roAp STARS AS OBJECTS FOR ASTEROSEISMOLOGY

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ABSTRACT. To date the rapidly oscillating Ap (roAp) stars are one of the best-studied objects of the Main Sequence. There are reviewed the recent results for HD 99563 and γ Equ as examples of stars with stable and unstable oscillations. HD 99563 for its turn compared with the well-studied HR 3831. There are shown how the data obtained in multi-longitudinal photometric campaigns using small apertures' telescopes and the data of time-resolved spectroscopy from large telescopes, even the VLT (Very Large Telescope), supplement each other promoting the high specification of the atmospheric and fundamental stellar parameters, of the magnetic fields' geometries and evolutionary state. There are described the difficulties and recent results of roAp stars' searching in the northern hemisphere and, particularly, the data from the Mt. Dushak-Erekdag survey of Odessa Astronomical Observatory.

Key words: Stars: Chemically peculiar - stars: Oscillations - stars: Variables - stars: individual: γ Equ, HD 99563, HR 3831.

1. Introduction

This rare type of pulsating peculiar A stars was discovered by Donald Waine Kurtz in 1978 in the South-African Observatory. The history of its discovery and investigations (Kurtz,1990, Kurtz& Martinez, 2000) is one of the best samples of a "good study" of small, but extremely important for astroseismology group of stars.

The roAp stars lie within the δ Scuti instability strip and exhibit high-overtone non-radial p-mode pulsations in contrast to low-overtone modes which characterize typical variables of the strip. Such a way, the roAp stars have considerably smaller periods, for today are known from 5.65 to 21.0 min and ampitudes of an order of mmag. Most of the stars are multiperiodical, and that is the main concern of asteroseismology. Another important thing these chemically peculiar cool A and early F stars evolutionary are close to the Sun at the Main Sequence.

The features of this group of Ap stars:

- belong to the mostly cool ($T_{eff} \sim 7400°K$) SrCrEu group of the chemically peculiar A-F IV-V stars;
- are slow rotators, vsini $\leq$ 100 km/sec;
- have strong magnetic fields with variation from some days to decades;
- magnetic fields cause that abundance anomalies are accumulated in spots on the stellar surface.

The last attribute appears in the modulation of the mean apparent brightness of the star with the rotation period. Stibbs (1950) produced the oblique rotator model suggesting that the axis of dipol magnetic field is not aligned with the stellar rotation axis. Kurtz (1982) developed this model for oscillating Ap stars, so called the oblique pulsator model (OPM) with the assumption that the pulsation axis coincides with the magnetic axis of the star. The OPM suggests that for a rotating star dipole ($l=1$) pulsation modes will be split into equally spaced triplets, quadrupole ($l=2$) modes will be split to equally spaced quintuplets, and the frequency differencies are exactly the rotation frequency.

Further Dziembowski & Goode (1985) expanded the OPM for the presence of magnetic field which affects the pulsations that observationally bring the additional multiplet components surrounding the first-order frequency configuration. Developing of these models and the possibility checking the models with high accuracy (see Kurtz, 1992) shows roAp stars as ideal laboratories for application of the theory of asteroseismology. Such a way, the seaches for and comprehensive investigations of these stars consider a specially actual matter.

2. Searching for roAp stars in the Northern hemisphere observatories

Up to date the list of roAp stars comprises 34 objects, and about 80 % of the stars were discovered in South-African Observatory (see Kurtz, 1990; Martinez et al., 1991; Martinez & Kurtz, 1994a, 1994b). Probably, that is one of the reasons of a mysterious disproportion in the number of known roAp stars in the two hemispheres of the sky. Until 1998 only two roAp stars with positive declination were discovered although several surveys were aimed for searches of especially northern roAp stars (Mattews & Wehlau 1985, Heller & Kramer 1988, Nelson & Kreidl 1993).

