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Pulsation tomography of roAp atmospheres:

resolving the third dimension

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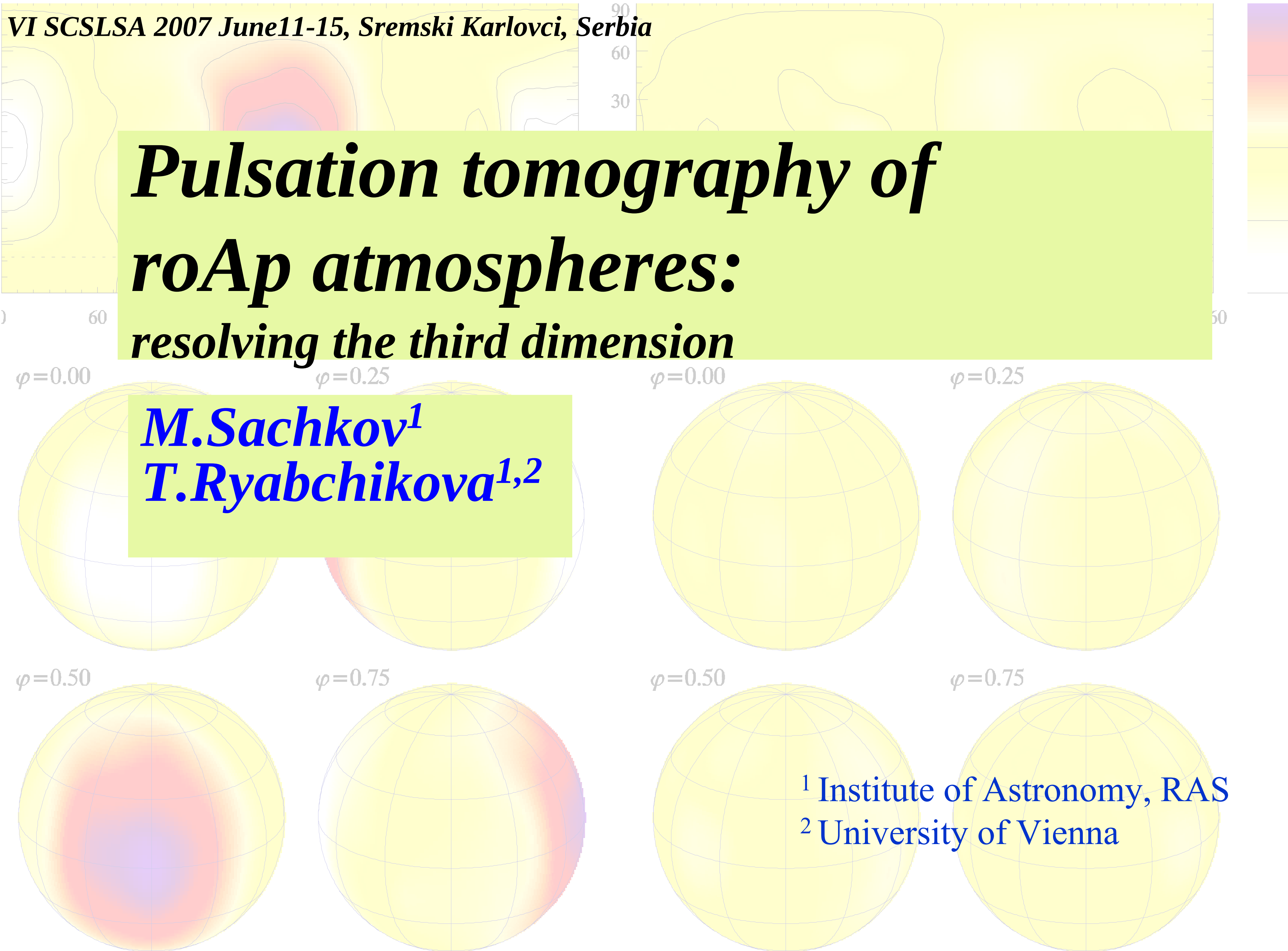
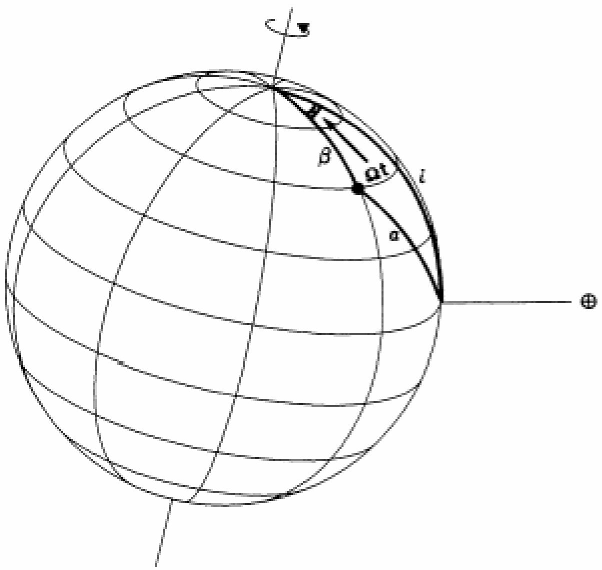


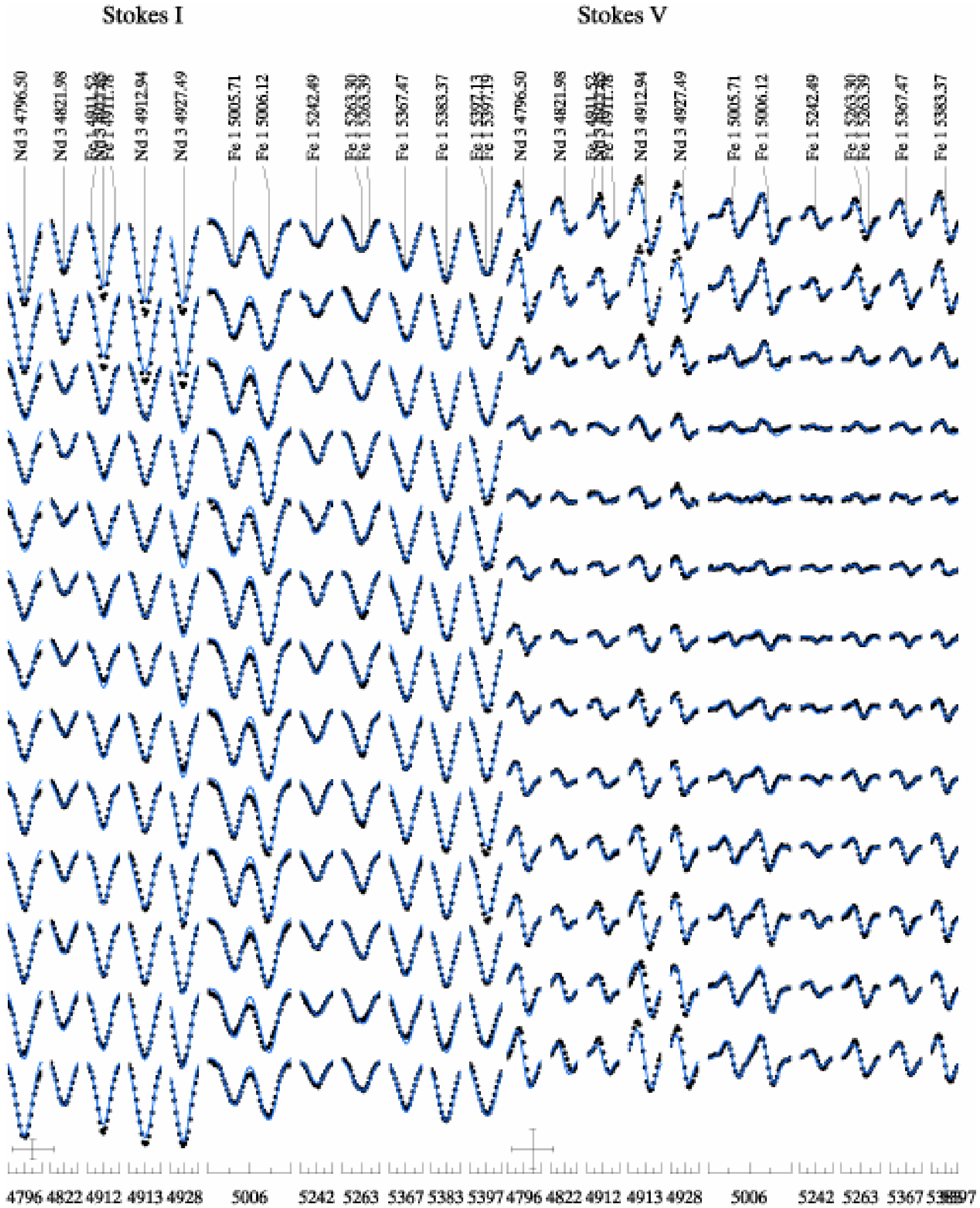
roAp stars=Rapidly oscillating chemically peculiar A stars



The magnetic chemically peculiar (Ap) stars are upper-main-sequence stars with anomaly strong lines of certain (Si, Cr, Sr, Eu) chemical elements in their spectra and strong globally organized magnetic fields.

