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Abundance structure of the atmospheres of magnetic CP stars

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Abstract. A review of the recent results on abundance and stratification analysis of the magnetic CP stars is presented. It includes a brief description of the methods as well as a comparison between the element distributions derived from observations and provided by the self-consistent diffusion model atmosphere calculations. He and Ca isotopic separation in the atmospheres of CP stars is considered. The importance of stratification analysis for the study of pulsations in roAp atmospheres is emphasized. Finally, I briefly discuss the recently published identification of unstable elements in spectra of Przybylski's star (HD 101065).

Key words: stars: chemically peculiar – stars: atmospheres – stars: abundances – diffusion

1. Introduction

Most of the observed abundance anomalies in the atmospheres of chemically peculiar magnetic stars (Ap) can be explained qualitatively by the particle diffusion process (Michaud, 1970) under the mutual action of radiative acceleration and gravitational settling. Subsequent calculations of the diffusion in stellar envelopes by Michaud *et al.* (1976) extended from solar-like stars to $T_{\rm eff}$=13 500 K predicted both underabundances of some elements (He, CNO, Mg, Si, Ca, Y) as well as overabundances for Ti, V, Cr, Mn, Co increasing with the effective temperature. For all models Fe should be slightly underabundant. However, an analysis of the abundances as a function of effective temperature (see Ryabchikova *et al.*, 2004; Ryabchikova, 2005 b) showed that in the 6500 – 9500 K range we have a rapid increase of both Cr and Fe abundances and Fe is overabundant up to 2 dex. Fe and Cr results taken from Ryabchikova (2005 b) are displayed in Fig. 1 (right two columns). The mean abundances are derived using a set of individual spectral lines and averaging over them.

At the same time, we have both empirical and theoretical evidence of a nonhomogeneous vertical distribution of some elements in stellar atmospheres (Babel, 1992; Wade *et al.*, 2003; Ryabchikova *et al.*, 2002; 2005; 2006; Kochukhov *et al.*, 2006; Khalack *et al.*, 2007). Self-consistent model diffusion calculations for chemically peculiar stars (LeBlanc and Monin 2004, herafter LM) have provided the Ap spectroscopists with the theoretical abundance distributions (*abundance*

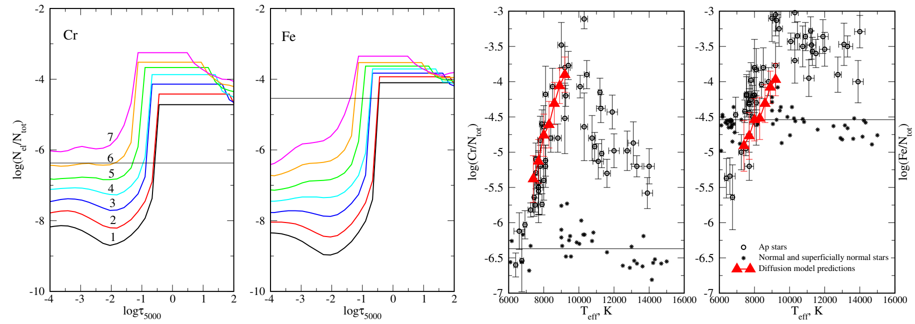

Figure 1. Left two panels: LM theoretical diffusion Cr and Fe distributions in stellar atmospheres with $T_{\rm eff}$ from 7400 to 9200 K with a 300 K step (labelled with numbers 1–7). Right two panels: averaged Cr and Fe abundances as a function of $T_{\rm eff}$. Open and filled circles represent Ap and normal stars, respectively. Filled triangles show averaged theoretical abundances derived from the corresponding LM distributions by standard abundance analysis procedure. Horizontal lines indicate solar abundances.

