compared to other stars. There are several similarities with helioseismology. First, the excited spectrum of roAp stars are due to high-overtone p-modes showing equal-spacing of pulsation frequencies (Kurtz 1990). Second, the identification of high-overtone p-modes is relatively simple due to the equal spacing of modes that makes the discrimination of $l =$ odd and $l =$ even groups of modes possible. The oscillations in roAp are easier to detect as they have higher amplitudes which are relatively stable compared to oscillations in the sun and the solar-type stars.

Another important advantage in asteroseismology of roAp stars is the possibility of the spatial filtration of NRP modes (Mkrtichian 1994). Spatial filtration exploits the fact that elements on the surface of Ap (including roAp) stars are distributed inhomogeneously. Spectroscopic radial velocity measurements of elements that have a spotted distribution on the surface measure a pulsational velocity that can originate from a small region on the star. The cancellation effects are thus smaller and higher degree modes can be detected as well as low amplitude ones. Recent work has demonstrated the efficiency of radial velocity spectroscopy for detection of low-amplitude modes (Hatzes & Mkrtichian 2004; Mkrtichian & Hatzes 2005; Kurtz *et al.* 2004).

There is growing evidence of the presence of a standing wave with a radial node in the atmospheres of some roAp stars. Using RV measurements of α Cir over narrow wavelength intervals Baldry *et al.* (1999) found that about 15% of the wavelength bands pulsated 180° out-of-phase with respect to most other lines. A similar result was found in 33 Lib by Mkrtichian *et al.* (2003) based on RV measurements of individual spectral lines. In particular they showed that Nd II and Nd III lines pulsate exactly out-of-phase. The existence of additional monotonous phase changes across the atmosphere was also seen in 33 Lib by Mkrtichian *et al.* (2003) and Kurtz *et al.* (2004). The vertical scale of the acoustic wave was found to be comparable to the size of line-forming regions of the atmosphere. In the roAp stars with a vertical acoustic standing or running wave there should be a one-to-one mapping between the pulsation phase and amplitude of the mode with respect to atmospheric geometric depth. Information on the vertical structure can come from the pulsation phases and amplitudes of the individual spectral lines of different elements that are formed at different atmospheric depths, as well as from bisectors of strong lines or lines of stratified elements. This important fact gives a chance for accurate acoustic study of the atmosphere using acoustic cross-sections.

The spatial resolution throughout the atmosphere is determined by the accuracy of the pulsation phase and amplitude measurements. The longer the time base of the observing, the higher the accuracy of the phase and amplitude determination. Moreover, different modes are expected to have different depths for the acoustic node and different phase profiles across the atmosphere. These thus will probe different atmospheric layers.

Several years ago, we started a program "Asteroseismology with spatial resolution" in order to study the three-dimensional structure of the atmospheres of roAp stars. An important part of these studies is the verification of the diffusion theory for the abundance anomalies in Ap stars that can be done by the determination of the acoustic and chemical profiles of the atmosphere. The acoustic confirmation of vertical separation of elements will be the most robust confirmation of the diffusion theory when combined with other approaches.

2. HD 101065 project motivation

The star HD 101065 was discovered by Przybylski (1961) as an extremely chemically peculiar star with strong spectral lines of rare-earth elements. The four magnetic field measurements by Wolff & Hagen (1976) show a longitudinal magnetic field in the range of $H_z = -2100$ to -2500 ± 450 (Gauss). No significant magnetic field variability was found with these data. Recent magnetic field measurements by Hubrig *et al.* (2004) yield a longitudinal magnetic field strength of half the value, or $H_z = -1014 \pm 72$ Gauss.

HD 101065 was found to be pulsating by Kurtz (1978) and is a prototype star of the roAp group. The pulsation spectrum of the star was studied in detail by Martinez & Kurtz (1990) who found multiperiodic oscillations with amplitude and phase modulations of the dominant mode; however, the equal spacing of frequencies was not reliably determined. The detailed historical review on studies of HD 101065 (also known as Przybylski's star) and the problems with the determination of its main stellar parameters were given by Kurtz & Martinez (2000).

The chemical abundance investigation of this star is intriguing. In early work, Wegner & Petford (1974) identified the spectral lines of 51 chemical elements. Cowley *et al.* (2000) performed abundance determination for 54 elements and found that lantanoids were overabundant by 4–5 dex. Cowley *et al.* (2004) also confirmed with a high degree of confidence the presence of lines of Tc and the short-lived (half-life $\tau = 17.7$ years) element Pm. The abundance and the isotopic content of Li was determined by Shavrina *et al.* (2004). Gopka *et al.* (2004) estimated the abundance limits of Tc, Pb, Bi and increased the number of elements with known abundances up to 59. They also identified the lines of all radioactive elements with atomic numbers from Z = 84 to Z = 99, except for Z = 85 and 87 (At and Fr).