Afterwards some new substantial projects were initiated:

- Handler & Paunzen (1999) in a frame of the Vienna survey examined for rapid oscillations 17 objects, with twin 0.75 m APT in Arizona, and 0.9 m and 2.1 m telescopes at McDonald Observatory, discovered 1 northern roAp star (HD122970) and 3 δ Scuti variables.
- The Naini Tal, Indo-SA (South-african) survey has been initiated by using the 1-m telescope at Naini Tal Observatory (Ashoka et al. 2000) There were investigated more than 150 candidates, discovered 1 northern roAp star (HD12098), two Ap stars were suspected for the rapid oscillations and 3 δ Scuti variables (see Joshi, 2005, Girish, 2005).
- The UBC-OAN Survey (Canada & México) monitored about 50 cool A-Fp stars with a single-channel photoelectric photometer and a Johnson B filter, attached to 84-cm and 1.5-m telescopes at the Observatorio Astronomico Nacional (OAN) in Mexico.

After all efforts the list of roAp stars with positive declination run up to 4.

Actually, the detection of roAp stars in the Northern hemisphere seems a stubborn problem. The reason, possibly, is that the Northern hemisphere's atmospheric transparency is distorted by an influence of so-called "a human factor", it is much more polluted with products of a human vital activity, than an atmosphere of Southern hemisphere.

3. Latter results on field stars from the Mt. Dushak-Erekdag Survey

We continued the observations for Mt. Dushak-Erekdag Survey which was initiated in 1993. The search scheme and the first results have been presented with details in Dorokhova (1997).

Table 1 lists for all observed field stars HD numbers, visual magnitudes, spectral types from HD Catalogue and spectral types from Catalogue of Am and Ap stars (Renson, 1991), observational interval in hour (for HD 217401 for 2 nights, BD 8087 for 4 nights), mean deviation σ for high-frequency region in mmag. The bottom part of the table under the line presents the observations of 2001-2003 years.

Since we could use only the short fragments of observational time we have developed the methods of clearing data which were obtained under a non-ideal atmospheric transparency. A low-frequency atmospheric and instrument trends of the data were removed with using Butterworth's filters of the different degrees and cutoff frequencies (Dorokhova & Dorokhov, 2005).

A rectangle filters were applied to comparison stars' data for smoothing. The programs PERIOD (Breger 1990), FOUR (Andronov 1994) and Period98 (Sperl 1998) were used for the frequency analysis.

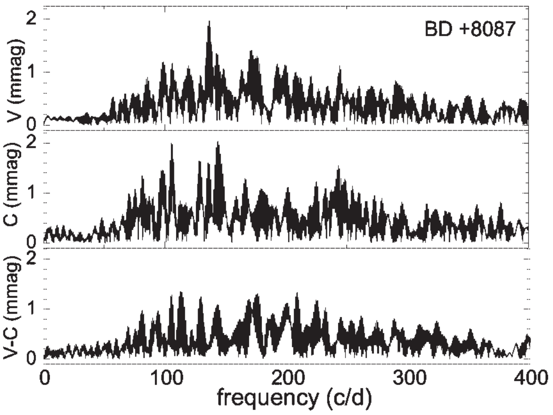

Figure 1: Fourier spectra of BD +8087 (upper), comparison star (middle) and differences var-comp (bottom).

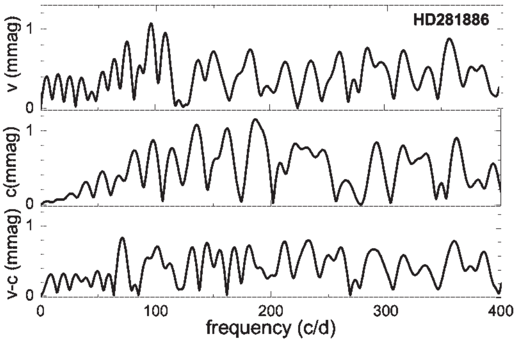

Figure 2: Fourier spectra of HD281886 (upper), comparison star (middle) and differences var-comp (bottom).

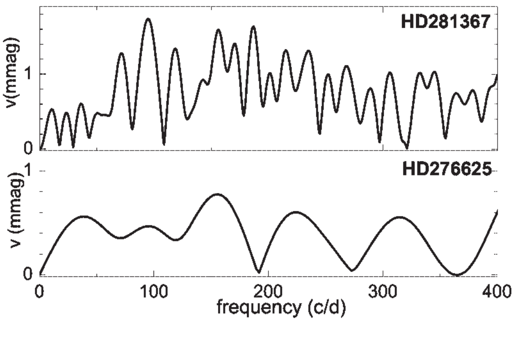

Figure 3: Fourier spectra of HD281367 and HD276625.

