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# Statistical analysis of roAp, He-weak, and He-rich stars

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## ABSTRACT

To enlarge our data base of chemically peculiar stars, we compiled published data concerning the He-weak and He-rich stars observed by high-resolution spectroscopy techniques during last decades. Twenty He-weak and 28 He-rich stars have been added to the data base. We have also distinguished roAp stars from stars previously identified as Ap stars. To deepen our knowledge on statistical overview of the abundance anomalies versus the physical parameters of stars, we compared our data with previous compilations. We applied statistical tests on our data and found interesting correlations for effective temperature and surface gravity for all type of stars and a few correlations for projected rotation velocity only for He-rich stars. Because of the lack of the data, we could not check whether being a member of binary system is affecting on chemical peculiarities of those stars.

**Key words:** methods: statistical – techniques: spectroscopic – catalogues – stars: abundances – stars: chemically peculiar – stars: individual: roAp, He-weak and He-rich.

## 1 INTRODUCTION

The main goal of our paper is to include in a unique catalogue of chemically peculiar (CP) stars rapidly oscillating Ap (roAp) stars, He-weak, and He-rich stars, which were observed using high-resolution spectroscopy, and for which detailed abundance determinations were done. He-weak and He-rich stars are now added in the data base we have discussed in Ghazaryan, Alecian & Hakobyan (2018, hereafter [Paper II](#)). We proceed to statistical analysis on them. All these stars are main-sequence CP stars and show peculiar abundances for many elements in their atmospheres. The abundance peculiarities of CP stars are generally considered to be the consequence of atomic diffusion (Michaud 1970) that is a physical process that the effects are detectable if mixing motions are weak enough in outer layers. In that case, the average force on atoms (radiative forces against gravity) leads to a migration of chemical species. Since radiative force is different from one species to the other, abundances become inhomogeneous inside stellar zones where mixing is weak or inexistent. Looking for correlation of abundances with respect to physical parameters of stars, gives important information on processes in play (see the discussion in Section 5.4). For instance, a correlation between chemical abundances of a given element with respect to effective temperature suggests that radiative acceleration plays a dominant role for that element, and so, it may be considered as the strongest signature of atomic diffusion process. If there is a correlation

between abundances and surface gravity, this may show a stellar evolution effect on atomic diffusion process. And finally, if there is a correlation between chemical abundances and rotation velocity, one may consider the effect of rotational mixing (see Michaud, Alecian & Richer 2015). These correlations with respect to physical parameters are only indicative, since abundance stratification build-up is a complex non-linear process where the efficiency of atomic diffusion depends on various parameters, and could depend on the evolution history of each star during its life on the main sequence (see Bailey, Landstreet & Bagnulo 2014, for evolution of magnetic Bp stars).

RoAp stars are the coolest magnetic Ap(SrCrEu) stars on which rapid pulsations with 5–10 min periods were detected (see Kurtz 1982). First, detection of rapid pulsation with 12.14 min period was in the atmosphere of the Przybylski’s star HD101065 by Kurtz (1978), and then followed the discovery of pulsations in 5 Ap(SrCrEu) stars. More than 40 roAp stars were discovered before 2008 (Bruntt et al. 2008) in the effective temperature range of  $7000 \lesssim T_{\text{eff}} \lesssim 10\,000$  K. In our data base, only 40 of them are included because of the lack of abundance measurements in other stars identified as belonging to roAp group. The roAp stars are interesting subject for asteroseismology: the detailed study of their pulsations and abundance stratification in their atmosphere will help to argue theoretical models with abundance stratification, which is due to atomic diffusion.

He-weak (or He-w) stars are often found in the range of effective temperature  $10\,000 \lesssim T_{\text{eff}} \lesssim 20\,000$  K. Historically, He-weak stars were identified as a subgroup of CP stars by Norris (1971) because of their significant underabundances of helium and for peculiar abundances of some metals. Even though helium deficiency is a

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general property of CP stars (see Deutsch 1947; Sargent 1964), it was originally observed more deficient (by the factor of 2–15) in He-weak stars than in other CP stars (see Michaud et al. 2015, for more details). There are two types of He-weak stars – magnetic and non-magnetic. The non-magnetic He-weak stars are sometimes named P-Ga or phosphorus-type stars. They show overabundances of P (up to a factor of 2) and Ga (up to a factor of 5) as compared to their solar values (see LeBlanc 2010).