profiles) for as many as 39 chemical elements from H to La. Due to a lack of accurate atomic data for the ions of some elements such as La, for example, where only two ions were included in the diffusion calculations, some *abundance profiles* may not be considered too seriously. However, for the elements Si, Ca, Cr, Fe the diffusion calculations are based on a sufficient number of ions with rather accurate atomic data and may therefore be used for comparisons with the abundances and abundance distributions in the atmospheres of Ap stars derived from observed spectra. F. LeBlanc (private communication) performed self-consistent diffusion calculations for a set of atmospheric parameters typical for cooler Ap stars. These calculations were done for $7400 \leq T_{\rm eff} \leq 9200$ K, $\log g = 4.0$ with a 300 K step. Cr and Fe distributions are shown in Fig. 1 (two left panels). We performed standard stellar abundance analysis, but using set of line profiles of typical Cr I, II and Fe I, II lines synthesized with LM models as the observed spectrum. The results are shown in Fig. 1 (right panels) by filled triangles and they demonstrated clearly that the observed temperature dependence of Cr and Fe abundance is an appearance of the element stratification predicted by the diffusion theory.

In next two Sections I will consider the observed element distributions over Ap atmospheres, including the stratification of isotopes.

2. Observed stratification versus theory predictions

The procedure of stratification analysis is rather simple. We choose a number of spectral lines with accurately known atomic parameters (mainly oscillator strengths and Stark damping constants) which are differentially sensitive to the abundance changes at a particular atmospheric depth and fit the observed line profiles to the calculated ones, applying one of the following codes.

– Step function approximation. Following theoretical *abundance profiles* (Babel, 1992) the expected element distribution is described by four parameters: chemical abundance in the upper atmosphere, abundance in deep layers, the vertical position of the abundance step and the width of the transition region where chemical abundance changes between the two values. All four parameters can be optimized simultaneously with the least-squares fitting routine, based on observations of an unlimited number of spectral regions. The search for stratification parameters is performed using the DDAFIT – an automatic procedure for the determination of vertical abundance gradients written by O. Kochukhov (see Ryabchikova *et al.*, 2005).

– Vertical Inverse Problem (VIP). An inverse problem is solved in order to find the distribution of a chemical element with depth in the stellar atmosphere without having to guess about the shape of the *abundance profiles*. It is similar to abundance Doppler imaging, except that the aim is to obtain the best-fit chemical stratification instead of a 2-D picture of the horizontal abundance distribution (Kochukhov *et al.*, 2006).

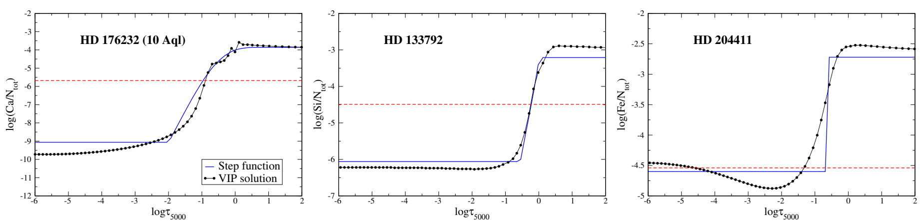

Figure 2. Comparison between DDAFIT and VIP stratification solutions for different elements in different stars. Solar abundances are shown by horizontal dashed lines.

Our experiments with both DDAFIT and VIP showed that generally they give similar abundance distributions (Fig. 2), which justify the use of a step function approximation in most stratification studies, in particular for stars with resolved Zeeman patterns, because at present only DDAFIT is working with the magnetic spectral synthesis (Kochukhov, 2007).

Stratification analysis has now been performed for the following groups of stars:
- PGa stars: He isotopic stratification (Bohlender, 2005).
- HgMn stars: Mn increase towards the upper atmosphere (Alecian, 1982; Sigut, 2001; Thiam *et al.*, 2008).
- HB stars: S concentration in the upper layers (Khalack *et al.*, 2007), Fe concentration in the deeper layers (Khalack *et al.*, 2008).