Table 1: List of field Ap stars tested for the rapid oscillations.

Star	m_v	Sp	Sp (Rn)	Δ T	σ
HD15257	5.4	F0		6.0	0.9
HD17317	8.3	A5p		1.1	6.5
HD99563	8.2	F0	F0 Sr	2.0	1.6
HD115606	8.3	A2	A2 Sr	4.0	1.1
HD217401	8.0	A2p	A2 Sr	7.2	1.2
HD276625	10.0	A7	A7 CrEu	1.5	1.0
HD281367	10.0	A7	A8 SrEu	2.2	1.6
HD281886	8.9	F0p	F0 Sr	2.5	1.0
BD+8087	9.6	Ap	F0 SrEu	15.5	2.8

We concentrated our efforts on researches of the northernmost star BD+8087 (Fig.1). In a single non-ideal photometric night of 2001 the target revealed oscillations with period about 11 min and amplitude of 7 mmag. In the data of 2003 once more the peak at 136 c/d was detected, however, the comparison star data showed the peak at 142 c/d. Nevertheless, rather large standard deviations of about 3 mmag indicate the possible rapid variability.

HD281886 was observed simultaneously with the comparison star in the channel 2. The Fourier spectra at the Fig.2 show the absence of rapid variability within the detection limits of 0.8 mmag. HD281367 and HD276625 (Fig.3) are less investigated, and we suggest to continue testing them for rapid oscillations.

4. NGC752

The attempts testing cluster stars for the presence of rapid oscillations were undertaken earlier (e.g. Matthews et al. 1988), however, so far none roAp stars were revealed in cluster.

NGC 752 provides an ideal test of a variety of evolutionary phenomena and it seems a very suitable due to plenty of early F type stars. This intermediate-age, estimations from 1.7 ± 0.1 Gyr to 1.9 ± 0.2 Gyr, open cluster for which full suite of comprehensive investigations has been performed (see, for example, Daniel et al. 1994). There were also some efforts hunting for variable stars, especially, for variable blue strugglers in the cluster (Milone &Latham 1994).

However, a test for the presense of roAp stars in this cluster was never carried out, possibly, considering its metal-poor nature although estimates of Fe/H are rather different: -0.09 (Hobbs & Thorburn 1992), -0.15 (Daniel et al.1994). -0.27 (Dinescu et al. 1995).

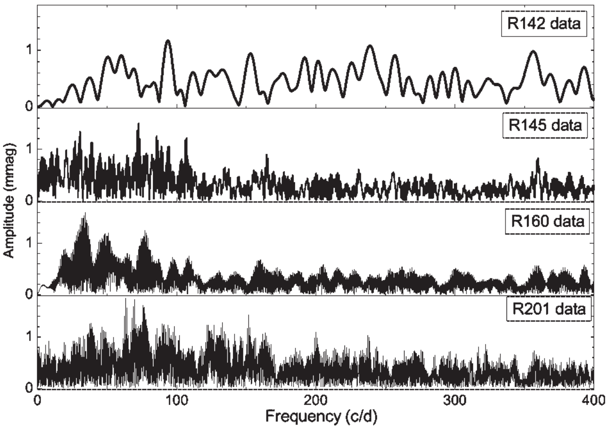

Figure 4: Fourier spectra of NGC 752 objects, the numbers in the right corners according to Rebeirot (1970).

Table 2: List of stars tested for the rapid oscillations in NGC 752.

No K	No H	No R	BD	mg	Sp
47	171	142	+36 363	10.6	F2V
56	193	145	+36 365	10.4	F0III
59	205	160	+37 431	10.5	F2III
81	263	201		11.1	F3

The list of stars tested for the rapid oscillations in NGC 752 presented in Table 2: in the columns 1, 2, 3, 4 the numbers of investigated stars are indicated according to lists of K - Kazanasmas et al. (1981), H - Heinemann (1926), R - Rebeirot (1970) and BD catalogue; the columns 5 and 6 show photographic magnitudes and spectral type.