The discovery of the first He-rich (or He-r) star  $\sigma Ori E$  was done by Berger (1956), and the existence of the group of He-rich star by Osmer & Peterson (1974). He-rich stars are characterized by strong excess of helium (by a factor up to 10). Their effective temperature is generally larger than about 16 000 K. He-rich stars are mostly slow rotators (99.5 per cent of those stars have  $v \sin i < 130 \text{ km s}^{-1}$ , see Zboril & North 2000), they have strong magnetic fields, which are correlated with metal abundances (Hunger, Groote & Heber 1991). Vauclair (1975) explained overabundance of helium in He-rich stars as due to atomic diffusion processes combined with a stellar wind.

In Section 2, we represent our updated data base and recall how it was developed. In Section 3, we show the results of the comparison with previous compilations. In Section 4, we look for correlations between fundamental parameters and abundances, as well as ‘multiplicity’ (only for single, close binaries) and abundance anomalies. In Section 5, we discuss the compiled data in the framework of the usual models considered for these stars, and finally, we give some general considerations about the abundance stratification build-up process.

## 2 THE UPDATED DATA BASE

Our updated data base contains additional stars for which abundances were determined by various authors through high-resolution spectroscopy. Among them, 28 are identified as He-rich stars and 20 are He-weak stars. Also, 40 stars that are in the data base of Paper II with the CP-type ApBp are actually roAp stars. They are now identified as roAp. All these new stars, or stars with changed attributes, are given in the Appendix with their physical parameters, as they were provided in publications, including effective temperature, surface gravity, rotation velocity ( $v \sin i$ , actually), and bibliographic references.

As in our previous papers Ghazaryan & Alecian (2016, hereafter Paper I) and Paper II, we considered the mean of the abundance values of different ions for a given element, and the error bars were recalculated by the rms standard deviation as in Paper I and Paper II. Here also, to have more homogeneous data set, if for a given element different abundances by several authors were given, we kept the value from the publication where many other abundances of elements were given. All abundances were rescaled to solar values given by Asplund et al. (2009, hereafter AGS09). The detailed abundances (element per element) for each star are provided as online data.<sup>1</sup> In the Appendix, we give also ‘multiplicity’ information (binarity, belonging to a cluster, etc.) of these stars according to Simbad<sup>2</sup> archive. In Section 3, we present comparison results with previous compilations (see Paper I, Paper II, and Smith 1996).

<sup>1</sup>These data, and some more may be also found on the following website [http://gradsvp.obspm.fr/CPstars/CPstars\\_home.html](http://gradsvp.obspm.fr/CPstars/CPstars_home.html) (site maintained by Observatoire de Paris, responsible of this web page: G. Alecian).

<sup>2</sup><http://simbad.u-strasbg.fr/simbad/>.

## 3 COMPARISON WITH OTHER CP TYPES

In Fig. 1(a), we compare the abundance peculiarities found in roAp stars to those of cool ApBp stars (discussed in Paper II) that are in the same effective temperature range ( $T_{\text{eff}} \leq 10\,300 \text{ K}$ , see Section 5.1), and for which no oscillations were presently found. See discussion about roAp stars in Section 5.1.

As shown in Fig. 1(a), there are no helium and neon abundances determinations for roAp stars. Oxygen is underabundant in both type stars, but for ApBp stars there are a few measurements of overabundance which is up to about 100. The same situation holds for titanium. Iron underabundance is more pronounced by one order of magnitude in roAp stars (this is related to their low effective temperature, see Section 5.1). It is important to note that among these differences there are several metal abundance determinations that are absent for ApBp stars.

