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Study of Pulsations in the Atmosphere of roAp star HD 137949*

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Abstract. The roAp star HD 137949 (33 Lib) shows the most complex pulsational behaviour among all roAp stars. Mkrtichian et al. (2003) found nearly anti–phase pulsations of Nd II and Nd III lines, which they attribute to the presence of a pulsation node high in the atmosphere of HD 137949. This was confirmed by Kurtz at al. (2005), who also find that in some REE lines the main frequency, corresponding to 8.27 min, and its harmonic have almost equal RV amplitudes. Based on high accuracy observations Ryabchikova et al. (2007a) studied pulsational characteristics of the HD 137949 atmosphere in detail.

In general, spectroscopy provides 3D resolution of modes and allows to search for the photometrically undetectable frequencies. The high–accuracy space photometry provides very high–precision measurements of detected pulsation frequencies and enables an accurate phasing of multi–site spectroscopic data. A combination of simultaneous spectroscopy and photometry represents the most sophisticated asteroseismic dataset for any roAp star.

In 2009 the star HD 137949 became a target of an intense observing campaign that combined ground–based spectroscopy with space photometry, obtained with the MOST satellite. We collected 780 spectra using the ESPaDOnS spectrograph mounted on the 3.6–m CFHT telescope; 374 spectra were obtained with the FIES spectrograph mounted on the 2.56–m NOT to perform the time–resolved spectroscopy of HD 137949. In addition, we used 111 UVES spectra (2004) from the ESO archive to check the mode stability.

The frequency analysis of the new radial velocity (RV) measurements confirmed the previously reported frequency pattern (two frequencies and the first harmonic of the main frequency), and revealed an additional frequency at 1.991 mHz. The new frequency solution fits perfectly the RV variations from the 2004 and 2009 observational sets providing a strong support for the p–mode stability in the roAp star HD 137949 for at least 5 years.

Key words: stars: atmospheres – stars: chemically peculiar – stars: magnetic fields – stars: oscillations – stars: individual: HD 137949

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* Based on observations collected at the European Southern Observatory, Paranal, Chile (program 077.D–0491 and a program 077.D–0150, retrieved through the ESO archive) and at the Nordic Optical Telescope (NOT).

1 Introduction

The rapidly oscillating peculiar A–type (roAp) stars are the key objects for asteroseismology, which presently is the most powerful tool for testing the theories of stellar structure. Deep within the 3D envelope of a pulsating star, acoustic waves are excited and propagate through regions of varying temperature, density and composition, which influence the wave speed, frequency and direction. Conventional asteroseismology has focused on the interpretation of the light and radial velocity variations produced by these waves as they arrive at the stellar surface. This is a tremendous limitation because the complex 3D details of the acoustic wave pattern (e.ġ. relative phase of waves, radial evolution of wave amplitude, running vs. standing waves, etc.) are nearly impossible to unravel from such simple 2D surface observations. However, peculiar atmospheres of magnetic roAp stars provide a unique possibility of extending observational asteroseismology to the radial dimension, and to thereby build a complete 3D model of a pulsating stellar atmosphere. This capability is a consequence of element stratification in Ap atmospheres (Wade et al., 2001; Ryabchikova et al., 2002, 2003) where spectral lines of different elements are formed at different heights. According to the elemental diffusion theory (Michaud, 1970) the iron–peak elements in atmospheres of cool Ap stars tend to concentrate near the photospheric layers, while the heavier elements, like rare earths are pushed out by the radiative force and may produce overabundant "clouds" in the upper atmosphere. This property extends the optical depth range, accessible for determining the pulsation velocity by orders of magnitude. This capability has been demonstrated for the roAp stars γ Equ (Ryabchikova et al., 2002), HD 24712 (Ryabchikova et al., 2007a,b) and 10 Aql (Sachkov et al., 2008a). The basic idea for vertically resolving the stellar atmosphere and determining the depth dependence of the pulsation velocity field is to measure the pulsation amplitude and phase of the amplitude maximum in the spectral lines as a function of optical depth. As we all know, the absorption line wings are formed statistically deeper in the atmosphere than the line cores (since the opacity in the core is larger, escaping photons must originate, on the average, at a smaller continuum optical depth). A corollary of this is that the cores of weak lines are formed deeper in the atmosphere than the cores of strong lines. Using these properties, observers are able to use the absorption lines formed in the spectrum of any star to coarsely trace the atmospheric properties (including, say, the pulsation velocity field) as a function of atmospheric depth. This ability is fundamentally limited by the fact that the lines are usually formed over a broad range of depths within the atmosphere, and consequently our vertical "vision" is blurry. In the case of roAp stars, the presence of REE clouds dramatically enhances this capability to vertically resolve the atmosphere (e. g., Ryabchikova et al., 2007a). Because the spectral lines of REEs are formed almost entirely within the relatively dense clouds, the line formation depths are extremely well–defined. As the pulsational distortions of a line must correspond to the acoustic wave properties at the characteristic (and well–defined) height of formation of the line, we are able to vertically resolve the waves with a relatively high precision.

One of the reasons why oscillations of roAp stars are so important lies in the fact that many oscillation frequencies are excited simultaneously giving a great potential for asteroseismic studies.

Usually the researchers try to find a regular "large spacing" and a "small spacing". The regular frequency spacing in the oscillation spectra of solar–type and roAp stars is a signature of the excitation of consecutive overtones of high overtone p–modes. The "large frequency spacing" is the spacing between the consecutive overtones of modes of the same degree: $\Delta\nu = f(n,l) - f(n-1,l)$, where n is radial order and l the degree of the mode. The "small spacing" is the frequency difference of modes of the same parity $\Delta\nu = f(n,l) - f(n-1,l+2)$. In the roAp stars the magnetic field of a few kG can change the pulsation frequency by $\sim 10-30\,\mu$Hz, depending on the latitudinal degree l. The frequencies of $l=0$ and $l=3$ modes tend to be affected more strongly (Saio, 2005). Thus the resulting frequency spacings can be quite different from those expected without a magnetic field.