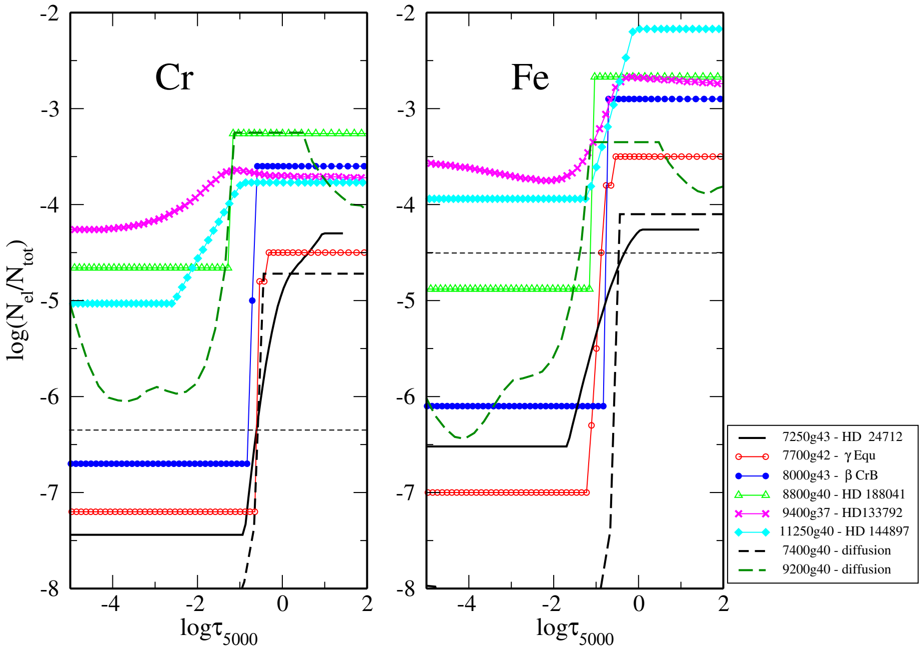

Figure 3. Cr and Fe abundance stratifications in a sample of Ap stars. Theoretical diffusion calculations are shown by dashed lines, solar abundances are indicated by horizontal lines.

- Ap stars: Mg, Si, Ca, Ti, Cr, Mn, Fe, Ba, Pr, Nd.

Ca stratification is derived in the atmospheres of 25 stars (Ryabchikova *et al.*, 2002; 2007 a; Cowley *et al.*, 2007)

Generally, Si, Ca, Ti, Cr, Fe and Ba are concentrated in the deeper atmospheric layers below $\log \tau_{5000} = -0.5... - 1.0$ with a steep abundance decrease (abundance jump) towards the upper atmosphere. Although this behaviour is predicted by the diffusion calculations, empirically obtained *abundance profiles* do not always agree with the predicted ones. Fig. 3 shows examples of Cr and Fe distributions in the atmospheres of a few Ap stars with different effective temperatures and their comparison with LM calculations. These are the best cases of agreement between the observed stratification and the diffusion predictions.

The small number of stars for which Cr and Fe stratification has been derived do not allow us to investigate a possible dependence on the magnetic field. However, we have two pairs of stars with close temperatures and very different magnetic field strengths $\langle B_s \rangle$: HD 133793 ($T_{\rm eff}$=9400 K, $\langle B_s \rangle$=1.1 kG) – HD 66318 ($T_{\rm eff}$=9200 K, $\langle B_s \rangle$=14.5 kG) and HD 170973 ($T_{\rm eff}$=10 750 K, $\langle B_s \rangle$=0 kG) – HD 144897 ($T_{\rm eff}$=11 250 K, $\langle B_s \rangle$=8.8 kG). The size of the abundance jump seems to be larger in the atmospheres of Ap stars with a strong magnetic field