For He-weak stars, we compare our compilation with Smith’s one (Smith 1996). Considering his fig. 5, we notice that in our compilation helium is deficient by a factor of  $\sim 2.5$ , while in Smith’s data it is a bit stronger (see Fig. 1b). On the contrary, phosphorus excess is a bit more (300 instead of 100), we compiled only one krypton abundance value (for HD 120709), which excess factor reaches 2500. The comparison results obtained for gallium, sulphur, silicon, manganese, and iron are more or less the same. Notice that HD149363 is very atypical, since its effective temperature is 30 000 K according to Zboril & North (2000), all others He-w stars being cooler than  $T_{\text{eff}} \approx 18\,500 \text{ K}$ . Considering the trend of metals overabundances, it appears to be a little bit less pronounced but more or less similar to what is found for ApBp stars (including HgMn).

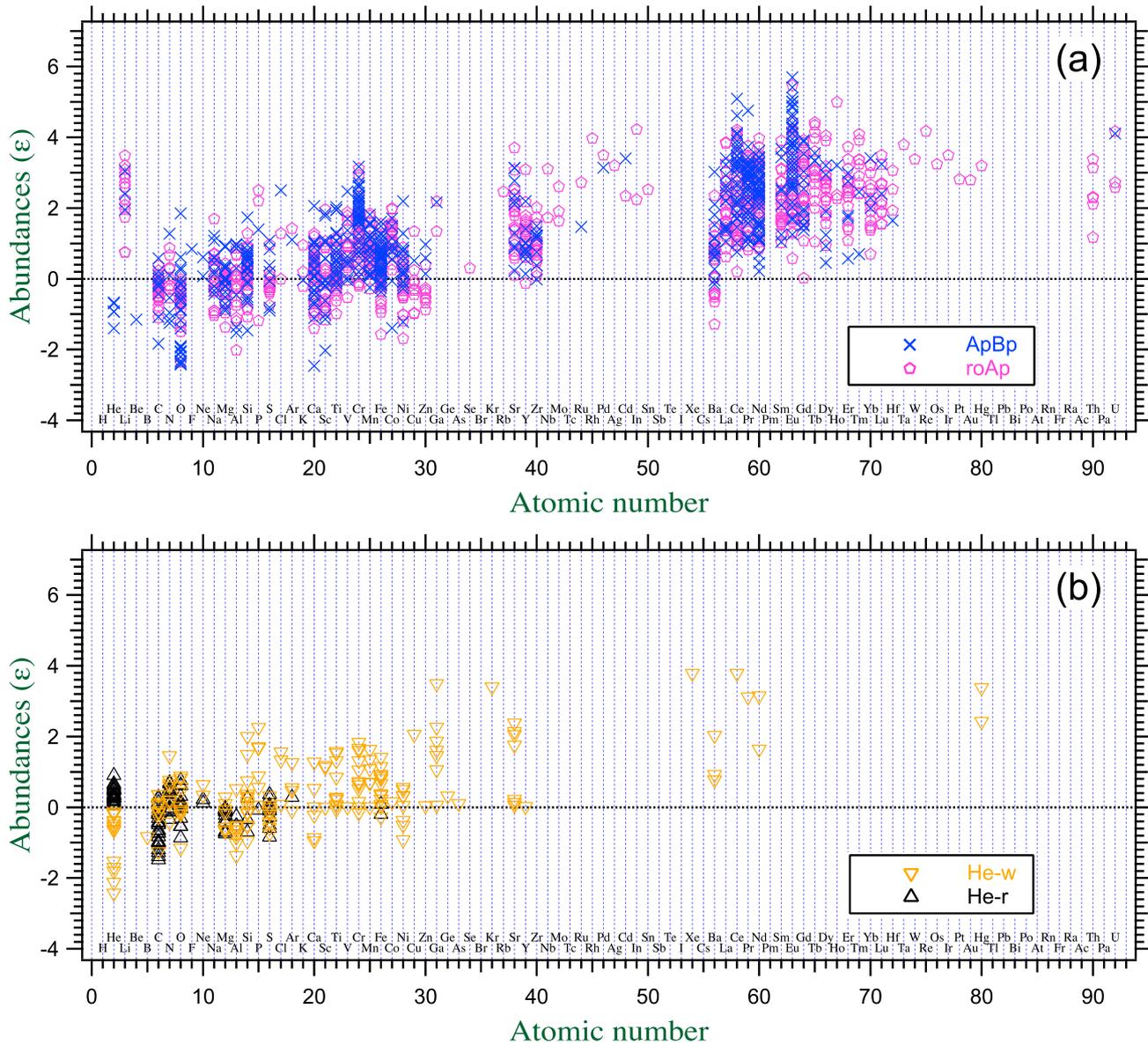
Here also we confirm that in Sr-Ti He-weak stars carbon and silicon abundances are normal, whereas titanium, chromium, and iron are enhanced (see Vilhu, Tuominen & Boyarchuk 1976). We found more rare earth elements enhanced abundances, which are absent in Smith’s compilation, but for detailed study of them more values are needed.