All but one papers on roAp modeling dealt with the detailed comparison between the observed and nonadiabatic theoretical frequencies for the best fitting models: α Cir (Bruntt et al., 2009), 10 Aql (Huber et al., 2008), γ Equ (Gruberbauer et al., 2008), HD 101065 (Mkrtichian et al., 2008). These models vary in stellar masses, chemical compositions (X, Z) (where X and Z are the mass fractions of hydrogen and heavy elements), $T-\tau$ relation above the photosphere as well as the l value and magnetic field strength.

In the paper by Saio et al. (2010) for the roAp star HD 24712 for the first time the distributions of the phase and amplitude of RV variations as a function of atmospheric height were modelled and compared with the observed distributions. The gradual outward increase of the phase lag in the outermost layers is well reproduced by the theoretical results obtained with a running–wave outer–boundary condition. Although the described models agree with most of the observed properties of the oscillations in the atmosphere of HD 24712, no excited oscillation modes with frequencies appropriate for this star were found, e. g. all the modes examined are damped. The κ–mechanism does not seem to be strong enough to excite the supercritical high–order p–modes in HD 24712.

Based on realistic models of wave propagation in magnetised stellar atmospheres, the pulsation theory in the presence of the magnetic field (see, e. g. Sousa & Cunha, 2008) argues that in the magnetically–dominated regions of the stellar envelope waves are decoupled into the orthogonal standing magnetic and running acoustic components. These oscillations are oriented perpendicular and along the magnetic field lines, respectively. The total projected pulsation velocity, produced by a superposition of these two components, can have a widely different apparent vertical profile, depending on the magnetic field strength, inclination and aspect angle. For certain magnetic field parameters and viewing geometries the two components cancel out, creating a node–like structure, or imitate an inwardly running wave.

Using a method based on these concepts, phase jumps in the radial velocity curves, indicating a nodal surface, were discovered in the roAp star HD 137949 by Mkrtichian et al. (2003), and in 10 Aql by Sachkov et al. (2008a). Kurtz et al. (2006) subsequently obtained a time series of 2 hours (111 VLT/UVES spectra) of HD 137949 indicating the frequencies undetectable by the ground–based photometry for which a highly controversial interpretation could be the stochastic variations of pulsation amplitudes in the magnetoacoustic boundary layer. A reanalysis of the UVES spectra (Ryabchikova et al., 2007a) confirmed a phase jump, they also found spectral lines formed close to the position of the nodal zone showing variations at half (!) of the pulsation period (a resonant excitation of the harmonic oscillation?).

HD 137949 with its nodal zone seems to allow for testing the pulsation theory. Thus, this star represents a unique laboratory for guiding the theoreticians towards a physically consistent model of dynamic roAp star atmospheres.

At the same time, the current observational data are clearly unable to provide an unambiguous picture and confrontation with the theory. Therefore, we suggest to obtain a much longer spectroscopic time series of HD 137949 and a simultaneous MOST photometry. This combination of the spectroscopy (which provides a 3D resolution of waves as well as sensitivity to the frequencies undetectable photometrically) with the photometry (which provides a very high precision diagnosis of detected pulsation frequencies, allowing for accurate phasing of the spectroscopic data) will represent the most sophisticated asteroseismic dataset for any roAp star.

2 Observations and Data Reduction

Spectroscopic monitoring of 33 Lib was performed using the ESPaDOnS spectrograph mounted on the 3.6–m CFHT during 3 nights: May 02, 05, and 11 2009 and with Fibre–fed Echelle Spectrograph (FIES) mounted on the 2.56–m Nordic Optical Telescope (NOT) during 5 nights: April 29, May 05, 12, 17, and 21 2009. 780 high–quality spectra were obtained with the ESPaDOnS and 374 spectra were obtained with the FIES. These spectra were acquired simultaneously with allocated ultra-

Table 1: Journal of observations of 33 Lib

Start HJD (245 0000+)	End HJD (245 0000+)	Spectral range, Å	No. of exposures	time resolution, s	Typical S/N	Instr.
53071.76313	53071.84598	4960 – 6990	111	69	100	UVES
54951.52764	54951.64601	4766 – 7364	74	140	80	FIES
54953.89440	54954.07997	4950 – 7200	240	67	90	ESPaDOnS
54957.55330	54957.67169	4766 – 7364	75	140	80	FIES
54957.87190	54958.05284	4950 – 7200	240	67	90	ESPaDOnS
54962.84950	54963.08189	4950 – 7200	300	67	65	ESPaDOnS
54964.54251	54964.66090	4766 – 7364	75	140	80	FIES
54969.51152	54969.62990	4766 – 7364	75	140	80	FIES
54973.50093	54973.61941	4766 – 7364	75	140	80	FIES

precise broadband photometry by the MOST minisatellite between April 23 and May 22. In addition we used 111 UVES spectra extracted from the ESO archive to check the mode stability. A journal of observations is presented in Table 1, where the Julian Date of the beginning and the end of each time series, the spectral range, the number of exposures and S/N ratio are given.

2.1 Time–Series ESPaDOnS Spectra

To adequately time–resolve the dominant 8–minute pulsation period of HD 137949, individual exposure times are limited to a maximum duration (including readout) of about 60 seconds. Using a fast readout mode (readout time = 25 s) and $R = 80000$ spectroscopic mode, this will provide a peak S/N per spectrum of 150:1 (according to the ESPaDOnS ETC), sufficient to achieve a spectral quality suitable for analysis of the line profile variations in the spectral orders 25 – 50.

2.2 Time–Series FIES Spectra

We have used the Fibre–fed Echelle Spectrograph (FIES) at the 2.56–m Nordic Optical Telescope (NOT) to perform the time–resolved spectroscopy of 33 Lib. The observations were obtained during 5 nights (April 29, May 05, 12, 17, 21) about 3 h each night. We collected 374 stellar spectra using an exposure time of 90 s. With the overhead of 48 s this gave us a sampling rate of approximately one spectrum every 138 s, sufficient to achieve a spectral quality suitable for the analysis of the line profile variations with a dominant 8 min pulsation period of this star.