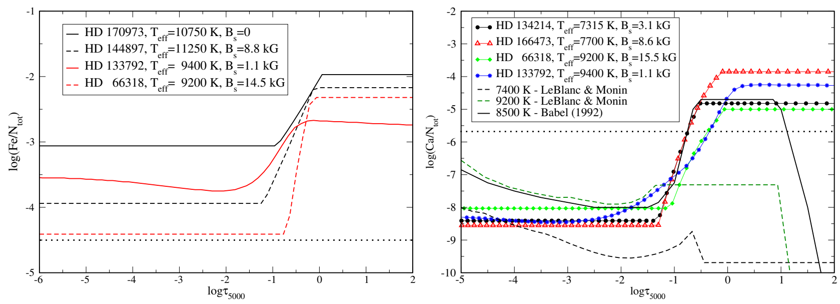

Figure 4. Left: Fe stratification in two pairs of Ap stars with similar $T_{\rm eff}$ but different magnetic field strengths. Solar Fe abundance is indicated by horizontal dotted line. **Right:** Ca stratification for a few stars with different $T_{\rm eff}$ and $\langle B_{\rm s}\rangle$ compared to LM and Babel's diffusion calculations.

(Fig. 4 left), and the jump itself is shifted downwards in the atmosphere. The range of optical depths where we hope to get reliable abundance distributions is defined by the formation depths of the lines analysed in any stratification procedure. Outside of this range the solution is formal. In the lower atmosphere we are limited by the photospheric layers, $\log\tau_{5000}$=0, while the upper boundary is defined by depth formation of the cores of the strongest lines. For Cr and Fe the working range is $-2.5 \leq \log\tau_{5000} \leq 0$ in cool Ap stars. The use of the Ca II 3933 resonance line and the lines of the IR triplet extends Ca abundance distribution analysis up to $\log\tau_{5000} = -7$.

For Si and Ca an agreement between the LM diffusion calculations and the observed distributions is not as good. Our stratification analysis always give Si and Ca overabundances relative to solar ones in the deeper atmospheric layers while in LM diffusion calculations these elements are either of solar abundance (Si) or even slightly underabundant (Ca) for all temperatures. However an abundance drop at $\log\tau_{5000} = -1... -1.5$ still exists for Si and Ca. Contrary to LM Babel's (1992) diffusion calculations for $T_{\rm eff}$=8500 K predict Ca distribution which is comparable to the observed ones (see Fig. 4 right). LM do not include magnetic effects in their self-consistent modelling. The first calculations of the element stratification in magnetic atmospheres are presented by Alecian and Stift (2008).

A few elements show a tendency to be concentrated in the upper atmospheric layers. This is the case for Mn in HgMn stars (Alecian, 1982; Sigut, 2001; Thiam *et al.*, 2008); Mg in two Ap stars HD 133792 (Kochukhov *et al.*, 2006) and HD 204411 (Ryabchikova *et al.*, 2005); the rare-earth elements – REE (see NLTE analysis of Nd in the atmospheres of roAp stars γ Equ and HD 24712 by Mashonkina *et al.*, 2005). An REE anomaly, where abundances derived from the lines of second ions (Pr III, Nd III) exceeds by 1.5–2 dex those derived from the lines of singly ionized species, seems to be a common property of the coolest

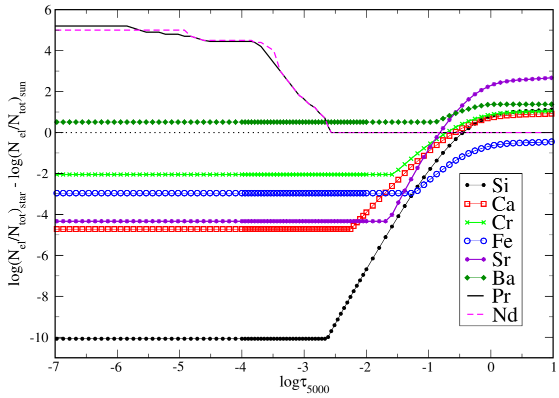

Figure 5. Abundance distribution in the atmopshere of HD 24712 ($T_{\rm eff}$=7250 K). For convenience, abundances are given relative to the solar values.