They often show remarkable variations of line strengths, light and magnetic field with periods ranging from a few days to many years.

It is believed that this abnormal chemical composition is limited only to the outer stellar envelopes. Chemical diffusion altered by a global magnetic field can produce surface abundance non-uniformities.



5 Nd lines:

Nd III 4796

Nd III 4821

Nd III 4911

Nd III 4912

Nd III 4927

7 Fe lines:

FeI 5005

FeI 5006

FeI 5242

FeI 5263

FeI 5367

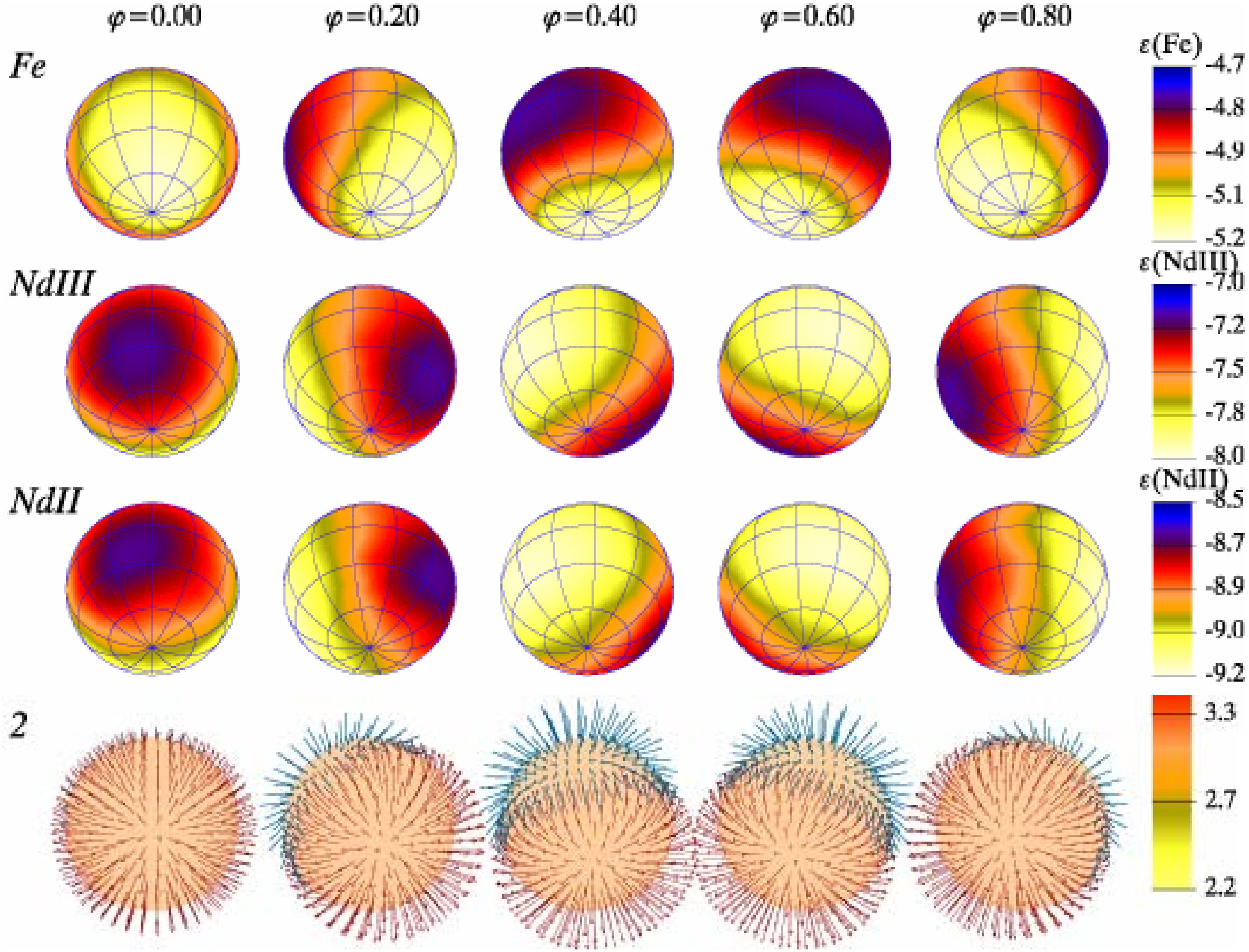
FeI 5383

FeI 5397

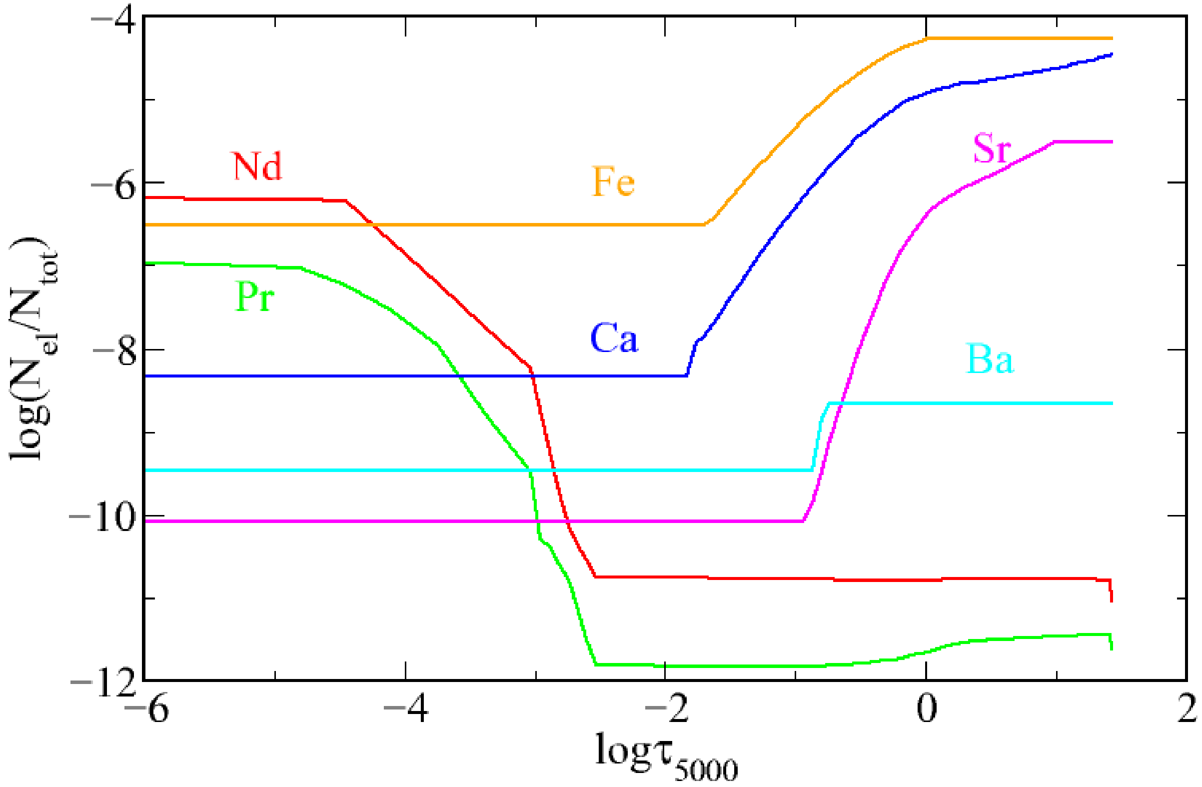
Zeeman Doppler Imaging Results

(Luftiner, Kochukhov, Ryabchikova et al.)

Fe, NdIII, NdII distribution and magnetic field geometry WITHOUT ANY a priory asumptions!!!!