The FIES instrument was configured to use the medium-resolution mode, which provides a wavelength coverage of the 4765 – 7360 Å region at the resolving power of $R = 47000$. We used the REDUCE package (Piskunov & Valenti, 2002) to perform the standard steps of the echelle spectra reduction (construction of the master flat field and bias frames, order location, flat–fielding and wavelength calibration), followed by the optimal extraction of the stellar spectra. The typical signal–to–noise ratio of the individual observations is 80 around $\lambda\,5000$ Å.

3 Model Atmosphere, Line Identification and Radial Velocity Measurements

A self–consistent model atmosphere of HD 137949 was calculated iteratively with the LL MODELS code using the abundances and stratification of Si, Ca, Cr and Fe derived at each iteration. Ex-

Table 2: Summary of the RV pulsational analysis in 33 Lib

Ion	Frequencies detected	Amplitudes, m/s	Central wavelength of lines used, Å
H I	f_1	302	Hαcore
	f_3	53	6562
Eu II	f_1	210	6438, 6645
Y II	f_1	85	5546, 5663,
	f_2	30	5728
Dy II	f_1	90	5164, 5169
Dy III	f_1	40	5730
Tb III	f_1	100	5847, 6092,
	f_2	56	6323, 6687
Th III	f_1	190	5375, 6599
La II	f_1	100	5805, 5808, 6100,
			6262, 6320, 6399,
			6642
Li I	f_1	110	6707
Pr II	f_1	130	5292, 5681, 6165
	f_2	40	
Pr III	f_1	94	5300, 6160, 6866,
	f_2	39	7030
	f_3	34	
	f_4	42	
Nd II	f_1	114	5132, 5182, 5277,
	f_2	53	5311, 5320, 5486,
	f_3	25	5534, 5804, 6638,
	f_4	20	6650
Nd III	f_1	78	5051, 5152, 5677,
	f_2	28	5803, 5845, 5851,
	f_3	23	6145, 6327
	f_4	26	
Fe I	f_1	25	5415, 5424, 5676
Fe II	f_1	30	5414, 5425, 6247

tended tables of observed and predicted lines of the rare–earth elements were used for line opacity calculations. For the final model we adopted $T_{\rm eff} = 7500 \pm 100$ K and $\log g = 4.0 \pm 0.1$. With the Hipparcos parallax we estimated the radius of HD 137949 as $R = 2.05\,R_{\odot}$

To perform a careful line identification and choose lines suitable for the pulsation analysis, we have synthesized the observed spectral region for the star with these parameters. Atomic data were extracted from the Vienna Atomic Line Database (VALD, Kupka et al., 1999) and the synthetic spectrum calculations were carried out with the SYNTHMAG code (Kochukhov 2007).

The radial velocities were measured with a centre–of–gravity technique. We used spectral lines that were selected in our previous study (Ryabchikova et al., 2007a). Taking into account the observed pulsation amplitudes and accuracy of RV measurements, we have selected about 100 lines for the frequency analysis and the study of the pulsational wave propagation through the stellar atmosphere.

Table 3: Frequencies for the RV data

Label	Frequency, d^{-1}	Significance	Amplitude, m/s	Phase [$-\pi$, π]
H_α core				
f_1	174.075204	117.9	301	−2.895628
f_3	170.978821	6.8	53	−1.726288
Eu II				
f_1	174.070340	61.7	211	0.907241
Nd II				
f_1	174.074649	104.3	114	−1.625773
f_2	348.147294	39.2	53	2.638426
f_3	171.554097	9.8	25	−2.937492
f_4	155.482824	6.5	20	−0.936600
Nd III				
f_1	174.071151	81.6	78	0.133982
f_2	348.140230	14.9	28	1.458686
f_4	155.727163	13.8	26	2.509509
f_3	170.973465	11.3	23	−2.983738
Pr III				
f_1	174.073599	39.2	94	−2.905973
f_4	155.738266	9.4	42	−1.850699
f_2	348.146463	8.0	39	−0.631134
f_3	170.971336	6.7	34	−3.010928

Aiming to improve the signal–to–noise ratio of the RV data, we averaged measurements of different lines of the same ions with close pulsational phases and amplitudes. In Table 2 we report the lines for which the RV measurements were averaged.

4 Frequency Analysis

HD 137949 is a unique case where different lines reveal a different set of frequencies. The most demonstrative examples are the Hα and Pr III lines. The Hα core pulsates with the highest dominant amplitude about 0.3 km/s, but we are able to see only two frequencies. At the same time, the Pr III lines having a 3 times less dominant amplitude (0.1 km/s) pulsates with at least 4 periods.

We carried out the frequency analysis by applying the standard combination of the discrete Fourier transform (DFT) and the least–squares fitting. First we applied the DFT to the RV data. The period corresponding to the highest pulsation amplitude value was then improved by the sine–wave least square fitting of the RV data with pulsation period, amplitude, and phase treated as free parameters. This fit was removed from the data and then the Fourier analysis was applied to the residuals. This procedure was repeated for all the frequencies with the significance above 5.