Ap stars (Ryabchikova *et al.*, 2004), therefore one may expect to have the same REE distribution in the atmopsheres of other cool Ap stars as it was derived in γ Equ and HD 24712.

A present-day picture of the chemical atmospheric structure of a typical cool Ap star HD 24712 is shown in Fig. 5, where abundance distributions are given relative to solar abundances. This star belongs to a group of rapidly oscillating (roAp) magnetic peculiar stars. The outstanding feature of these pulsations is a selectivity of amplitudes and phases of the radial velocity variations. It strongly depends which particular element/ion the spectral line comes from (see, for example, Ryabchikova *et al.*, 2007 b), therefore an understanding of the chemical structure of roAp atmospheres is required for a detailed analysis of line formation and pulsation wave propagation.

3. Isotope separation in the atmospheres of CP stars

Bohlender (2005) found that in spectra of hot PGa stars 3 Cen A ($T_{\rm eff}$=17 500 K) and HR 7467 ($T_{\rm eff}$=15 500 K) line profiles of He I lines that show a presence of ^{3}He isotope can be fitted under the assumption of He isotopic separation in the stellar atmosphere. Moreover, he found that the spectral feature corresponding to the ^{3}He line does not have strong Stark wings compared to that of the ^{4}He line and hence the ^{3}He isotope should be concentrated higher in the atmosphere. Quantitative analysis showed that in both stars ^{3}He is concentrated in the layer -2.5< $\log\tau$ <-1.50 while ^{4}He has a tendency to settle down below $\log\tau = -0.5... - 0.2$.

Cowley and Hubrig (CH05) discovered a significant presence of the heavy Ca isotope ^{48}Ca in the atmospheres of cool Ap stars by measuring the wavelength shifts of the centre-of-gravity of the Ca II IR triplet. In most stars Ca II line profiles have a rather narrow feature at the position of lines corresponding to ^{48}Ca. A combined analysis of Ca stratification including isotopes performed by Ryabchikova, Kochukhov and Bagnulo (see Ryabchikova, 2005 a; Ryabchikova *et al.*, 2007 a) resulted in the discovery of Ca isotopic separation in the atmospheres of 21 Ap stars. This number has now increased to 23 stars. As in the case of helium, ^{40}Ca, which is the dominant isotope in the terrestrial mixture (96%), is responsible for a spectral feature with developed Stark wings, while a narrow feature is observed at the position of ^{46,48}Ca line. The observed line profile of the IR Ca II λ 8498 line is described by a stratified Ca distribution where ^{40}Ca is concentrated in the deeper atmospheric layers and ^{48}Ca is left in the upper atmosphere. Fig. 6 illustrates the Ca II λ 8498 line formation in the atmosphere of 10 Aql (HD 176232).

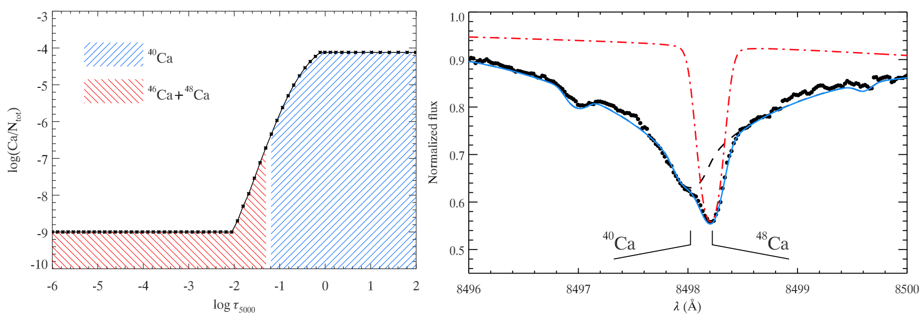

Figure 6. Ca isotopic distribution in 10 Aql (HD 176232) atmosphere (left panel) and the observed Ca II 8498 line profile (right panel). ^{40}Ca and ^{48}Ca contributions are shown by dashed and dashed-dotted lines, respectively.