He-rich stars, which show age-dependent increase of helium abundance (see Zboril, Glagolevskij & North 1994), exhibit often light elements deficiencies such as carbon, nitrogen, and oxygen, and small deficiency of metals such as magnesium, aluminium, silicon, and also deficiency of sulphur. Neon, argon, and iron abundances are close to solar ones (Fig. 1b).

## 4 STATISTICAL ANALYSIS

It is interesting to know if the abundances in the atmospheres of all CP stars (that may be understood in the framework of atomic diffusion theory) are somehow correlated with physical parameters of the star such as effective temperature, surface gravity, and rotation velocity. To check the possible correlations, following Paper II we applied the Spearman’s rank correlation test<sup>3</sup> (Spearman 1904) between abundances and fundamental parameters. Our results of the correlation test for roAp, He-weak, and He-rich stars are presented in Table 1. All significant correlations ( $p$ -value  $\leq 0.05$ ), which were

<sup>3</sup>Spearman’s rank test performs a hypothesis test on a pair of two variables with null hypothesis that they are independent, and alternative hypothesis that they are not. Usually, one accepts the alternative hypothesis of the test when  $p$ -value is less than 5 per cent (see Feigelson & Babu 2012 for more details). Spearman’s coefficient  $\rho$  is a non-parametric measure of rank correlation ( $\rho \in [-1; 1]$ ), it assesses how well the relationship between two variables can be described using a monotonic function.



**Figure 1.** Abundances versus atomic number. Abundances ( $\epsilon$ ) are the logarithm of the abundances divided by the solar AGS09 ones, the zero line corresponds to solar abundances. (a) Abundances for roAp (open pentagons) and cool ApBp stars (crosses). Abundances of cool ApBp stars are taken from Paper II. (b) Abundances for He-weak (top-down triangles) and He-rich stars (top-up triangles).

found for the mentioned CP types, are marked in boldface in Table 1, and all marginal cases ( $0.05 < p\text{-value} < 0.06$ ) are marked as underlined. As in Paper II, we think that small number statistics for elements with less measurements make the test ineffective, this is why we selected a threshold of 11 measurements and applied the test only for each element measured in more than that threshold value (for roAp and He-abnormal stars).

Our preliminary statistical results show that for roAp stars there is a correlation between oxygen, silicon, calcium, titanium, chromium, manganese, iron, nickel, lanthanum, terbium, ytterbium, and  $T_{\text{eff}}$ , marginal correlation exists for sodium and  $T_{\text{eff}}$ .

There is also a correlation between lithium, scandium, vanadium, europium, dysprosium, and surface gravity. We could not find any correlation between an element abundance and projected rotation velocity in roAp stars.

For He-weak stars, we found correlation between iron abundance and  $T_{\text{eff}}$ . There is no significant correlation between abundances and surface gravity, as well as abundances and projected rotation velocity.

For He-rich stars, correlation between helium, nitrogen abundances, and effective temperature was detected. For surface gravity, we found correlation for helium, carbon, nitrogen, and oxygen abundances, and for projected rotation velocity, we found correlations for oxygen and magnesium abundances, and marginally for helium abundance.