The presence of short-living radioactive elements in Przybylski's star is enigmatic. Cowley *et al.* (2004) proposed that some unrecognized processes, perhaps flare activities, were taking place in the atmospheres of Przybylski's star. On the other hand, Gopka *et al.* (2004) suggested that the existence of elements with Z < 92 is due to the natural radioactive decay of thorium and uranium stratified in the upper atmosphere. The existence of the elements with Z > 92 is due to neutron capture in the stratified layers of the atmosphere with large overabundance of Th and U. In spite of 43 years of investigations, the extraordinary chemical anomalies of Przybylski's star are still unexplained.

We started a detailed study of Przybylski's star with the goals:

- to find and identify the *p*-mode oscillation spectrum,
- to determine the acoustic cross-sections of the atmosphere in order to confirm the existence of an acoustic node in line-forming atmosphere,
- to check for the presence of vertical stratifications of elements and thus confirm diffusion theory.

If the diffusion theory is valid, then there should be vertical stratifications of elements and with the majority of peculiar heavy elements levitated in the upper atmosphere. Spectral lines of elements formed on opposite sides of an acoustic node should pulsate with opposite phase to lines of non-peculiar elements formed in the lower atmosphere, similar to what was found in Nd II and Nd III in 33 Lib (Mkrtichian *et al.* 2003). The acoustic check for stratification of peculiar elements in upper layers should be the most accurate confirmation of the diffusion theory. Here we report the first results from four consecutive nights of RV measurements for HD 101065.

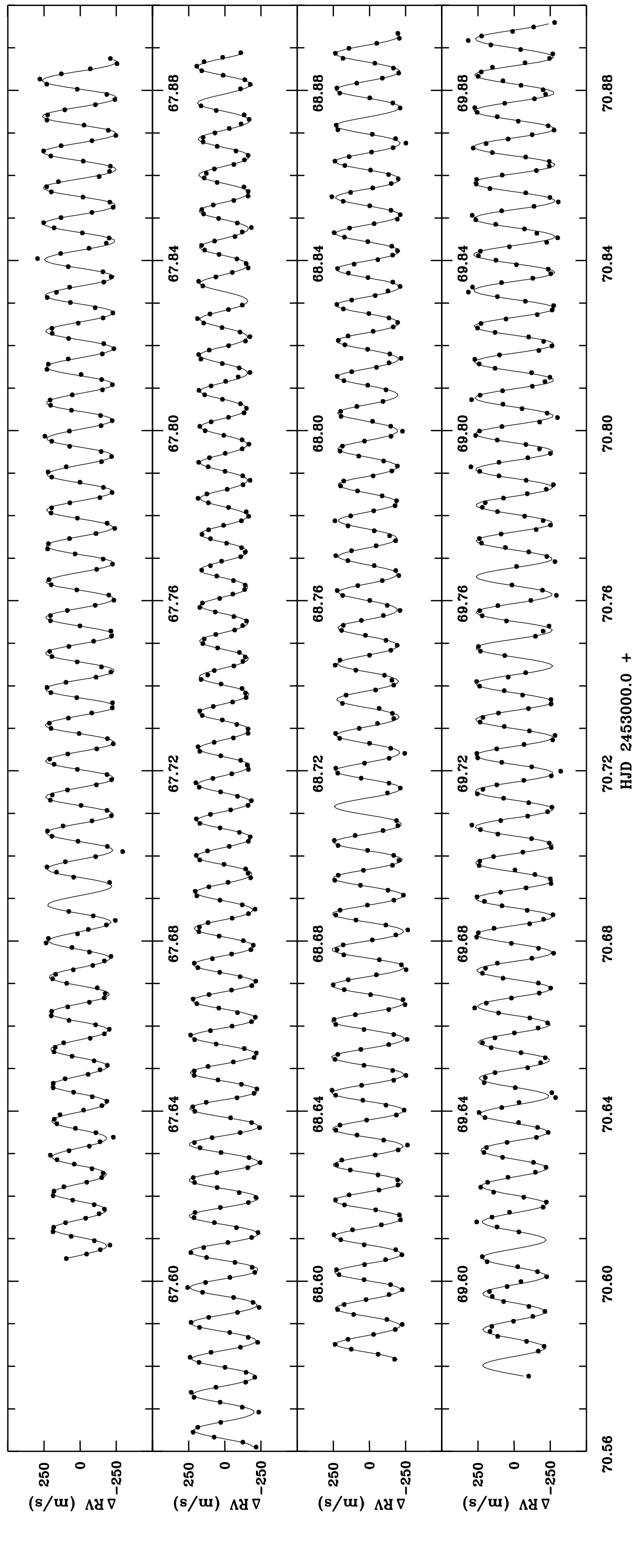

Figure 1. The "integrated" (over the interval 5000–6200 Å) radial velocities for HD 101065 on the four nights.