From a similar analysis undertaken for 23 stars with different $T_{\rm eff}$ and $\langle B_{\rm s}\rangle$ we concluded that the contribution of the heavy Ca isotopes decreases with increasing magnetic field, becoming non-detectable for magnetic fields above 6–7 kG. Based on wavelength shift measurements Cowley *et al.* (2007) came to a similar conclusion, but with some reservation. The dependence of Ca isotopic separation on magnetic field strength favours light-induced drift - LID (Atutov, Shalagin 1988) as the main process responsible for this separation. Indeed, the LID effect is based on radiation field anisotropy within the line profile, which takes place for a weak ^{48}Ca line lying in the wing of stronger ^{40}Ca line. Zeeman splitting removes this anisotropy and may prevent isotopic separation.

4. Heavy elements in HD 101065 (Przybylski's star)

Przybylski's star (HD 101065, hereafter PS) is the coolest representative of the whole class and hence has underabundances of Fe-peak elements (see Fig. 1).

However, it is the richest in the REE abundances. Based on wavelength coincidence statistics Cowley *et al.* (2004) provided evidence for the presence of short-lived elements Tc and Pm in the atmosphere of PS. If short-lived elements are really present, then nuclear synthesis rather than diffusion is responsible for the observed abundances of the heavy elements sequence. Yushchenko *et al.* (2006) seem to support Tc identification synthesizing a couple of Tc lines. Tc I 4124.217 shown in Fig. 4 of their paper provided the most convincing evidence for Tc although the stellar feature is slightly shifted to the red. Recently published transition probabilities and partition function calculations for Tc I (Palmeri *et al.* 2005), Tc II (Palmeri, *et al.* 2005), Pm II (Fivet *et al.*, 2007) make it possible to check short-lived element lines in the atmosphere of PS. Fig. 7 shows parts of PS spectrum in the region of Tc I 4124.217 ($E_{\rm i}$=0.45 eV) and resonance Tc I 4297.058 lines. Obviously, if the first line is present, the second one should be much stronger. Both lines are synthesized with $\log({\rm Tc}/{\rm N_{tot}}) = -8.0$ that agree very well with the Tc abundance estimated by Yushchenko *et al.* (2006). The same spectrum of PS was used in both analyses. Atmospheric parameters and abundances were taken from Cowley *et al.* (2000). From Fig. 7 we may conclude

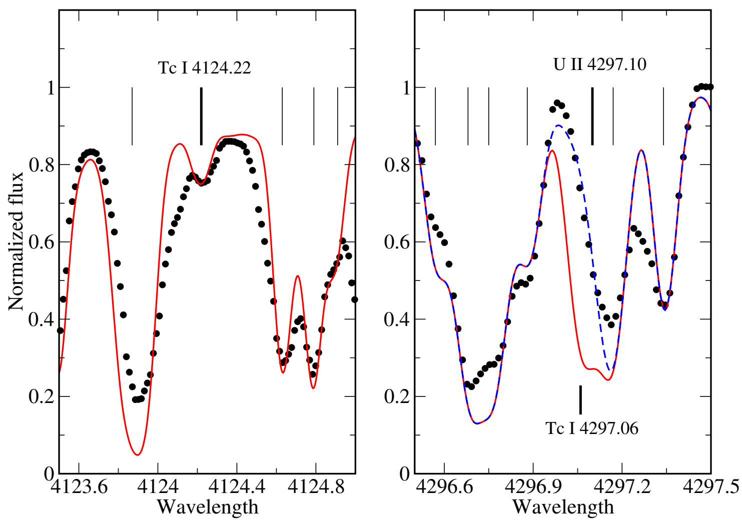

Figure 7. Tc I lines in Przybylski's star. Obseravtions are shown by dots, calculations with $\log({\rm Tc}/{\rm N_{tot}}) = -8.0$ are shown by the solid line, without Tc presence in 4297 Å region – dashed line. Positions of the Tc I and U II lines are marked by thick marks, positions of the other lines are marked by thin marks.

that an identification of the 4124.2Å feature as a Tc I line is spurious, taking into account an absence of the resonance Tc I 4297.058 line in the observations. All the strongest Tc II lines in 3000–10 000 Å region fall very close to the position of strong REE or other lines of anomalous species (Co I, Ru I), and therefore cannot provide any support for Tc identification in PS.