It is important to note that the abundances and physical parameters of stars, which were measured by different authors with different techniques, could affect the statistical results. However, for several stars in our data base with given parameters and obtained abundances from different sources, the differences in determinations

**Table 1.** Spearman’s rank test results for roAp, He-weak (He-w), and He-rich (He-r) stars. Statistically significant correlations are shown in boldface ( $p$ -value  $\leq 0.05$ ), marginal ones are underlined ( $0.05 < p$ -value  $< 0.06$ ).

Elements	$\epsilon(T_{\text{eff}})$			$\epsilon(\log g)$			$\epsilon(v \sin i)$		
	$\rho$	$p$	$N$	$\rho$	$p$	$N$	$\rho$	$p$	$N$
	<i>roAp</i>								
Li	0.23	0.452	13	<b>0.61</b>	<b>0.027</b>	<b>13</b>	-0.32	0.286	13
O	<b>-0.58</b>	<b>0.005</b>	<b>22</b>	0.23	0.299	22	-0.17	0.449	22
Na	<u>0.44</u>	<u>0.053</u>	20	-0.14	0.551	20	0.14	0.557	20
Si	<b>0.36</b>	<b>0.043</b>	<b>32</b>	0.02	0.908	32	0.02	0.931	32
Ca	<b>0.65</b>	<b>0.000</b>	<b>33</b>	-0.01	0.976	33	0.11	0.545	33
Sc	0.20	0.377	22	<b>0.42</b>	<b>0.049</b>	<b>22</b>	-0.22	0.321	22
Ti	<b>0.73</b>	<b>0.000</b>	<b>28</b>	0.19	0.331	28	-0.13	0.495	28
V	-0.19	0.409	21	<b>0.54</b>	<b>0.012</b>	<b>21</b>	-0.01	0.969	21
Cr	<b>0.81</b>	<b>0.000</b>	<b>36</b>	-0.27	0.114	36	0.19	0.276	36
Mn	<b>0.59</b>	<b>0.003</b>	<b>24</b>	-0.11	0.614	24	-0.09	0.677	24
Fe	<b>0.82</b>	<b>0.000</b>	<b>36</b>	-0.06	0.729	36	-0.03	0.864	36
Ni	<b>0.76</b>	<b>0.000</b>	<b>24</b>	0.27	0.197	24	0.092	0.669	24
La	<b>0.46</b>	<b>0.020</b>	<b>25</b>	0.14	0.499	25	0.10	0.632	25
Eu	0.24	0.174	33	<b>0.35</b>	<b>0.048</b>	<b>33</b>	-0.30	0.095	33
Tb	<b>-0.53</b>	<b>0.036</b>	<b>16</b>	-0.21	0.431	16	-0.18	0.493	16
Dy	-0.10	0.698	18	<b>-0.56</b>	<b>0.015</b>	<b>18</b>	-0.43	0.075	18
Yb	<b>0.62</b>	<b>0.014</b>	<b>15</b>	-0.29	0.289	15	0.02	0.955	15
	<i>He - w</i>								
Fe	<b>0.55</b>	<b>0.043</b>	<b>14</b>	0.19	0.525	14	-0.26	0.399	13
	<i>He - r</i>								
He	<b>0.46</b>	<b>0.019</b>	<b>26</b>	<b>-0.40</b>	<b>0.043</b>	<b>26</b>	<u>-0.44</u>	<u>0.051</u>	<u>20</u>
C	-0.29	0.138	27	<b>-0.44</b>	<b>0.022</b>	<b>27</b>	-0.02	0.923	22
N	<b>-0.41</b>	<b>0.038</b>	<b>26</b>	<b>0.39</b>	<b>0.048</b>	<b>26</b>	0.23	0.311	22
O	-0.12	0.635	18	<b>0.56</b>	<b>0.016</b>	<b>18</b>	<b>0.55</b>	<b>0.034</b>	<b>15</b>
Mg	-0.23	0.358	18	0.32	0.201	18	<b>0.63</b>	<b>0.011</b>	<b>15</b>

are always within the errors of any unique measurement, so the impact of inhomogeneous data on our statistical results should be negligible.