3. First results – *p*-mode spectrum of HD 101065

HD 101065 was observed on four consecutive nights (3rd–6th March 2004) using the HARPS echelle-spectrometer of the 3.6-m telescope of ESO. The resolving power R = 115 000 in the wavelength range $\lambda\lambda$3800–6900 and the iodine absorption cell was used. To achieve the maximum radial velocity (RV) precision all spectral lines in the full spectral region covered by iodine cell were used. The radial velocity data is shown in Fig. 1. The preliminary time-series analysis performed for individual nights confirm the dominant $f_1 = 1.3728$ mHz mode. In order to investigate the amplitude and phase variability of the dominant f_1 mode, each night was divided into time segments consisting of 8–10 pulsation cycles and the best fit to the data of each segment was then found. Figure 2 shows variations of the amplitude and phase. Both data are variable with $f_m = 1.36$ day modulation period that can be considered as the star's probable rotation period. To search for low-amplitude modes we removed the variable contribution of the dominant mode from the data of each night. The Discrete Fourier Transform (DFT) analysis of the merged residuals revealed 4 additional modes that are shown in Fig. 3. The frequencies and mean amplitudes of modes are given in Table 1.

4. Discussion and conclusion

A remarkable feature of the oscillation spectrum of HD 101065 is the existence of two groups of low (f_3 and f_4) and high-frequency (f_1, f_2 and f_5) modes equally-spaced within each group by the mean value $\Delta\nu = 32.6\,\mu$Hz.

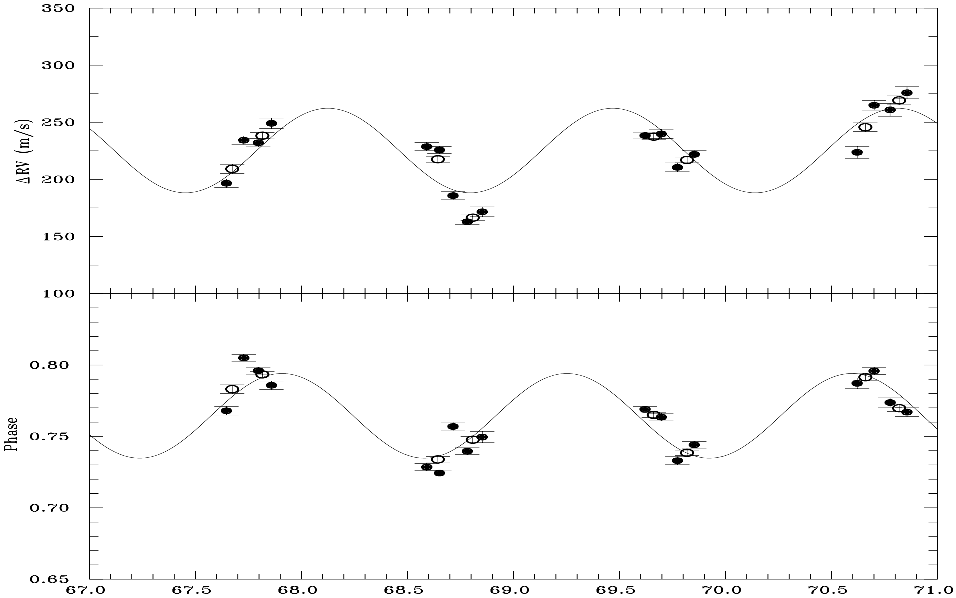

Figure 2. The modulation of amplitude (top panel) and phase (bottom panel) of the dominant $f_1 = 1372.8\,\mu$Hz mode.