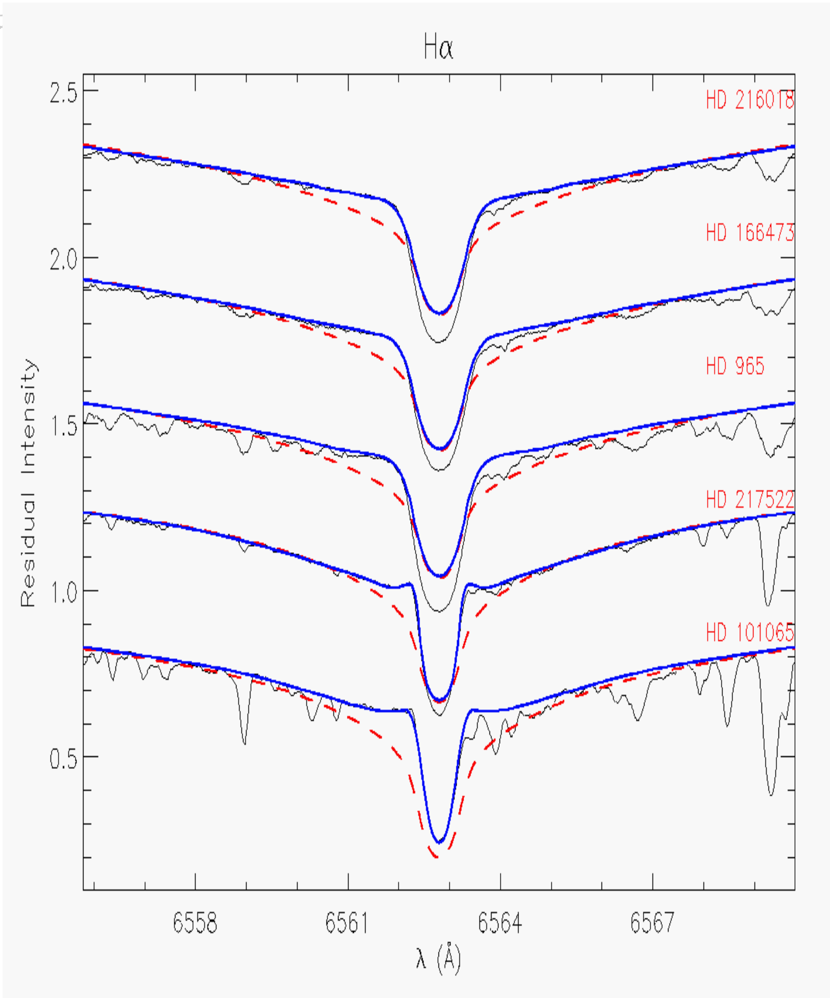
There is a number of observational features in spectroscopy and spectrophotometry which cannot be fitted with the best available chemically homogeneous atmospheric models and which require abundance stratification.



Core-wing anomaly (CWA) in the atmospheres of cool Ap stars.

(from Kochukhov et al. ApJ 578, L75, 2002)

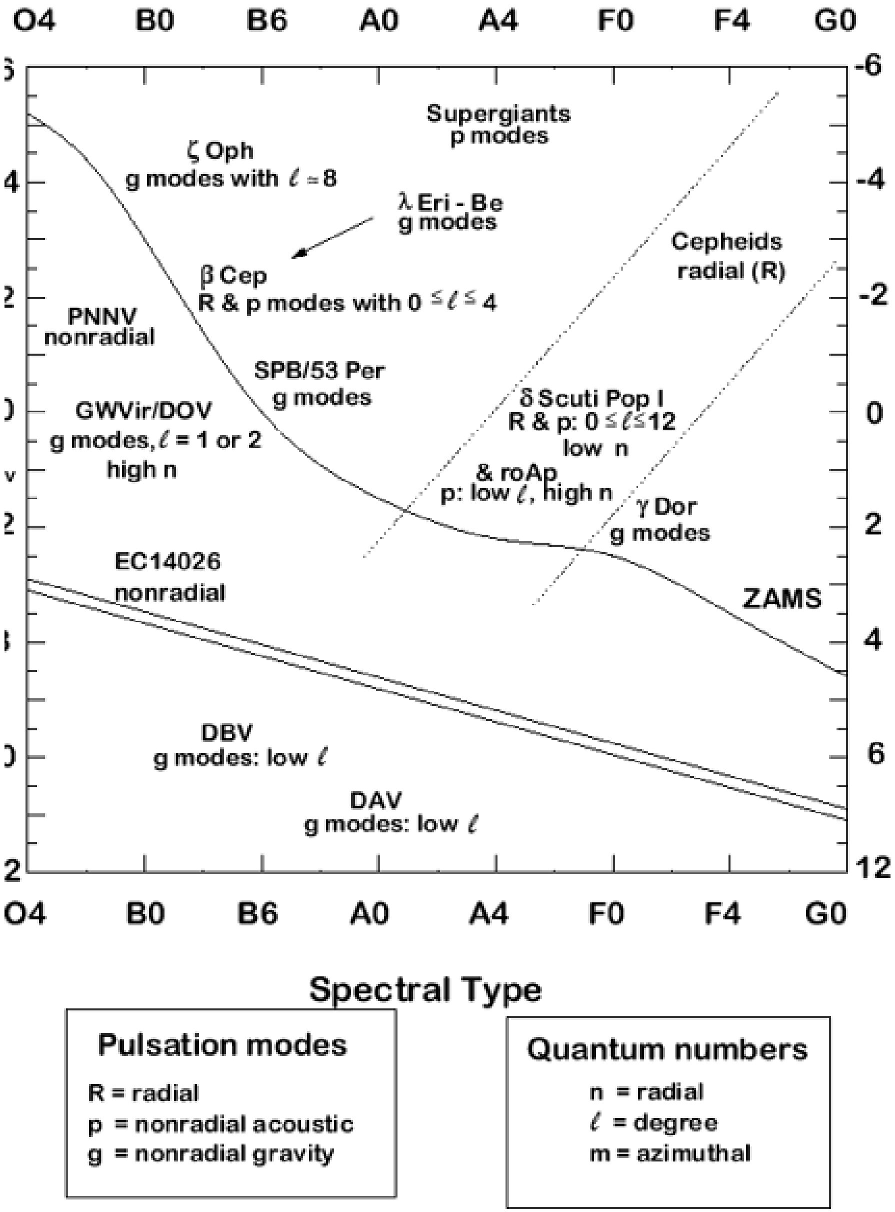
Broad wings indicative of temperatures in the range 7000-8000 K end narrow cores. The widths of these cores are compatible with those of dwarfs with temperatures 6000 K or lower



roAp stars=Rapidly oscillating chemically peculiar A stars

- Cool (Te ~ 6400-8200 K) chemically peculiar stars with a strong magnetic field (1-8 kG)
- 28 (of 32) roAp stars are on south hemisphere
- Multiperiodic non-radial puilsations with periods 5-15min
- Photometric amplitudes 0.8 – 15 mmag
- Close to the Main sequence (HIPPARCOS)

roAp stars=Rapidly oscillating chemically peculiar A stars



roAp stars as pulsators (with periods between 6min. and 20 min.), exhibiting moderate to strong magnetic fields and rotation, are ideal objects for the investigation of the interaction between magnetic field, pulsation, and atmospheric inhomogeneities like *vertical* and *horizontal* abundance distribution

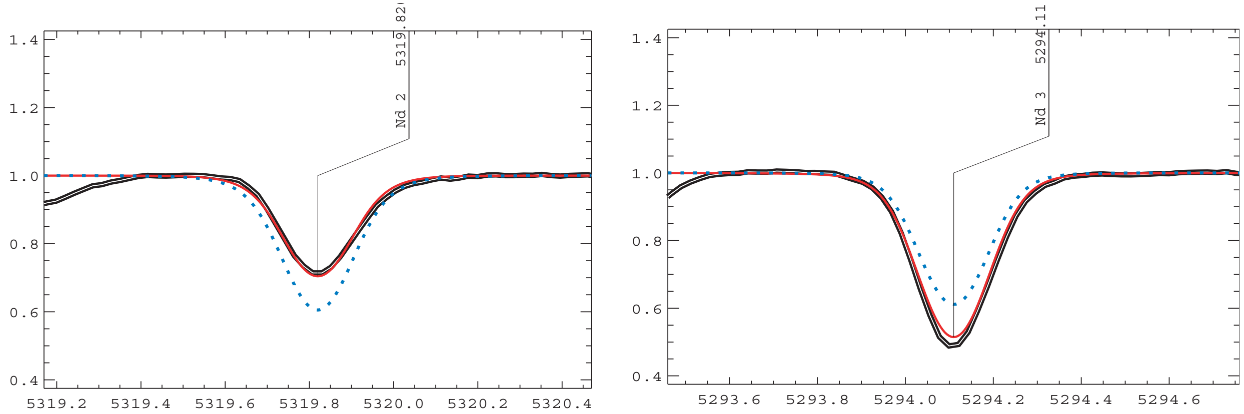
roAp/noAp co-exist in the same region of the parameter space (photometric, kinematical, abundances, magnetic field).

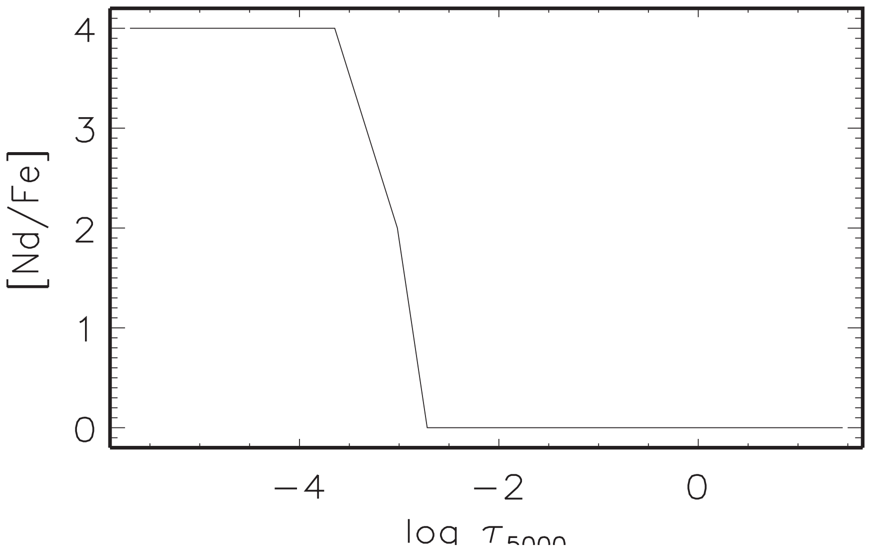
Contrary to the other pulsating variables known at that time, roAp stars are a subgroup of already "abnormal" stars.