The frequency analysis was performed on the RV data of the Hα core and the averaged RV data of Eu II, Nd II, Nd IIIand Pr III lines using the SigSpec (Reegen, 2007) and Period04 (Lenz & Breger, 2005) codes. Due to the problems with aliasing, the data of the ESPaDOnS and FIES were merged and analysed as one data set. Nine nights spanning over 22 days are available. The frequencies detected are given in Table 3. In the Nd III data, f_3 has a value of 170.97 while in the Nd II data the value is different by +0.58, however, the phases are equal (≈ -2.9 in both cases). The

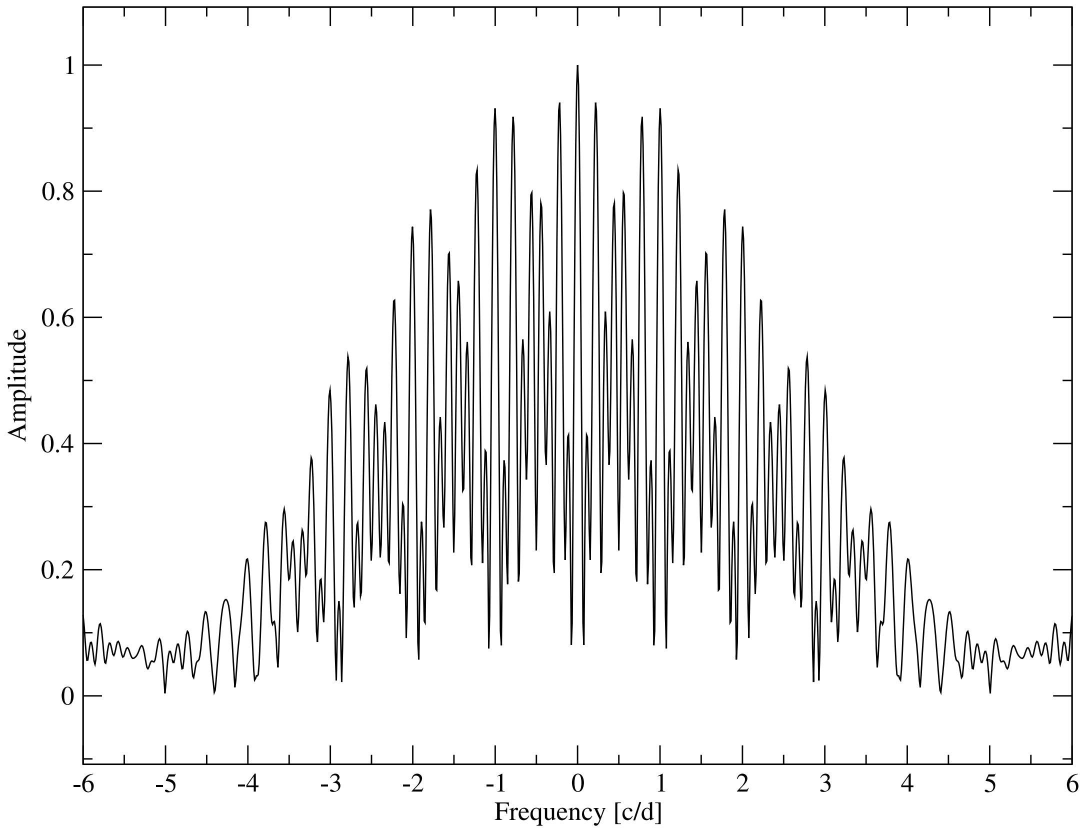

Figure 1: Spectral window of the combined FIES and ESPaDOnS data.

spectral window shows strong aliasing with 0.22, 0.78 and $1.0\,\mathrm{d}^{-1}$. The Nd III data have a better point–to–point scatter than the Nd II data, hence it is more probable that the value of $170.97\,\mathrm{d}^{-1}$ is correct, compared to $171.55\,\mathrm{d}^{-1}$. For Nd II and Nd III a phase lag of π is expected. To check for phase–dependent aliasing we subtracted $170.97\,\mathrm{d}^{-1}$ from the Nd II residuals after pre-whitening with the dominant frequency and its harmonic. Then we added again $170.97\,\mathrm{d}^{-1}$ but with different phases and checked the Fourier transforms. At phases close to 0.1 (i. e. $-3+\pi$) a peak at $171.55\,\mathrm{d}^{-1}$ shows the highest amplitude. This is a strong evidence that $171.55\,\mathrm{d}^{-1}$ is an alias, even though the spectral window (see Fig. 1) does not show a pronounced aliasing peak at 0.58. Figure 2 illustrates this circumstance.

Figure 3 shows the Fourier transform of the original data and Fig. 4 shows the Fourier transforms after pre-whitening with the dominant frequency and its harmonic. For the Nd II data (the middle panel), the peak at $171.55\,\mathrm{d}^{-1}$ is the highest, while in the Nd III data (the upper panel), the highest peak in the corresponding range is found at $170.97\,\mathrm{d}^{-1}$. Pre-whitening with f_4 does not change the picture significantly. For the sake of completeness, the same is demonstrated for the Pr III data.

5 Phase Relations Between Photometry and Spectroscopy

Spectroscopic and photometric techniques provide information on the boundary zone, relevant for any pulsation model and giving access to different modes and hence atmospheric layers. An observed phase lag between luminosity and RV variations is an important parameter for a first step towards modeling the stellar structure. To determine this phase lag, one needs simultaneous photometric and spectroscopic observations. Until now this was done only for two roAp stars: HD 24712 (Ryabchikova et al., 2007b) and 10 Aql (Sachkov et al., 2008a). For HD 137949 our spectroscopic