According Niedzielski & Muciek (1988) and Renson (1989) all selected stars are peculiar, however, its Strömgren indices from Catalogue by Hauck & Mermilliod (1990) do not fall within the margins indicated for roAp stars by Martinez, Kurtz & Kauffmann (1991).

The results of these observations:

- R142 is a constant within limits of 1 mmag;
- R143 frequency spectrum have showed some very low amplitudes and not stable from night to night peaks, apparently, being attributed to atmospheric transparency;
- in the data of R160 possible the presence of pulsations of 34 and 77 c/d but very low amplitudes and not stable from night to night;
- the frequency spectrum of R201 shows some peaks in the 60-75 c/d with amplitudes of 2 mmag, which are unstable from night to night and, apparently, caused by variations of atmospheric transparency.

We regret that this work was unfinished from political obstacles and hope that we continue the search of roAp stars in clusters with modern CCD techniques.

5. HD 99563 and HR 3831

A rapid variability of HD 99563 (XY Crt) was discoverd within the framework of Mt. Dushak-Erekdag Survey (Dorokhova, 1997). A year latter the periodic oscillations were confirmed by Handler & Paunzen (1999).

In 1998 Handler et al. (2002) carried out the multisite campaign for the star. 125 hours of the high speed photometry have been obtained using seven telescopes at four different longitudes' observatories. Handler et al. (2005) also acquired mean light observations for the star over four seasons. Here we explicate the recent campign results as an example of an advanced study of roAp stars.

HD 99563 classified as F0 in HD catalogue and F0 Sr in the Ap and Am stars Catalogue by Renson (1991), its Strömgren indices (Hβ = 2.830, δm_1 = 0.000 and δc_1 = -0.109) fall into a margin marked by Martinez, Kurtz and Kauffmann (1991). The star belongs to a binary system ADS 8167, B component is in a distance 1.7 arcsec and lighter on Δ V= $1.^m2$. This involves the correction of photometric amplitudes which should be increased by 30%. Handler et al. (2002) revealed 8 frequencies in the preliminary analysis which were equally separated in two group around 1.557 mHz and 3.115 mHz. Then Handler et al. (2005) ascertain position of the physical pair HD 99563 in the HR Diagram applying a complete set of the data from HIPPARCOS, Tycho-2, high resolved spectroscopy and fundamental photometry. On this base there were obtained the fundamental parameters of the components in the first approximation. From the analysis of the splitting in the frequency spectrum and mean light data they determined the rotation period of HD 99563A with accuracy of ±6 sec.

Assuming that HD 99563A pulsates with a single pulsation mode 1.557653 mHz and some first harmonics of it Handler et al. (2005) consider an equally spaced frequency triplet appears due to the rotation of the star. The additional components from quintuplet appear due to the distorting effect of magnetic field of the star. Then for HD 99563A the distortion of the pulsation modes has been modeled and the all parameters of the star were obtained and corrected. This complete set of the accurate parameters for both stars of HD 99563 binary we collected in the Table 4. With these model parameters Handler et al. (2005) perfectly reproduced the observed pulsational amplitudes and phases over the stellar rotation cycle. The fig.6 from Handler et al. (2005) is very similar to the inverse problem solutions which were obtained a decade before by Kurtz, Kanaan, Martinez (1993) for another roAp star HR 3831.

HR 3831 (HD 83368) is one of the best-studied roAp star, even so called prototype (see Kochukhov, 2004), and it is also a wide binary. In HR 3831 the separation between the components is 3.29 arcsec and difference in brightness is ΔV= 2.84.

Now after the work of Hundler et al. (2005) it is possible comparing HD 99563 and HR 3831 fundamental data (see the Table 3). The data in table 3 are mainly extracted from Hundler et al. (2005) for HD 99563 and from Kurtz, Kanaan, Martinez (1993) for HR 3831. The measurements of the mean magnetic field of HD 99563 are taken from Hubrig et al. (2004).

Both objects are remarkably similar but HD 99563 is more massive and, accordingly, more evolved system. If for HR 3831 there were carried out some multisite campaigns for consecutive years whereas HD 99563 is recently started for investigations.