To check whether multiplicity is playing a role in the abundance anomalies, we have considered single CP stars (in this case *multiplicity* is equal to 1) and those being in binary systems (in this case *multiplicity* is equal to 2).<sup>4</sup> Following Paper II, we have applied the well-known *Anderson–Darling* (AD) test<sup>5</sup> for roAp, He-weak, and He-rich stars. With this test, we do not find any relation between abundance anomalies and multiplicity in all mentioned CP-type stars, possibly because of the lack of data. However, our results on the multiplicity test should be taken into consideration with caution, because of Simbad data incompleteness.

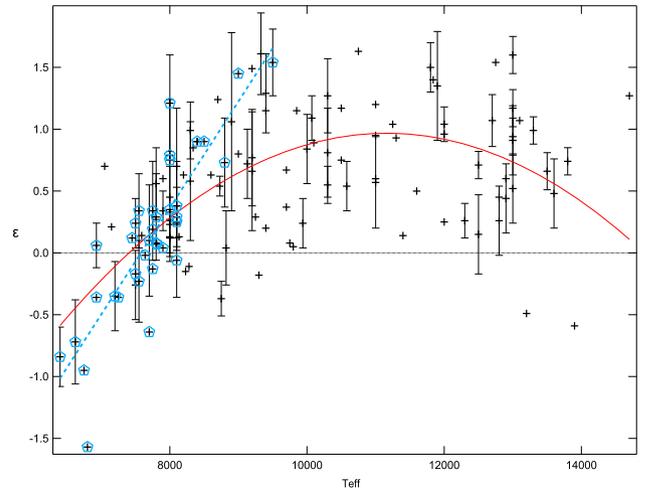
## 5 DISCUSSION

### 5.1 roAp stars

RoAp stars are essentially defined as being Ap stars for which rapid oscillations are detected. At first view, their abundance peculiarities

<sup>4</sup>It would be more reasonable to consider only the spectroscopic/interacting binaries (multiplicity is equal to 4) but because of the lack of published observational data, particularly for those binaries, we cannot perform such analysis.

<sup>5</sup>The null hypothesis for the two-sample non-parametric AD test corresponds to the case when two distributions are drawn from the same parent population, and the alternative hypothesis that they are not (again, with the threshold of 5 per cent for  $p$ -values). For more details, the reader is referred to Engmann & Cousineau (2011).



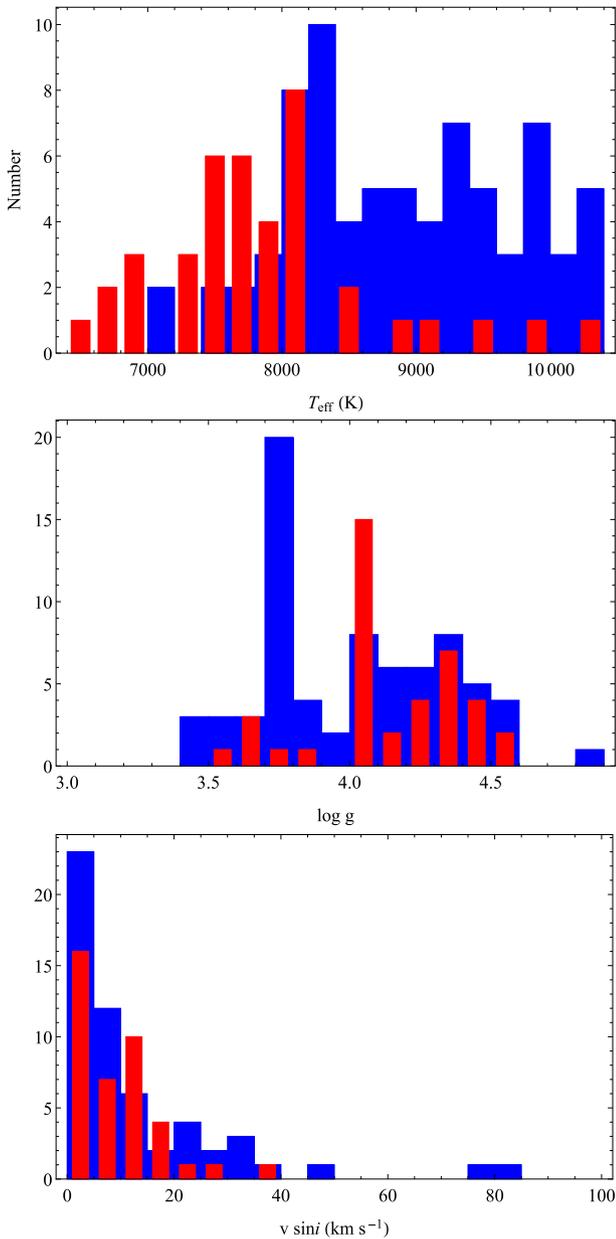
**Figure 2.** Fe abundances ( $\epsilon$ ) in ApBp and roAp stars versus  $T_{\text{eff}}$ . The red solid curve is a polynomial fit showing the correlation of  $\epsilon$  and  $T_{\text{eff}}$  for all ApBp stars (including roAp) of our data base for which iron abundance was measured. These Fe abundances and the red solid curve were shown in fig. 5 of Paper II. The light-blue symbols surround those of that stars that are identified as roAp stars in this work. The light blue dashed line is the linear fit for these stars.