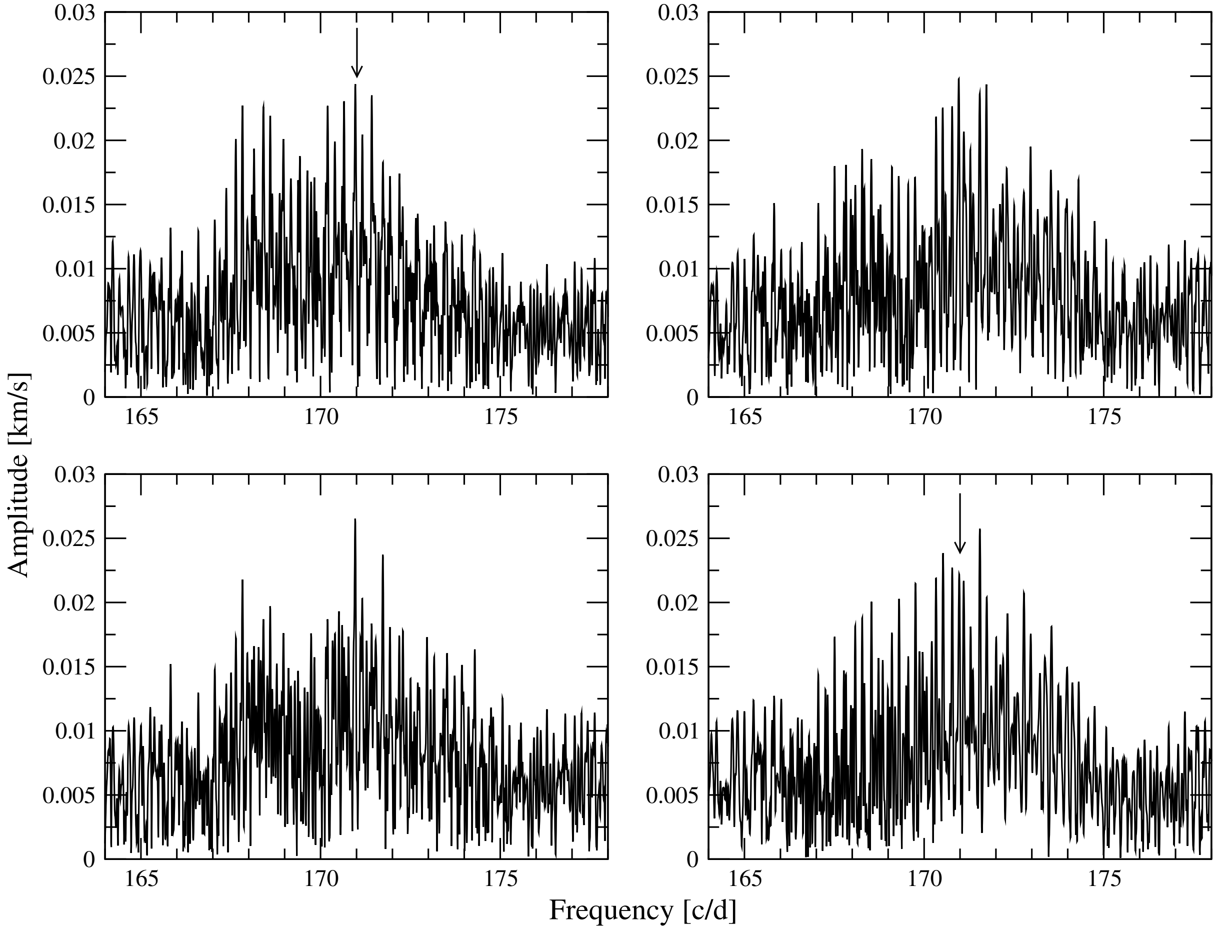

Figure 2: Phase–dependent aliasing. The input frequency is indicated by the arrow. Upper left: DFT of the residuals adding f_3 from Nd III without the phase lag. Lower left: the same but with the phase lag of +1. Upper right: the same but with the phase lag of +2. Lower right: phase lag 3.1.

time–series were carried out simultaneously with the MOST photometry. The high S/N and spectral resolution of present observations of HD 137949 allow us to derive phase lags for individual ions, sampling different atmospheric layers. In order to minimize the influence of the higher (with respect to the spectroscopic observations) point–to–point scatter of the photometric observations, we have constructed an artificial light curve based on the frequencies, amplitudes and phases of two frequencies (f_1 and f_2), as derived by a multi–sine fit to the MOST data. In the next step the artificial time–series were cross–correlated with the RV observations. The time interval for the cross–correlation was chosen from plus to minus 8.27 minutes (the period of the main frequency, f_1), with an increment of 1 second.

The results of the cross–correlation analysis for the Hαcore and for the averaged Eu II, Nd II, and Nd III lines are given in Table 4, where we define the phase lag as the difference between the RV maximum and the photometric maximum, expressed in seconds, or as a fraction of the main period $P = 8.27$ min. The error of the phase lag determination was estimated as follows. We added a normally distributed random signal to both the spectroscopic and photometric data, assuming that the noise amplitude corresponds to the observational error. For spectroscopy the error was derived from the RV determinations, and for photometry the MOST team recommended to use 2% of the signal. A phase lag was derived from these noisy data and repeated 200 times. The resulting standard deviation was adopted as an error of the phase lag determination.