Stratification

…….+

A difference of about 2 dex in the abundances derived from first and second ions





Stratification

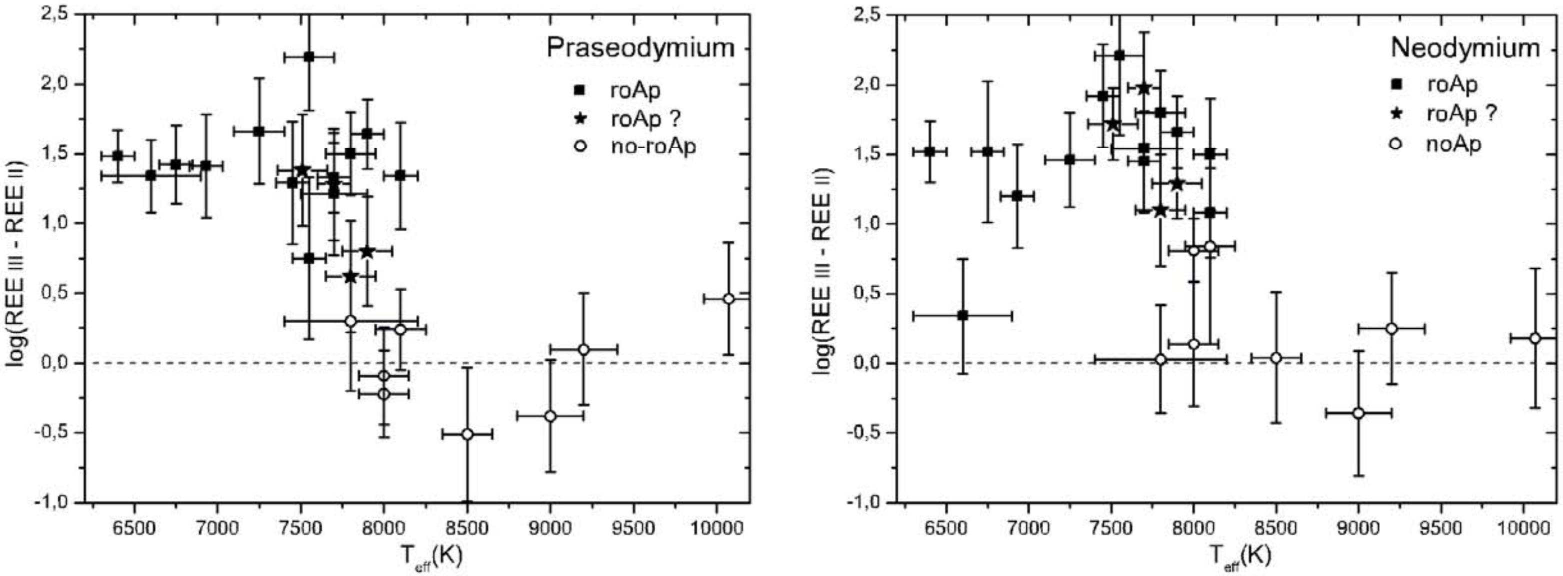


Fig. 7. Dependence of the Pr (*left panel*) and Nd (*right panel*) anomaly on temperature.

Asteroseismological potential of roAp stars

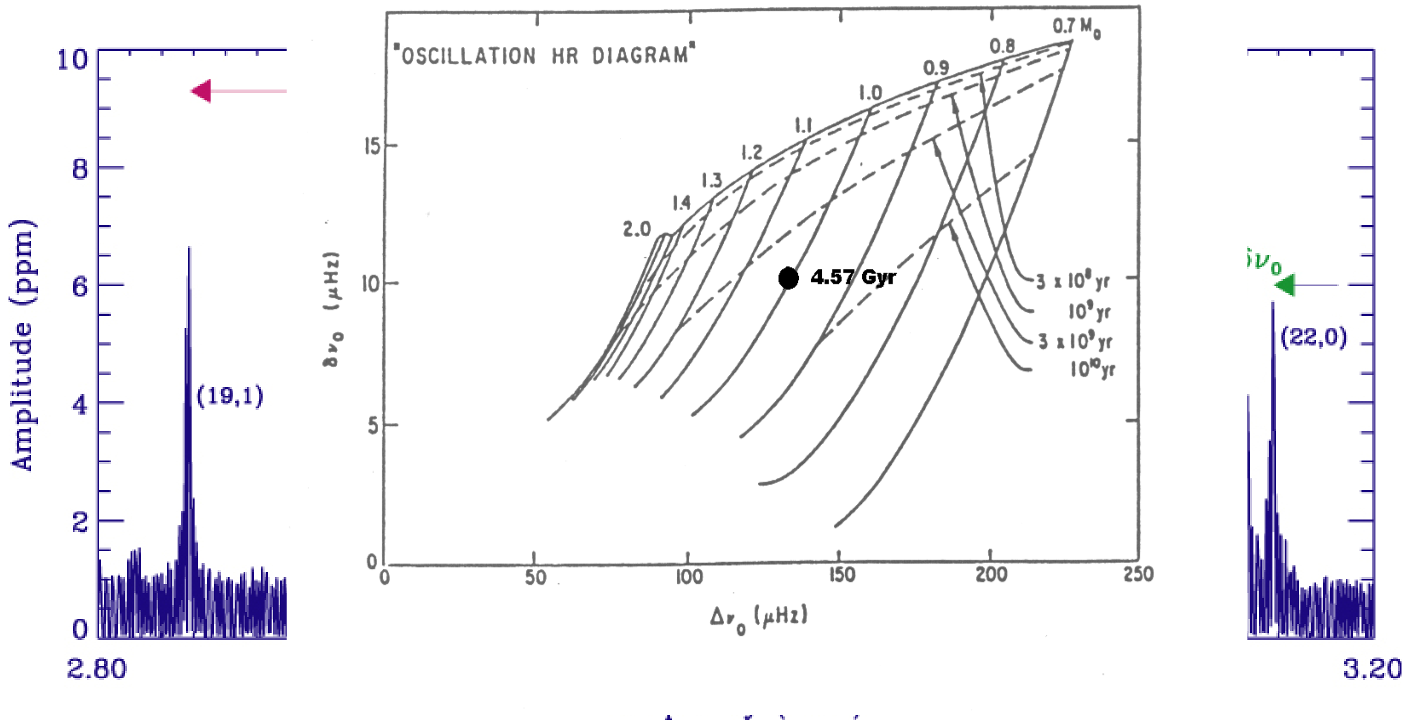
asymptotic theory of acoustic pulsations

(p-mode for $n \gg \ell$) :

$$\nu_{n\ell} \approx \Delta\nu(\boldsymbol{n}+\ell/2+\varepsilon) + \delta\nu,$$