Elkin, Kurtz & Mathys (2005) discovered from the series of 110 time-resolved spectra of HD 99563 the most extreme example of pulsational radial velocity variations with semi-amplitudes of up 5 kms^{-1} for some EuII and TmII lines. Such high amplitudes could yield the information on the structure of the Ap star's atmosphere with the best possible signal to noise. This factor and the favourable geometry of the star which allows seeing both pulsation poles during the small rotation period gives an opportunity to obtain the Doppler imaging (DI) of its surface.

In the recent work by Kochukhov (2004) the precise velocity map was recovered for HR 3831 with the DI techniques and it permits testing the theoretical speculations with the high accuracy. Kochukhov (2004) discovered that pulsations of the star are strongly confined to the magnetic field axis, that specifies the dominant role of a magnetic field in forming of pulsations' geometry completely according to predictions of Saio & Gautschy (2004) calculations.

These two stars are examples of typical roAp stars for which the stable pulsations during decades or, at least, years are proper. However, there exist a few of roAp stars which have very unstable frequencies and amplitudes of pulsations, for example, the well-known γ Equ.

6. γ Equ

γ Equ (HD 201601, V=$4^m.71$, F0p) - one of the brightest and, accordingly, the most investigated roAp stars. Babcock (1958) has discovered the Zeeman effect splitting lines in the star's spectrum with testified to a significant magnetic field. Intensity of a field slowly changed from 500 Gs in 1950s, passing through zero in early 1970s [74], and achieving -1000 Gs in 1988 (Mathys, 1991). Bonsack & Pilachowski (1974) have assumed, that the magnetic field of a star varies with the period 72 years.

Table 3: Fundamental data and parameters for components of HD 99563 and HR 3831 systems.

Parameter	HD 99563A	HR 3831A
Spectral type	F0p Sr	A7p V SrCrEu
Frequency	1.557653 mHz (P= 10.7 min)	1.4280128 mHz (P = 11.7 min)
Johnson's indices	V = 8.72, B-V = 0.20	V = 6.168, B-V = 0.25
Rotation period	2.91179 d	2.851982 d
Absolute magnitude M_v	1.9	2.0
T_{eff}	$\sim 8000°K$	$\sim 8000°K$
$vsini$	$28.5 \pm 1.1 kms^{-1}$	$33 \pm 3kms^{-1}$
Radius	$\sim$2.38 $R_\odot$	$\sim$1.9 $R_\odot$
Mass	$\sim$2.03 $M_\odot$	$\sim$ 2 $M_\odot$
Rotational inclination i	43.6 ±2.1°	70°
Magnetic obliquity β	86.4±0.3°	70°
Magnetic field	-688 Gs< B_{eff} <+ 580 Gs	-720 Gs< B_{eff} <+ 780 Gs
Age	620 Myr	1000 Myr
	HD 99563B	HR 3831B
Spectral type	A7V	G2V
Johnson's indices	V = 9.91, B-V=0.285	V=9.09, B-V=0.64
Absolute magnitude	M_v 3.1	M_{bol} 5.0
T_{eff}	$\sim$ 7400° K	$\sim 5800°K$
Radius	$\sim$ 1.1 $R_\odot$	$\sim$ 0.9 $R_\odot$
Mass	$\sim$1.58 $M_\odot$	$\sim$1 $M_\odot$

Leroy et al. (1993) by using polarimetric measurements determined the period of change of the star's magnetic field as 77±10 years, and assumed, that it coincides with the rotation period. Such a way, γ Equ is an example of an almost non-rotating star that makes it the best candidate for applying of simplified models.

Pulsations of γ Equ with the frequency 1.339 mHz (the period of 12.5 min) and the amplitude which is not exceeded of 0.8 mmag, were discovered by Kurtz (1983). He has paid attention to modulation of the amplitude.

Then during a decade there was discussion on the pulsation activity of the star (see for example, Weiss & Shneider, 1989).

The culmination of photometric testing of γ Equ pulsations was the multisite campaign of 1992 (Martinez et al., 1996). There were revealed unambiguously 4 pulsation frequencies of magneto-acoustic modes (see table 4).

Table 4: The results of the frequency analysis of γ Equ data (from Martinez et al., 1996)

f	μHz	c/d	Period (min)	Δf (μHz)
1	1339	115.7	12.35	
2	1366	117.9	12.18	27
3	1397	120.7	11.93	31
4	1427	123.3	11.68	30

Here we dwell upon the problem of the short time scale pulsation instability of the star which was only slighly touched in Martinez et al. (1996). We involve also the photometry obtained at the Mt. Dushak-Erekdag Observatory before and after the campaign.