For Pm the situation is slightly different. Four out of 8 of the strongest Pm II lines in the optical region from the list of Fivet *et al.* (2007) (4137.95, 4157.86, 5561.73, 5576.02 Å) have some room in blends. Abundances may be estimated from spectral synthesis, and these lines give an upper limit $\log(\mathrm{Pm/N_{tot}}) = -9.5$ for Pm abundance. At the same time there is no room in the observed blend for the Pm II 5556.88 line, which has nearly the same theoretical intensity as the Pm II 5561.73 line, and an inclusion of this line in the spectral synthesis does not fit at all to the observations. Cowley *et al.* (2004) suggested Pm II identification for two features measured in Przybylski's star at 6659.07 and 6772.28 Å. Using atomic data from the DREAM database (Biémont *et al.*, 1999) we found that both features are well represented by Ce II lines, the element obviously dominating in the PS atmosphere.

As I mentioned above, PS has the highest REE abundances among the Ap stars. Most of the REE's are observed in the second and third ionisation states. A few lines of the neutral REE's were also identified. In spite of recent progress in laboratory spectroscopy of the REE, accurate line classification and atomic data are scarce. The best case we have for Ce II. From 13700 classified Ce II lines in 3000 − 10 000 Å region, about 10 000 lines are present in the PS spectrum with intensities higher than 5% of the continuum. All known Nd II (1284), Sm II (1327), Gd II (890) lines are present in PS spectrum with intensities higher than 20%. This means that tens of thousands as yet unclassified spectral lines of the first REE ions are present in the PS spectrum. The same is true for the second REE ions. The best studied second ion, Pr III has about 1000 classified lines and 300 are measured in PS, while we know only of 70 classified lines of Nd III (the most abundant rare-earth element in PS). A new extensive study of REE spectra is required for a definite identification of the short-lived radioactive elements in Przybylski's star.

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References

Alecian, G.: 1982, *Astron. Astrophys.* **107**, 61
Alecian, G., Stift, M.J.: 2008, *Contrib. Astron. Obs. Skalnaté Pleso* **38**, 122
Atutov, S.N., Shalagin, A.M.: 1988, *Astron. Letters* **14**, 284
Babel, J.: 1992, *Astron. Astrophys.* **258**, 645
Biémont, E., Palmeri, P., Quinet, P.: 1999, *Astrophys. Space Sci.* **635**, 2691.
Bohlender, D.: 2005, in *Element Stratification in Stars: 40 Years of Atomic Diffusion*, eds.: G. Alecian, O. Richard and S. Vauclair, *EAS Publ. Ser.* **17**, 83
Cowley, C.R., Bidelman, W.P., Hubrig, S., Mathys, G., Bord, D.J.: 2004, *Astron. Astrophys.* **419**, 1087