$\Delta\nu$ – mean density indicator

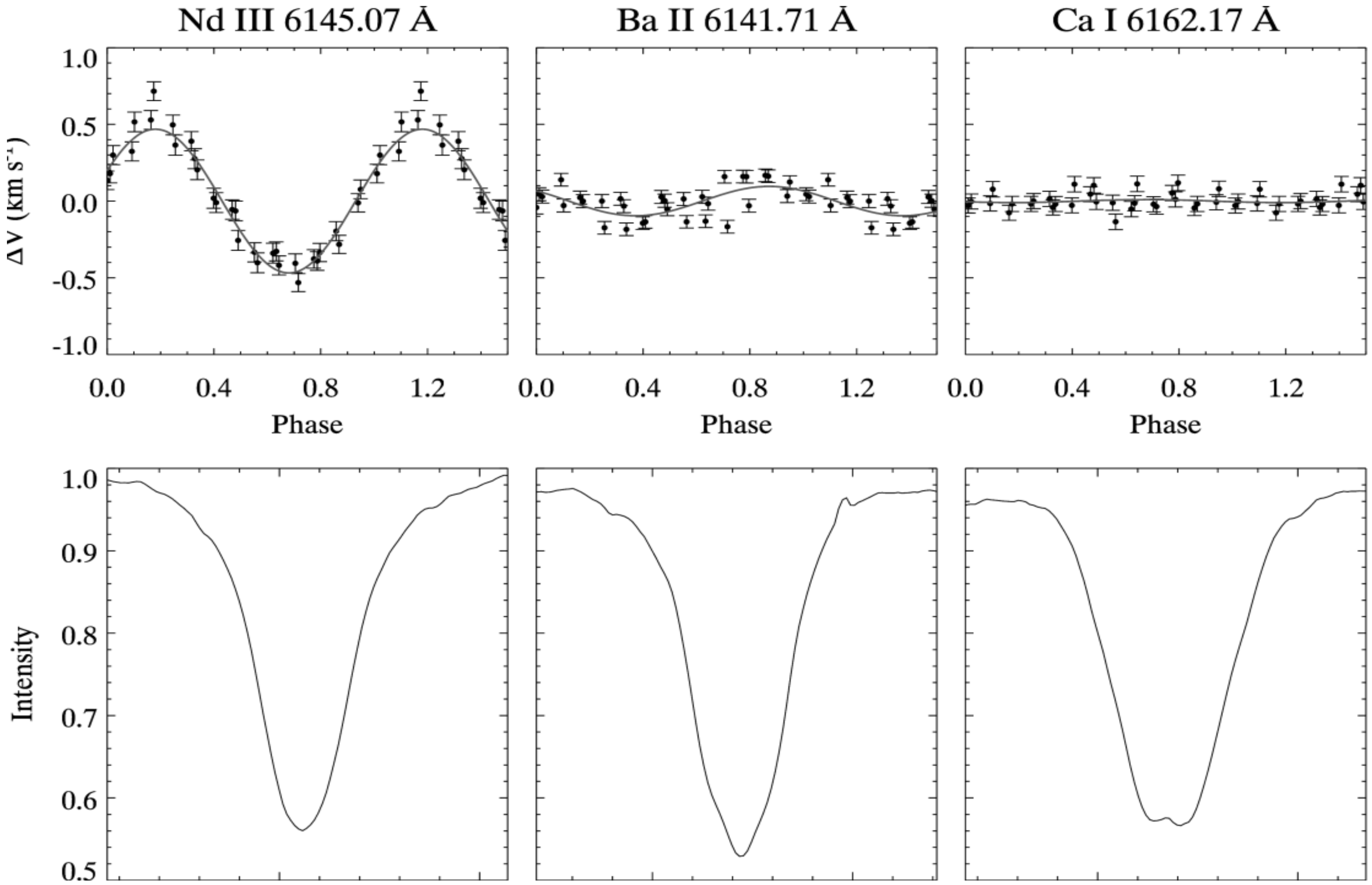
$\delta\nu$ - age indicator



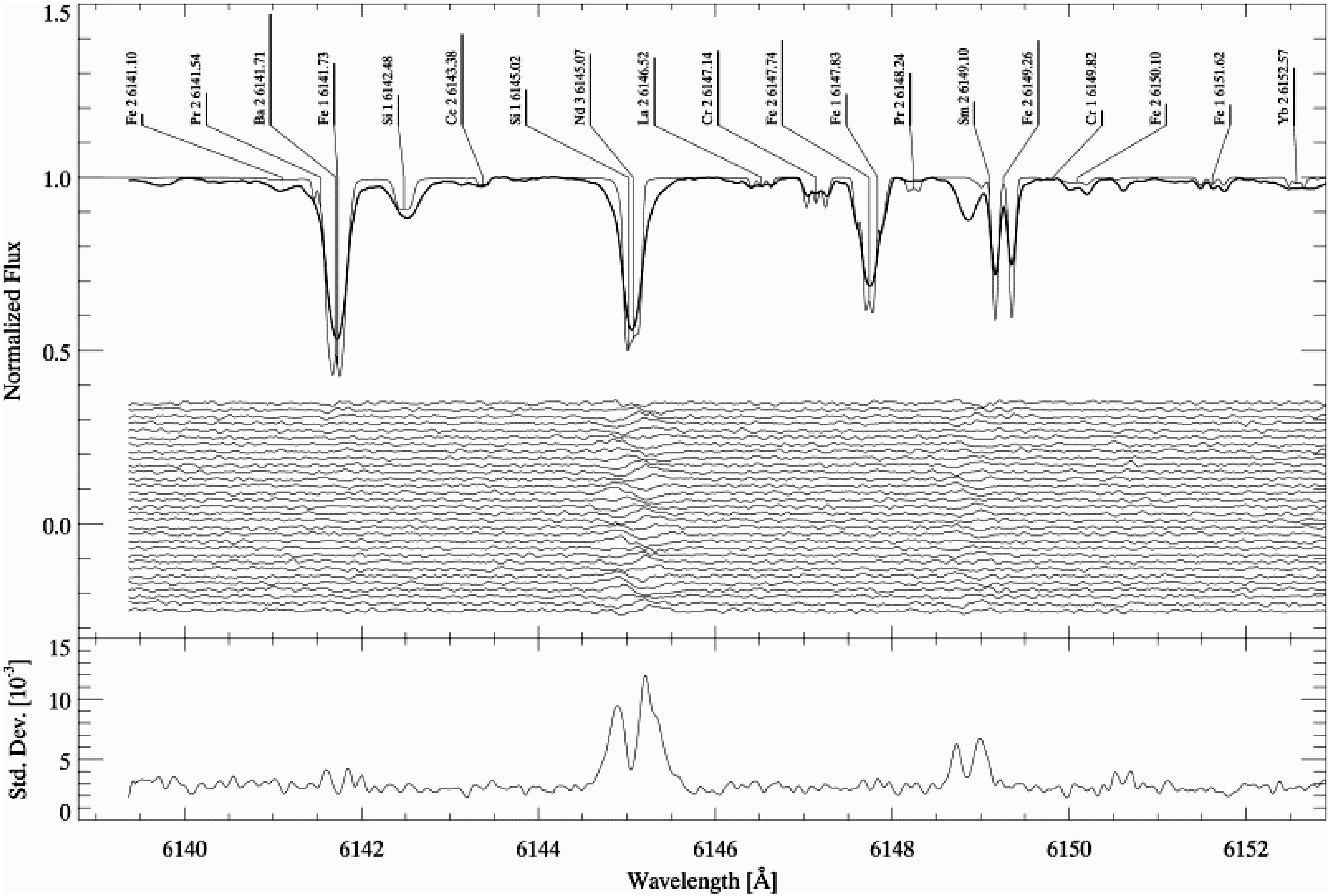
Pulsation selectivity

(Savanov, I.S., Malanushenko, V.P., & Ryabchikova, T.A. 1999, Astron. Lett., 25, 802)

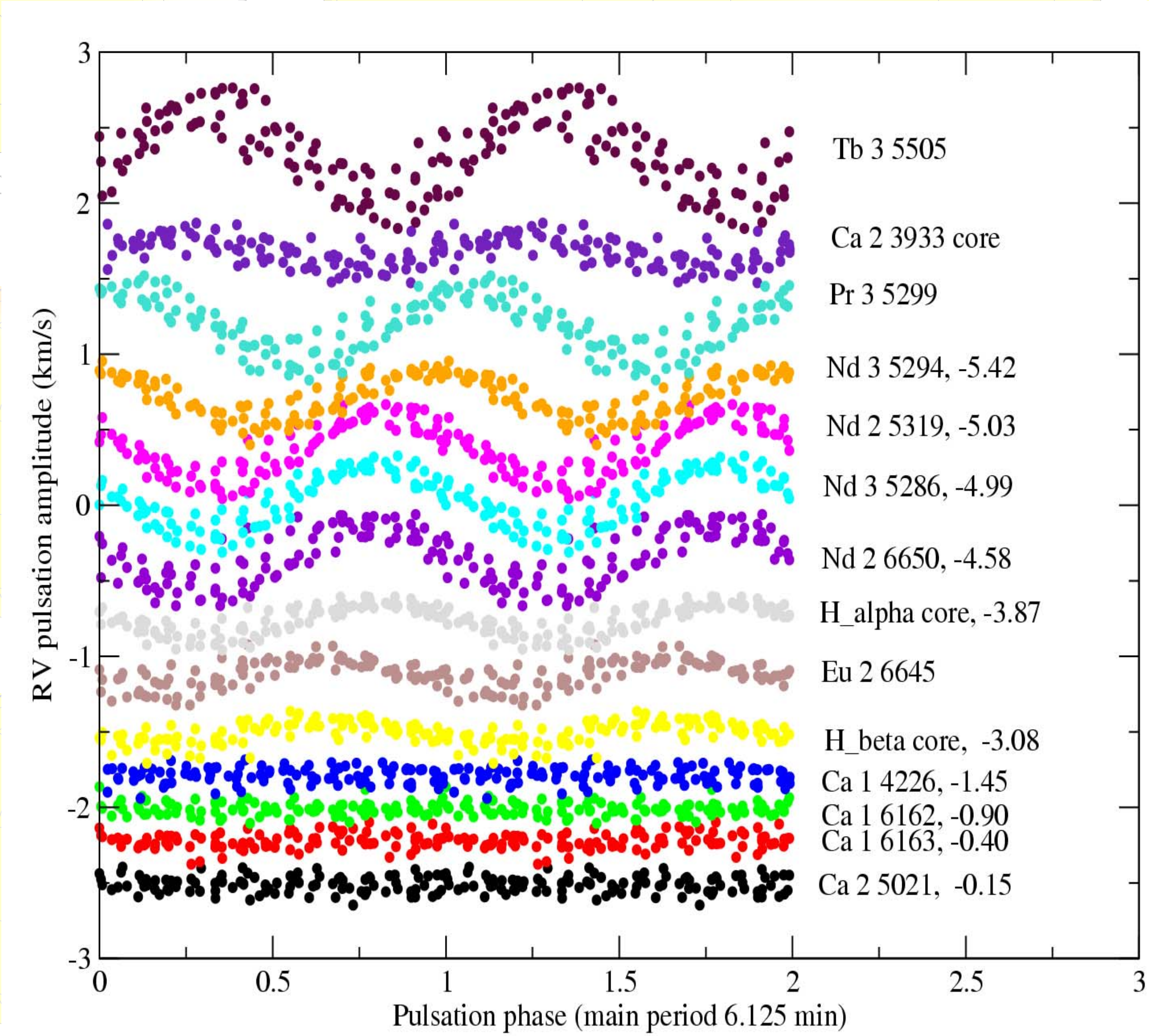
(roAp star γ Equ)