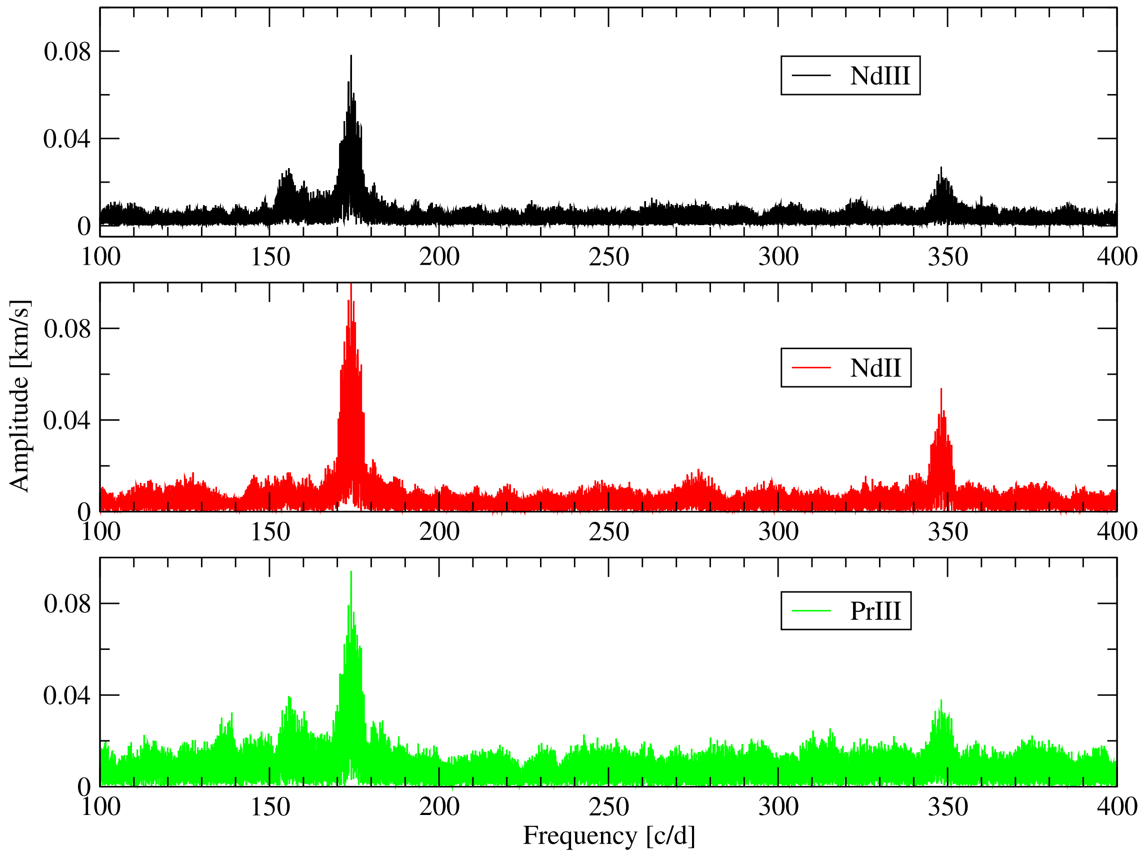

Figure 3: Fourier Transforms for the three RV data sets.

Table 4: Phase lags (seconds and fractions of the main period $P = 8.27$ min) between the maxima of luminosity and RV variations of different chemical species in the atmosphere of HD 137949

Ion	Phase lag	
	Seconds	Period fraction
H I	-20 ± 5	-0.24 ± 0.01
Eu II	-64 ± 8	-0.32 ± 0.01
Nd II	319 ± 9	0.43 ± 0.02
Nd III	74 ± 8	-0.05 ± 0.02

6 Mode Stability

Pulsation amplitude modulation for roAp stars were discussed in the literature as a consequence of a limited mode life time or beating frequencies. Studying γ Equ, the second brightest roAp star, Kurtz (1983) has detected a pulsation frequency of 1.339 μHz with an amplitude varying between 0.32 and 1.43 mmag. Beating with a closely spaced frequency has been proposed as the cause of amplitude modulation of this very slow rotating star (rotation period $\sim$ 77 years). Based on a cross–correlation radial velocity (RV) study, Libbrecht (1988) has discovered three frequencies at 1.365 μHz, 1.369 μHz and 1.427 μHz. He suggested that the amplitude modulation observed in the spectra of roAp stars may not be due to closely spaced frequencies, but rather caused by short ($\sim$ 1 day) mode lifetimes. Martinez et al. (1996) analysed a multi–site 1992 campaign data, 26 nights in

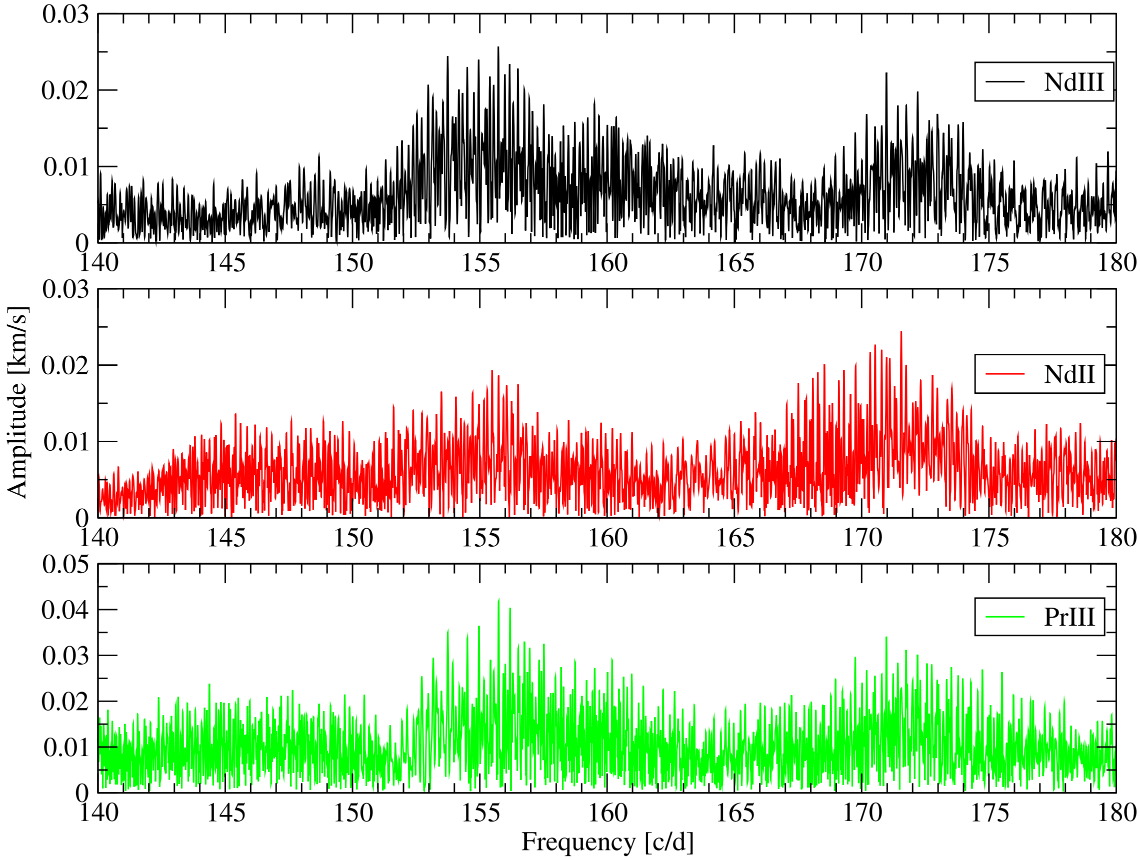

Figure 4: Fourier Transforms for the three RV data sets after pre-whitening with f_1 and f_2.