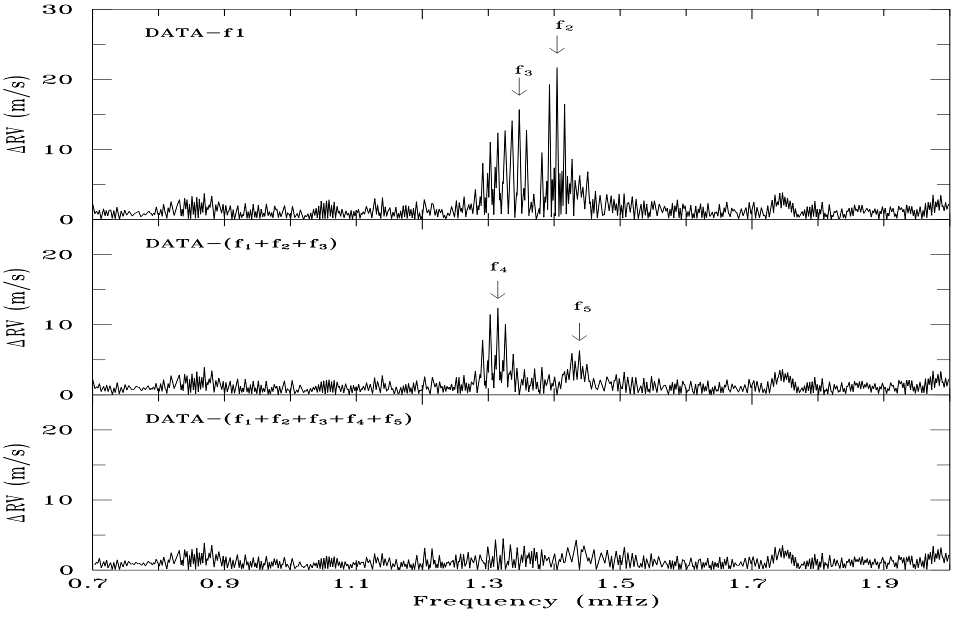

Figure 3. Consecutive prewhitening of the amplitude spectra. The top panel shows the DFT after removing the contribution of $f_1 = 1.3728$ mHz. Lower panels are the DFT after removal of the next dominant mode.

Table 1. Frequencies f_1–f_6 detected in RV analysis.

No	Frequency μHz	K $\mathrm{m\,s^{-1}}$	σ $\mathrm{m\,s^{-1}}$
f_1	1372.8	221.3	1.92
f_2	1404.4	20.6	1.03
f_3	1314.6	12.58	0.89
f_4	1347.0	11.61	0.99
f_5	1438.4	6.43	0.96
$f_6 = 2 \times f_1$	2745.2	6.22	0.90

The echelle-diagram for p-mode spectrum plotted with a frequency spacing of 65.2 μHz is shown in Fig. 4. The regularly spaced pattern of two groups of modes f_1, f_2, f_5 and f_3, f_4 that belong to modes of opposite l-parity is well visible. Modes with the same parity $l = 1, 3$ and $l = 0, 2$ are shifted in spacing on the echelle-diagram with respect to each other by the mean value $\delta\nu = 7.3\ \mu$Hz.

This echelle-diagram has similarities with the p-mode spectrum of the sun and other solar-like stars (e.g., Eggenberger *et al.* 2004) in that it shows both large and small separation in the spacing of modes. We conclude, that two odd and two even groups of modes are excited in Przybylski's star. A comparison with echelle-diagrams for roAp stars (Mkrtichian & Hatzes 2000, 2005) shows that HD 101065 is currently the first roAp star for which the spectrum of $l = 0, 1, 2$ and 3 excited modes has been detected.

Detailed results on the study of p-mode spectrum of Przybylski's star is in preparation and will be published elsewhere.

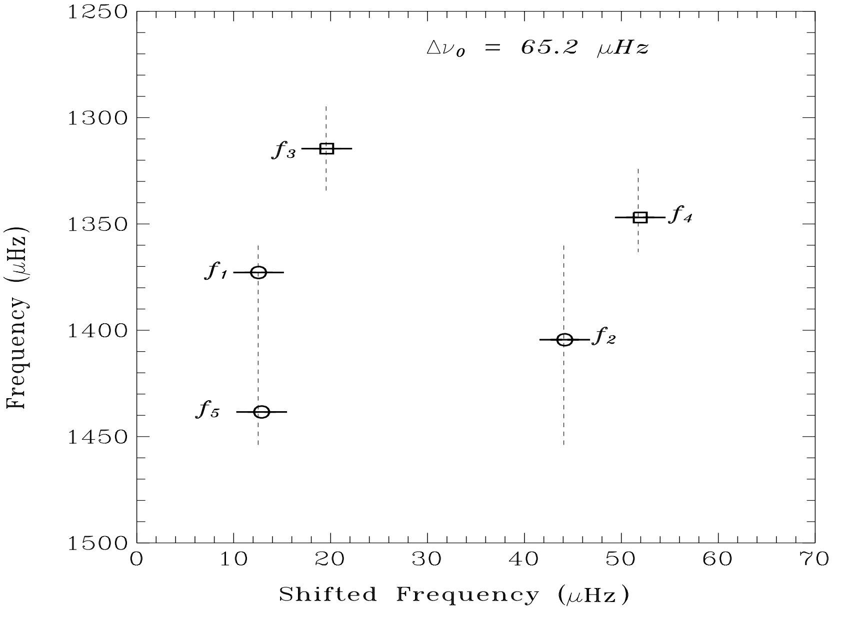

Figure 4. The echelle-diagram for HD 101065.

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