Pulsation selectivity
(roAp star γ Equ)



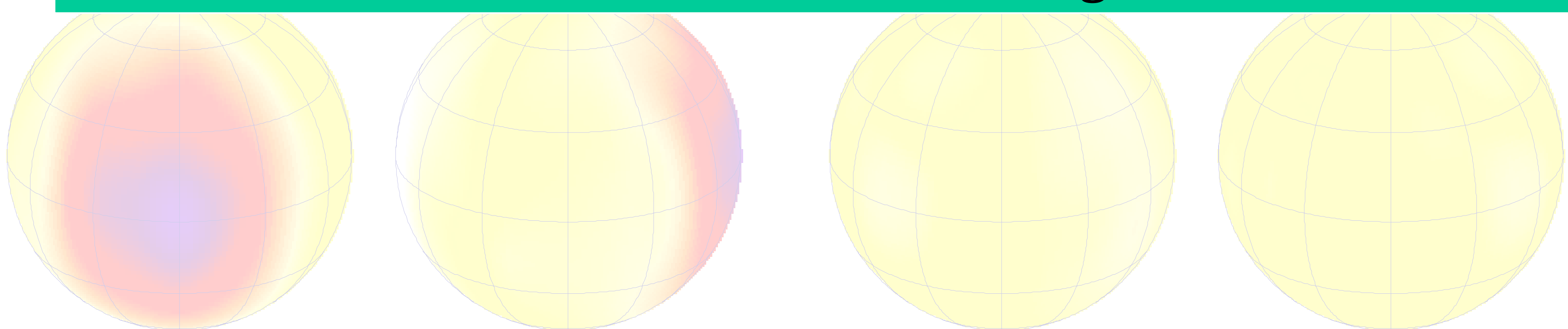
The *van Hoof* effect – phase lag between radial velocity curves of lines of different elements and ions – is one of the most interesting phenomena in the *roAp* stars. It yields a unique possibility for the vertical atmospheric structure analysis.



Pulsation tomography of roAp atmospheres:

resolving the third dimension

Reconstruction of the *roAp* vertical atmospheric structure encounters many difficulties: one has to take into account vertical stratification effects, should construct self-consistent stratified atmosphere model and then estimate influence of the surface element distribution and of the magnetic field.



We have used our own and archival time-series spectroscopic observations obtained with UVES at VLT. In addition, for HD 201601 data from NES at SAO 6-m telescope were used. For each star we measured *200-500* lines in the *4970 – 7010 Å* spectral region.

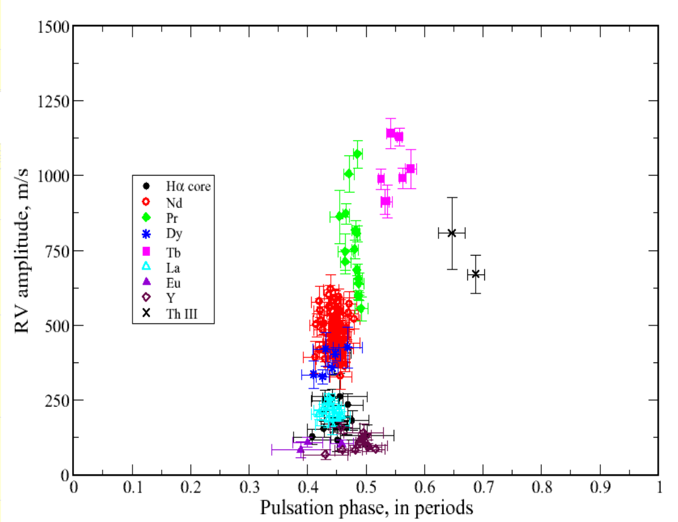
The table gives basic parameters for the roAp stars in our sample.

Star	***T*** $_{eff}$	***Log g***	***V sini***	***Bs***	***Analysed periods, min***
HD 12932	**7620**	**4.15**	**3.5**	**1.6**	**11.647**
HD 19918	**8110**	**4.34**	**3.0**	**1.6**	**11.038**
HD 24712	**7250**	**4.30**	**5.6**	**3.0**	**6.125, 6.282, 6.202**
HD 101065	**6600**	**4.20**	**2.0**	**2.3**	**12.148**
HD 122970	**6910**	**4.10**	**4.0**	**2.3**	**11.186**
HD 134214	**7500**	**4.00**	**2.0**	**3.0**	**5.691**
HD 137949	**7550**	**4.30**	**2.0**	**5.0**	**8.271, 4.136, 9.422**
HD 201601	**7700**	**4.20**	**0.0**	**4.0**	**12.210**

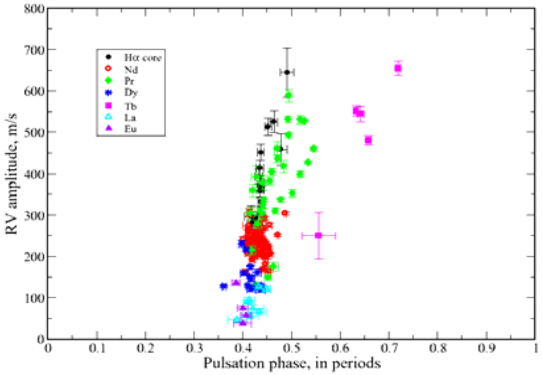
As we showed (Sachkov et al. 2006), Saio's (2005) model for the *roAp* star *HD24712* roughly explains amplitudes and phases up to $\log \tau_{5000} = -4$: amplitude and phase increase towards the outer layers. Thus, phases and amplitudes of pulsation should reflect features of propagating wave through the stellar atmosphere. In this way, the later in time pulsation wave reaches its maximum, the higher in the atmosphere a chemical element is concentrated.

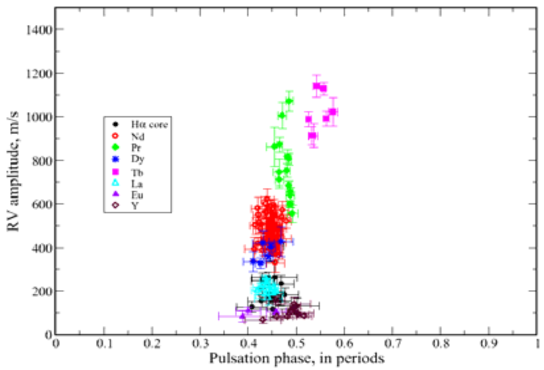
We propose to use the *"phase – amplitude"* diagram as a first step of the interpretation of *roAp* pulsational observations. Such approach has an advantage of being suitable to compare behaviour of different elements, which is impossible for studies of phase/amplitude dependence on line intensity.

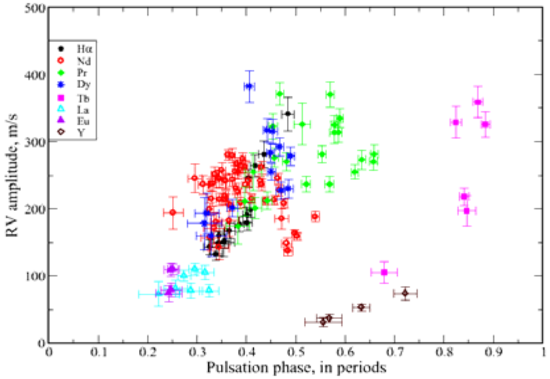
This analysis requires accurate measurements of both amplitudes and phases of even weak lines. Therefore, we have chosen a sample of slowly rotating *roAp* stars for our analysis.