look like those of non-oscillating Ap stars if one excepts the very peculiar case of Przybylski’s star (HD101065). Pulsations are supposed to be excited by  $\kappa$ -mechanism (see for instance Balmforth et al. 2001), which suggests a strong dependence on opacities in the atmosphere, and so, on the abundance stratifications produced by atomic diffusion.

To be more specific in analysing observational differences between the whole ApBp group and the subgroup of roAp stars, we have reconsidered in Fig. 2 the fig. 5 of Paper II, and revealed the contribution of roAp stars. Fig. 2 shows the iron abundances (with respect to the Sun) versus  $T_{\text{eff}}$  for all ApBp stars (black crosses) including roAp stars, and the corresponding polynomial fit (red line) shown in Paper II (such a trend may found also in Bailey et al. 2014). The light blue symbols surround those of stars that are now identified as roAp stars in our data base. We have checked that the  $T_{\text{eff}}$  of the maximum of the polynomial fit (red line) does not change significantly (nor the shape) when the fit is recomputed removing the roAp stars, it remains close to 11 000 K, slightly shifted towards 11 300 K. However, we notice that roAp stars have a major (or even exclusive) contribution at the cool end of the ApBp group, and are clearly responsible for the Fe deficiency we noticed in Section 3.

We show in Fig. 3, the histograms of the  $T_{\text{eff}}$ ,  $\log g$ , and  $v \sin i$  for roAp stars, to be compared to those for cool ApBp stars where rapid oscillation was not detected. The hottest roAp in our data base (HD9996a<sup>6</sup>) has  $T_{\text{eff}} = 10\,300$  K; therefore, this is the upper temperature limit we impose to our selection of cool ApBp stars (hereafter, we will call them simply Ap stars). We notice that for the roAps the histogram of  $T_{\text{eff}}$  has a maximum around 8000 K followed by a sharp decrease. There is also a maximum close to the same temperature for Ap stars, however, contrarily to roAp stars, it is not followed by a steady decrease. Considering  $\log g$ , the maximum is close to 4.0 for roAp stars, while it appears smaller for Ap stars that suggests that roAp stars are less evolved. Concerning

<sup>6</sup>Notice that the abundances for elements lighter than  $Z = 46$  are not available for this star except for vanadium.