total. They also suggested short life times of pulsation modes because different frequencies appeared in their analysis of individual nights. Based on the continuous 19 day data, obtained by the Canadian mini–satellite MOST (Gruberbauer et al., 2008) 7 frequencies were identified including a new one, $f_2 = 1.365411\,\mu$Hz, which is very close to the known frequency $f_1 = 1.364594\,\mu$Hz. This discovery explained the puzzling amplitude modulation in γ Equ as a beating of two closely spaced frequencies. Analysing these MOST photometric data and the spectroscopic data, obtained a year before with the NES spectrometer at the SAO RAS 6–m BTA telescope, Sachkov et al. (2008b) concluded that in γ Equ the excited frequencies are stable on the time scale of several years because the common photometric/RV solution reproduces the amplitude modulation seen in the light and RV curves.

As it was first noted by Kochukhov & Ryabchikova (2001) for α Cir, the time–resolved spectroscopic observations of roAp stars seemed to indicate that the pulsation amplitudes of REE lines can be modulated on a time–scale of a few hours. This was later observed by Kurtz et al. (2006) for a few other roAp stars. Since in many cases this modulation cannot be linked to the known photometric pulsation frequencies, Kurtz et al. (2006) suggested that such an amplitude modulation in spectroscopy means the discovery of a new type of a pulsational behaviour in the upper atmospheres of roAp stars. They proposed three possible explanations for the newly discovered frequencies: (1) there exist modes with nodes near the level, where the photometry samples that can be easily detected at the higher level of the Pr III lines formation; or (2) there are higher–degree, l, non–radial oblique pulsation modes that are detectable in the spectroscopy because the Pr III is concentrated towards the magnetic poles, where such modes have their highest amplitudes, but averaged out over the visible hemisphere in the photometry which samples the star's surface more uniformly; or (3) there is a significant growth and decay of the principal mode amplitudes on a

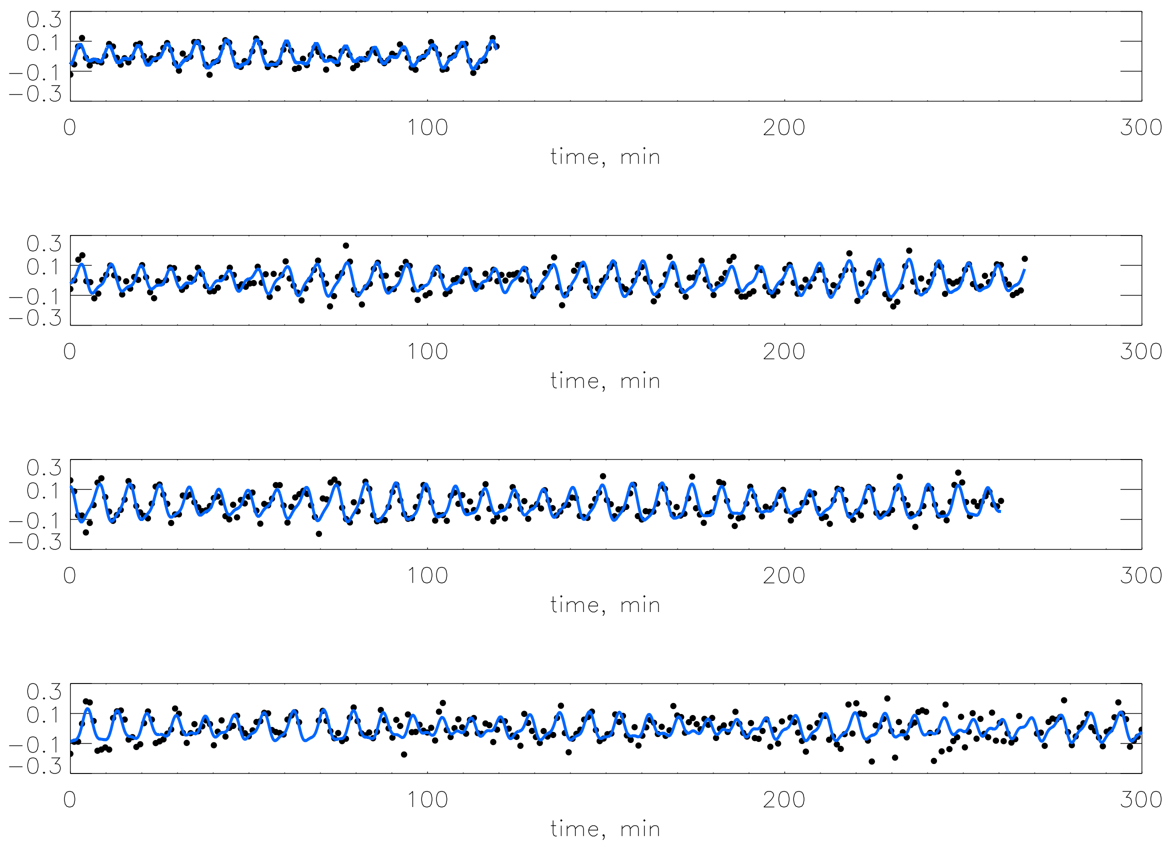

Figure 5: RV curves for the Nd III lines for the UVES (top) and ESPaDOnS data sets.

time–scale of just a few pulsation cycles at the high level of formation of the Pr III lines and the core of the Hα line. Sachkov et al. (2008a) concluded that short observational data sets (typically 2–h long) do not allow to resolve the frequency spectrum of multiperiodic roAp stars.