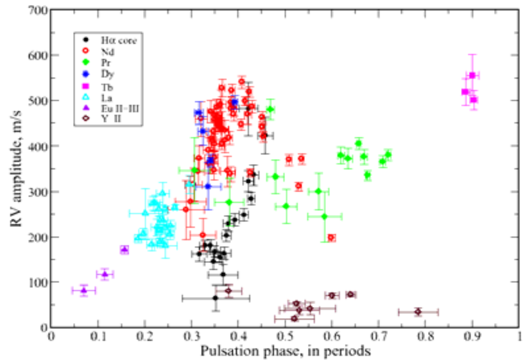


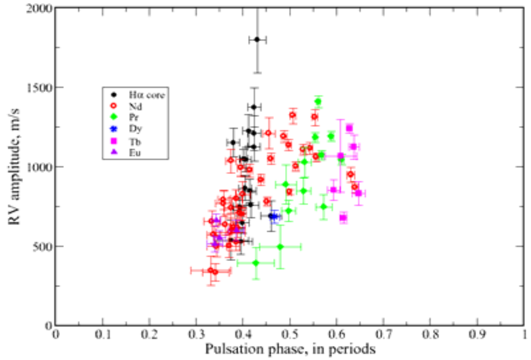
Common characteristics of roAp

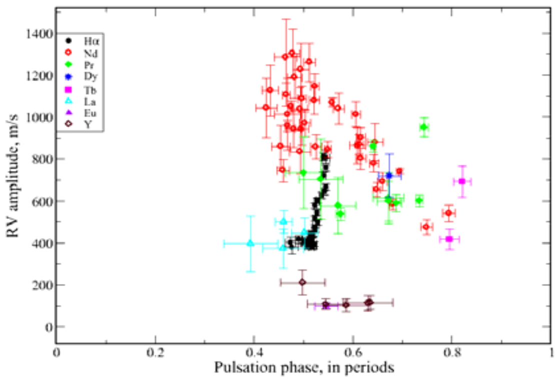


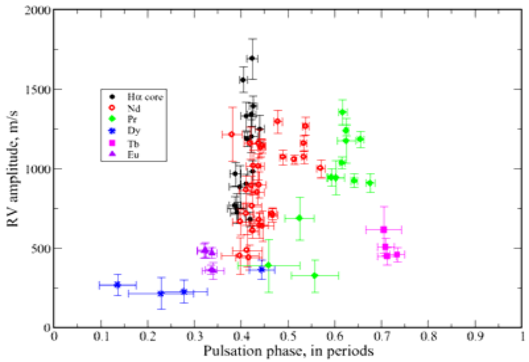


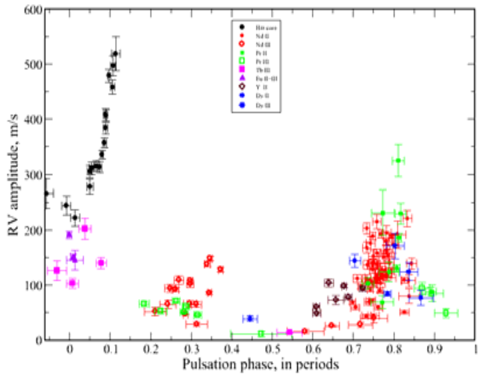












Common characteristics of roAp

Despite the fact that pulsational behaviour of *roAp* stars is not identical, we find certain similar features. The phase shifts of the ions are arranged in the following sequence:

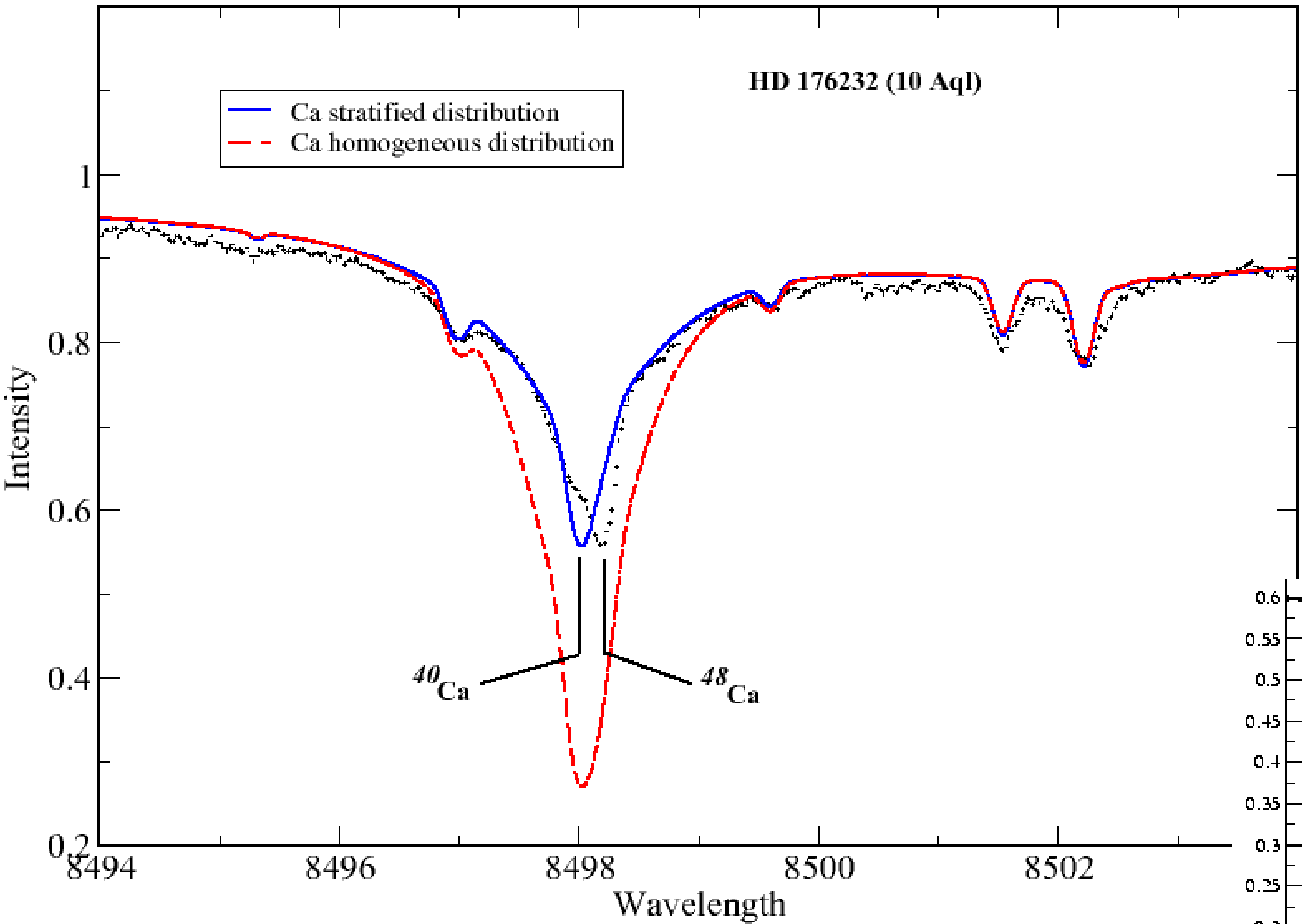
– pulsation appears in the layers with *Y* and *Eu* (+*Fe* in *33 Lib*) then goes through the layers where *H*α-core + *Nd* and *Pr* are formed, reaches maximum and then, in most stars, shows decrease of the amplitude;

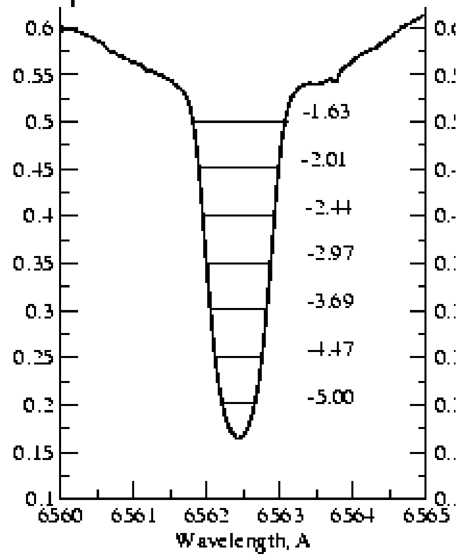
– the second ions are after the first ones;

– the largest phase shifts are detected in *Tb* and *Th* lines;

Pulsation wave appears to be similar to a standing wave in the deeper layers and then becomes the running one in the outer layers.