Cowley, C.R., Hubrig, S., Castelli, F., Gonzalez, J.F., Wolff, B.: 2007, *Mon. Not. R. Astron. Soc.* **377**, 1579
Cowley, C.R., Ryabchikova, T., Kupka, F., Mathys, G.; Bidelman, W.P.: 2000, *Mon. Not. R. Astron. Soc.* **317**, 299
Fivet, V., Quinet, P., Biémont, É., Jorissen, A., Yushchenko, A.V., van Eck, S.: 2007, *Mon. Not. R. Astron. Soc.* **382**, 944
Khalack, V.R., Leblanc, F., Bohlender, D., Wade, G.A. Behr, B.B.: 2007, *Astron. Astrophys.* **466**, 667
Khalack, V.R., LeBlanc, F., Behr, B.B., Wade, G.A., Bohlender, D.: 2008, *Contrib. Astron. Obs. Skalnaté Pleso* **38**, 417
Kochukhov, O.: 2007, in *Physics of Magnetic Stars*, eds.: D.O. Kudryavtsev and I.I. Romanyuk, SAO RAS, Nizhnij Arkhyz, 109
Kochukhov, O., Tsymbal, V., Ryabchikova, T., Makaganyk, V., Bagnulo S.: 2006, *Astron. Astrophys.* **460**, 831
LeBlanc F., Monin D.: 2004, in *Proc. IAU Symp.* 224, eds.: J. Zverko, J. Žižňovský, S.J. Adelman and W.W. Weiss, Cambridge University Press, Cambridge, 193.
Mashonkina L.I., Ryabchikova, T., Ryabtsev, A.N.: 2005, *Astron. Astrophys.* **441**, 309
Michaud, G.: 1970, *Astrophys. J.* **160**, 641
Michaud, G., Charland, Y., Vauclair, S., Vauclair, G.: 1976, *Astrophys. J.* **210**, 447
Palmeri, P., Fischer, C. Froese, Wyart, J.-F., Godefroid, M. R.: 2005, *Mon. Not. R. Astron. Soc.* **363**, 452
Palmeri, P., Quinet, P., Biémont, É., Yushchenko, A.V., Jorissen, A., van Eck, S.: 2005, Mon. Not. R. Astron. Soc. **374**, 63
Ryabchikova, T.: 2005 a, in *Element Stratification in Stars: 40 Years of Atomic Diffusion*, eds.: G. Alecian, O. Richard and S. Vauclair, *EAS Publ. Ser.* **17**, 253
Ryabchikova, T.: 2005 b, *Astron. Letters* **31**, 388
Ryabchikova, T., Kochukhov, O., Bagnulo S.: 2007 a, in *Physics of Magnetic Stars*, eds.: D.O. Kudryavtsev and I.I Romanyuk, SAO RAS, Nizhnij Arkhyz, 325
Ryabchikova, T., Leone, F., Kochukhov, O.: 2005, *Astron. Astrophys.* **438**, 973
Ryabchikova, T., Nesvacil, N., Weiss, W.W., Kochukhov, O., Stütz, Ch.: 2004, *Astron. Astrophys.* **423**, 705
Ryabchikova, T., Piskunov, N., Kochukhov, O., Tsymbal, V., Mittermayer, P., Weiss, W.W.: 2002, *Astron. Astrophys.* **384**, 545
Ryabchikova, T., Ryabtsev, A., Kochukhov, O., Bagnulo, S.: 2006, *Astron. Astrophys.* **456**, 329
Ryabchikova, T., Sachkov, M., Weiss, W.W., Kallinger, T. Kochukhov, O. Bagnulo, S., Ilyin, I., Landstreet, J. D., Leone, F., Lo Curto, G., Lüftinger T., Lyashko, D. Magazzú, A.: 2007 b, *Astron. Astrophys.* **462**, 1103
Sigut, T.A.A.: 2001, *Astrophys. J.* **546**, L115
Thiam, M. Wade, G.A., LeBlanc, F., Khalack, V.R.: 2008, *Contrib. Astron. Obs. Skalnaté Pleso* **38**, 461
Wade, G.A., LeBlanc, F., Ryabchikova, T.A., Kudryavtsev, D.O.: 2003, in *IAU Symposium* 210, eds.: N.E. Piskunov, W.W. Weiss and D.F. Gray, Astron. Soc. Pacific, San Francisco, D7
Yushchenko, A., Gopka, V., Goriely, S., Nazarenko, V., Shavrina, A. et al.: 2006, in *Nuclei in the Cosmos – IX*, CERN, 198.1