In HD 137949, the frequency solution based on our extensive 2009 data perfectly fits the UVES data obtained five years earlier (see Fig. 5). This fact allows us to conclude that the modes in the star HD 137949 are stable over the time scale of at least 5 years.

At the same time, the complex pulsational behaviour of the roAp star HD 137949, where different lines show a different set of frequencies, probing different layers of the stratified stellar atmosphere can be explained using the ideas by Kurtz et al. (2006).

7 Pulsations Across the 33 Lib Atmosphere

We performed a pulsation analysis of HD 137949 using the phase–amplitude diagrams (Fig. 6). Pulsation properties of this star are of considerable interest because together with 10 Aql these are the only roAp stars with clear signatures of a radial node in the upper atmosphere.

8 Discussions

As in many other recent studies of RV variations in roAp stars, one can interpret the measurements of RV amplitude and phase in terms of the outward propagation of pulsation waves in a chemically–stratified stellar atmosphere. The time–resolved spectroscopic observations acquired during several

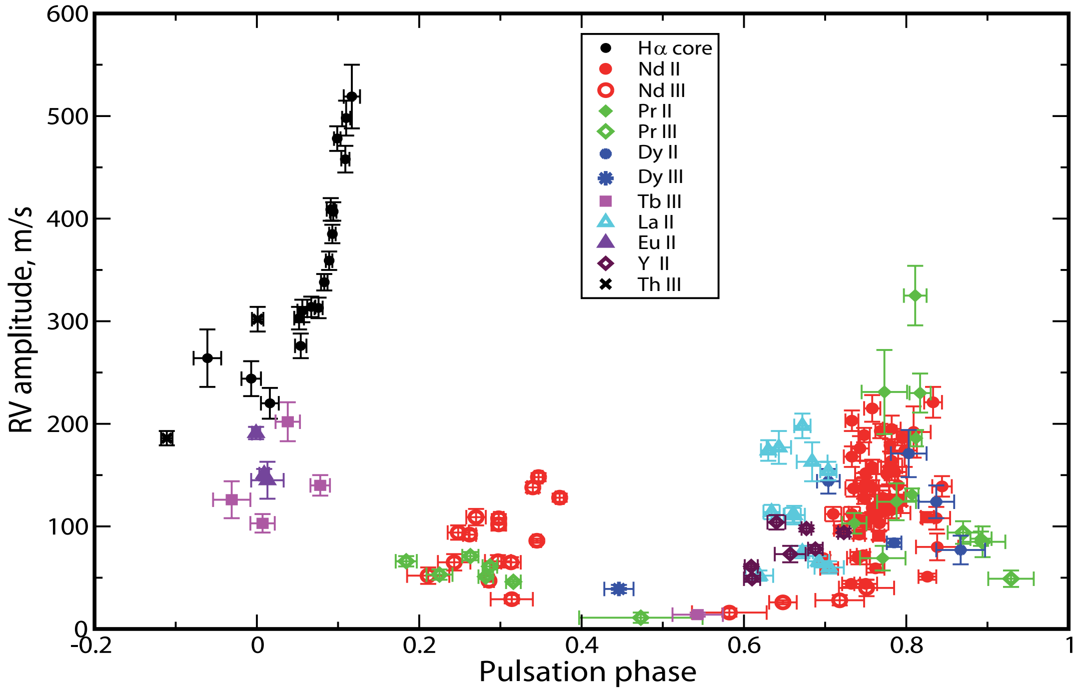

Figure 6: Amplitude–phase diagram for HD 137949. The phases are given as fractional pulsation period.

nights with a continuous photometric monitoring by the MOST at the same time allow us to directly derive the phase lag between the photometric and spectroscopic pulsational variations, which provide useful constraints for the subsequent modelling of oscillations. A comparison of the pulsation properties of HD 137949 and 10 Aql is of considerable interest because these are the only roAp stars with clear signatures of a radial node in the upper atmosphere that may be interpreted as a superposition of standing and running pulsation waves, mimicking an inwardly propagating wave, as discussed by Sousa & Cunha (2008). A detailed study of the chemical stratification and atmospheric structure of both stars is required for a secure interpretation of pulsation results and the subsequent theoretical modelling.

A strong sensitivity of the RV pulsation amplitude with atmospheric height is typical for roAp stars. As it was mentioned above, the roAp star HD 137949 shows a unique pulsation behaviour when different sets of frequencies are derived from the lines of different ions. Understanding that different lines probe different layers of the chemically stratified roAp atmosphere, and suggesting that a different mode can arise at (or can rich) a different height in such an atmosphere, one can explain the fact that different ion lines yield different pulsation frequencies. This is an analogue of explanation of the frequency analysis differences of the spectroscopic and photometric observations by Kurtz et al. (2006).

The original motivation of the simultaneous MOST and spectroscopic observations was to take an advantage of the accurate photometric frequency information in the analysis of spectroscopic data. Note that the high amplitudes of RV variations potentially allow to obtain mode frequencies even for rather short spectroscopic data strings, but with the penalty of an aliasing problem for such data sets with a poor duty cycle. A a high duty cycle, on the other hand, there is the strength of the continuous MOST data, but which, on the other hand, suffer of very small photometric amplitudes for more complex modes. A new frequency $170.9788\,\mathrm{d}^{-1}$ was detected in our spectroscopic data for HD 137949. Additional spectroscopic frequencies could offer a new view on the large frequency separation $\Delta\nu$, a crucial factor for asteroseismology, which is directly connected to the mean density in the star and describes the separation of consecutive radial overtones for the high–order acoustic pulsation.

The fact that the frequency solution, derived from our extensive 2009 spectroscopic data perfectly fits the UVES data, obtained in 2004 allows us to use the more precise UVES data together with the (non simultaneous) MOST photometric data for modelling. We also conclude that the modes in the star HD 137949 are stable on the time scale of at least a few years.

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