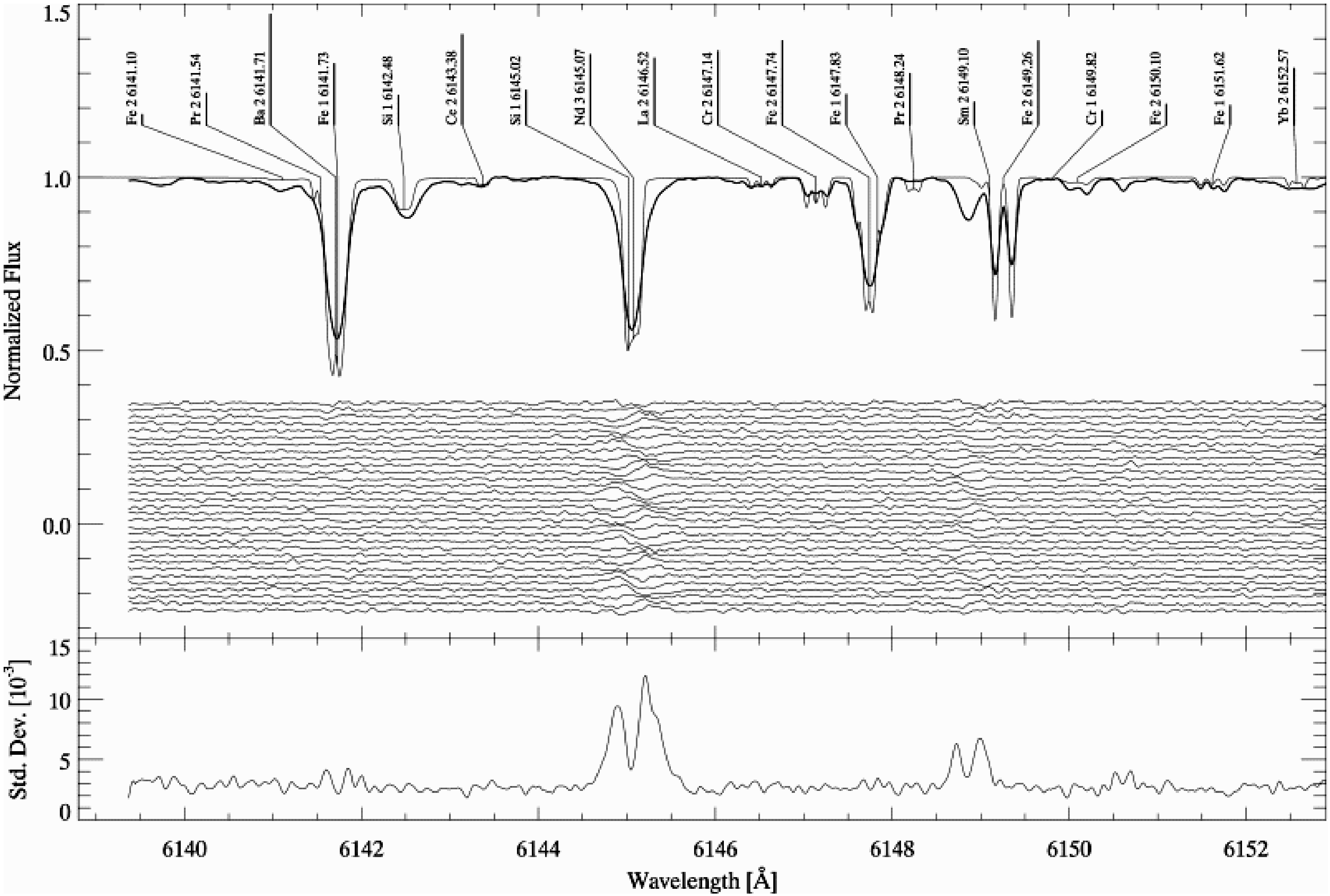
Pulsations and **Ca isotopic anomaly**



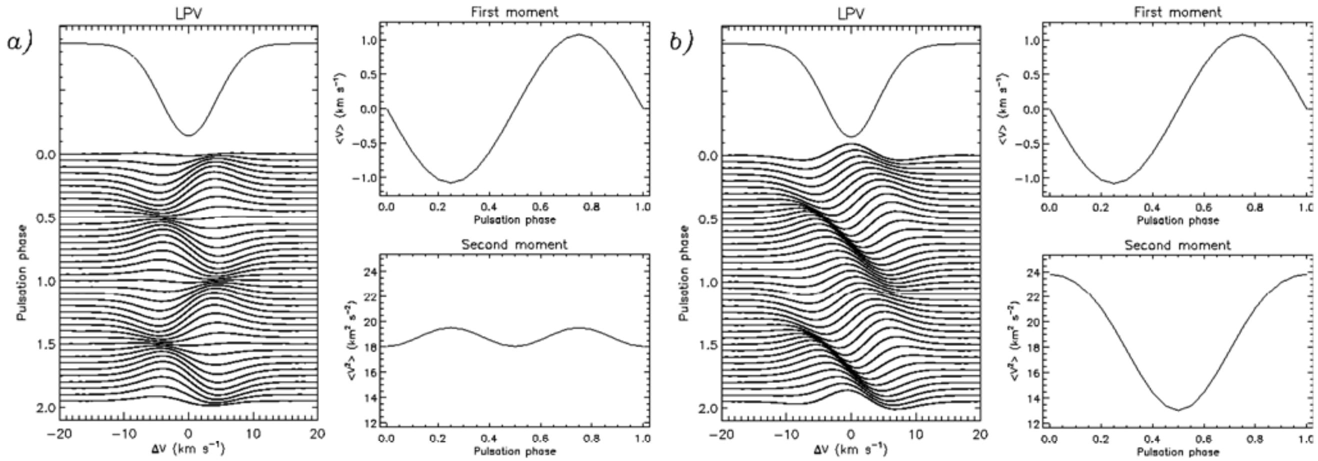


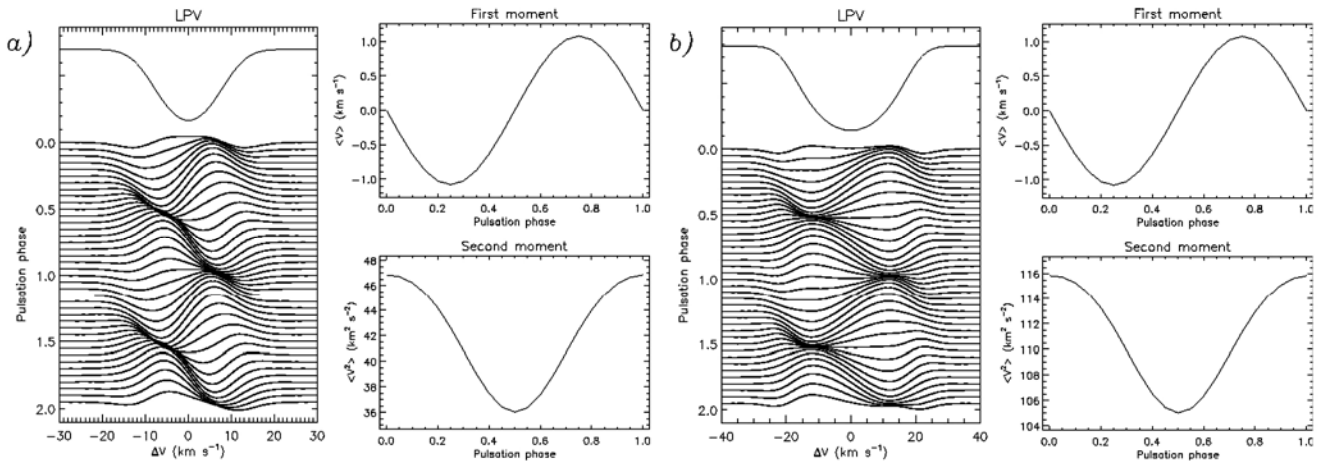
Pulsation selectivity

(roAp star γ Equ)



LPV in roAp stars: resolution of the enigma?





Pulsations for lines identification

- In roAp stars only lines of the rare-earth elements (REE) show high amplitude RV pulsational variations (up to 1 km/s and even more). Such unique pulsational behaviour can serve to identify unknown lines in roAp stars' spectra.

Line	Period (min)	Probability of Period	Amplitude ($m\,s^{-1}$)	Phasemax	Depth	EqW (mÅ)
4570.65	6.12(0.01)	1.0000	344(30)	0.425(0.014)	0.675	56
4642.99	6.20(0.04)	0.8993	176(37)	0.343(0.034)	0.778	50
4651.62	6.20(0.01)	1.0000	255(19)	0.422(0.012)	0.531	94
4734.76	6.14(0.04)	0.9922	170(32)	0.449(0.031)	0.733	65
4740.67	6.24(0.05)	0.8212	320(79)	0.402(0.040)	0.898	21
4759.54	6.17(0.02)	0.9999	200(19)	0.435(0.016)	0.584	97
5064.05	6.17(0.04)	0.9998	247(52)	0.382(0.034)	0.838	30
5083.85	6.13(0.04)	0.9967	323(58)	0.446(0.030)	0.847	35
5852.44	6.18(0.02)	1.0000	238(28)	0.339(0.018)	0.760	69
6012.30	6.17(0.03)	0.9993	194(29)	0.387(0.024)	0.799	49
6014.56	6.22(0.02)	0.9999	258(29)	0.431(0.018)	0.769	52
6148.86	3.69(0.03)	0.3565	81(44)	0.362(0.087)	0.882	30
6524.48	6.22(0.02)	0.9999	308(37)	0.363(0.019)	0.850	38
7873.68	6.19(0.02)	0.9955	283(27)	0.425(0.015)	0.779	76
8454.68	6.20(0.02)	0.9052	260(25)	0.492(0.016)	0.776	87