Fig.4 showed as far as the frequency spectrum of the star proves to be unsteady. If in JD 2448893 predominates the frequency 117.13 /d of a pretty amplitude A=0.64 mmag, then to JD 2448897 it transformed to the frequency 125.6 /d with amplitude at the noise level, A=0.29 mmag. Then the amplitudes gradually increased, however, the frequencies varied from night to night:

JD 2448898: f=117.7 /d, A=0.38 mmag;

JD 2448899: f=121.1/d, A=0.5 mmag;

JD 2448900: f=124.8 /d, A=0.53 mmag.

Fig.5 showed the enlarged part of the frequency spectrum within the interesting region. It is seen how the prominent peak at f=199.9 c/d tranformed to the peak at f=122 c/d. So far it is unknown the reason of such instability.

These solutions and questions were put with using small telescopes and simple photometric techniques. Recent investigations of γ Equ were made with analysis of high-resolution time-resolved spectral data from large telescopes, and even from VLT (Very Large Telescope). The spectroscopic study of the oscillations is very advanced due to narrow and sharp lines and, actually, the star is one of the most investigated with radial velocity measurements.

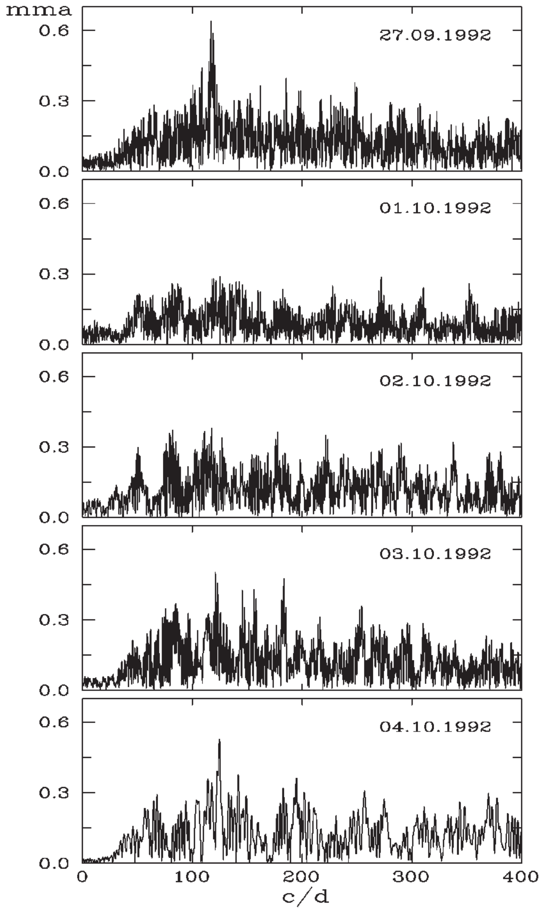

Figure 5: Fourier spectra of γ Equ for united series of data from 0.8 m telescope of the Mt. Dushak-Erekdag Observatory and 1.1 m telescope of the Lowell Observatory for the consequent nigts.

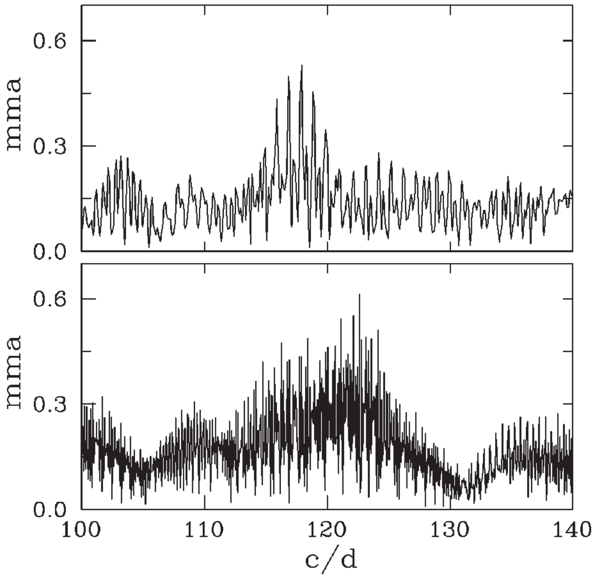

Figure 6: Fourier spectra of Strömgren v photometry of γ Equ: upper panel shows the data from JD 2448897 to JD 2448900, the most prominent peak is at the frequency 117.9 c/d; bottom panel shows the same data with adding the observations of JD 2448893 and JD 2448957, the maximal peak is at the frequency 122 c/d.

The first attempt was made by Libbrecht(1988) on observations in Fe I (6495 Å) at the Mt. Palomar 5m telescope. He reported about the detection of radial velocity variations of γ Equ with an amplitude of 42 m/s at two frequencies at 1366 μHz and 1427μHz.

Kanaan & Hatzes (1998) have considered RV variations of individual lines and showed that pulsations change visibly from one spectral line to another, however, they did not detected systematic trends or dependencies of these variations.

Further, Malanushenko, Savanov, Ryabchikova (1998) detected that the highest amplitudes of RV (radial velocity) variations are associated with the lines of NdIII and PrIII. Kochukhov &Ryabchikova (2001) analysed time-resolved line profile variations of REE (rare-earth elements, specially, PrIII and Nd III) and obtained a detailed picture of the vertical stratification of chemical elements and showed the possibility extracting the main characteristics of the pulsational modes taking into account the interaction between inhomogeneous vertical and horizontal distributions of chemical elements.

Leone& Kurtz (2003) discovered the magnetic field variations with the photometric 12.1-minute pulsation period. The origin of this phenomenon is still unclear but, possibly, it could clarify on the reasons of the intrinsic instability of γ Equ pulsations. But so far the question of exiting of magnetic variations is controversial. Kochukhov, Ryabchikova & Piskunov (2004) in the analysis of 210 high-resolution time-resolved spectropolarimetric observations find no evidence for variation of the mean longitudinal magnetic field over the pulsation period.

Returning to the γ Equ pulsations, it should be noticed their similarity to solar-like oscillations, e.g., in α Cen A & B (see Kjeldsen et al., 2005). Their mode lifetimes are about 2 d, similar to those in the Sun. Apparently, such type of pulsations is stochastically exited by turbulent motions in the uppermost part of the star's convective zone (see, for example, Samadi & Goupil, 2001).

7. Discussion

Asteroseismology as a whole and, specially of roAp stars, is evidently becoming a powerful diagnostic of stellar parameters.

By comparing the precise and thorough frequency spectrum to the modern pulsation theories, it is became a reality to specify the rotation periods, temperatures, luminosities, radii, masses of roAp stars, geometries of their magnetic fields, the vertical and gorizontal stratification of the elements in their atmospheres, the evolutionary scenarios.

Hubrig et al. (2000) detected the existence of significant kinematical differences between roAp and noAp stars, suggesting that roAp stars are older and less luminous than their non-pulsating counterparts. However, the authors noticed also that, statistically speaking, noAp stars truly represent a group where pulsations have very small amplitudes. This opinion corroborates by the theoretical point of view that pulsations are ubiquitous property of stars in general (Shibahashi, 2005).

On the other hand, Cunha (2002), developing the recent model (Balmforth et al. 2001) of pulsation mechanism in roAp stars, showed that oscillations with the periods from 15 up to 40 min are possible in Ap stars of a higher luminosity and temperature than in known roAp stars. This prediction was verified by detecting of 21 min oscillations in the radial velocities of the luminous Ap star HD 116114 (Elkin et al., 2005) by using the Ultraviolet-Visual Echelle Spectrograph at the VLT. The recent discoveries have demonstrated that radial velocity approach turn to be considerably more sensitive than traditional photometry. It becomes possible to extend swift the set of roAp stars partly from the numerous noAp stars with improving of an instrumentation and techniques.

However, at present the spectroscopy cannot supply with thorough knowledge of the stellar pulsation spectrum which could afford the multi-site photometric campaigns. Indeed, the mentioned paper by Handler at al. (2005) could give the comprehensive analysis and determine fundamental parameters and status of HD 99563 only uniting the data from the prolonged photometric campaign with the data from the VLT and prevous conclusions of time-resolved spectroscopy.

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