**Figure 3.** Histograms of the  $T_{\text{eff}}$ ,  $\log g$ ,  $v \sin i$  for roAp and cool ApBp stars by red and blue colours, respectively. HD320764 that has  $225 \text{ km s}^{-1}$  is outside of the  $v \sin i$  histogram).

the  $v \sin i$ , there is no roAp stars with higher projected velocity than  $35 \text{ km s}^{-1}$ , contrarily to Ap stars where higher velocities are found. We applied AD test on roAp and cool ApBp stars' physical parameters ( $T_{\text{eff}}$ ,  $\log g$ , and  $v \sin i$ ) and in two cases (for  $T_{\text{eff}}$  and  $\log g$ ) the distributions of physical parameters for roAp and cool ApBp stars are significantly different ( $p$ -value  $< 0.05$ ). For  $v \sin i$ , the  $p$ -value  $= 0.357$ , which means that the distributions are consistent with each other.

## 5.2 He-weak stars

Since one has only 20 He-w stars in our data base, and since determinations of He abundance from spectral data (that determines the belonging to this CP group) may be especially difficult, one

cannot safely proceed with histograms as we do above for ApBp stars.

In Section 3, we have noticed that the trend of metal overabundances is more or less similar to what is found for ApBp stars (including HgMn). This is not very surprising since CP stars with  $T_{\text{eff}} \lesssim 18000 \text{ K}$  should be generally He deficient according to atomic diffusion model (see Michaud et al. 2015). Actually, one could question the existence of a distinct He-w type. One cannot exclude that these stars simply belong to the other CP types with  $T_{\text{eff}} \lesssim 18000 \text{ K}$ .

## 5.3 He-rich stars

Considering the histograms for the 28 He-r stars we have included in the data base, we do not see very noteworthy structure in the distribution of the three stellar parameters. Apart the hottest member of the group (HD68450), all He-r have  $16000 \lesssim T_{\text{eff}} \lesssim 26000 \text{ K}$ , with a moderate peak around  $23000 \text{ K}$ . Their  $\log g$  most often (but not always) are larger than 4.0, which suggests that they are less evolved than usual CP-type stars.

He-rich stars may be understood in the framework of the unified model proposed initially by Vauclair (1975), and recently discussed in Michaud et al. (2015, see especially section 8.3.2.3). In a few words, the model considers that atomic diffusion has to be combined with the increasing mass-loss (or wind) with increasing effective temperature. Elements that undergo strong radiative acceleration and which appear overabundant in ApBp (and HgMn) stars are more easily expelled from the atmosphere of He-rich stars (that are hotter). This is because, the wind and the diffusion velocities are both positive, and wind velocity is expected to be larger than for ApBp stars. This does not mean that these elements will become underabundant, since mass-loss corresponds to a continual flux of matter from deep layers where abundances may be homogeneously distributed. Stronger is the mass-loss rate, faster is the replacement of the superficial matter by the deeper one. So, a strong mass-loss impeded atomic diffusion in stratifying abundances. Elements with weaker radiative accelerations (like He, or CNO), which sink by gravitational settling in usual CP stars (negative diffusion velocity), may accumulate in the atmosphere of He-r stars, according to the value of the wind velocity compared to the one of diffusion. Notice that this simple model is not generally accepted (Krtićka, Kubát & Groot 2006), but as much as we know, no alternate model is presently proposed. One cannot say that abundances in He-r stars other than the ones for He, as shown in Fig. 1(b), support strongly the simple unified model that is presently still qualitative. However, the underabundances observed for CNO and some heavier metals appear less pronounced than in ApBp stars as could be expected in the framework of the unified model. We would like to emphasize that numerical models including atomic diffusion together with mass-loss are presently lacking for hot CP stars (namely He-r).

## 5.4 Abundance stratification build-up versus stellar parameters and evolution

In this work, as in our previous Papers I and II, we have looked for correlations of superficial abundances with respect to physical parameters of stars. This is motivated by the fact that atomic diffusion cannot be directly observed, but only through its secondary effects such as for atmospheres superficial abundance anomalies or element distribution, for interiors through opacity effects (convection, pulsation, for instance). Because any star is different from

each other, and because atomic diffusion is extremely sensitive to any perturbation, theoretical models at this time may only address general trends, this is why looking for such correlations is helpful. The reader may find in Alecian (2015) a list of physical processes that should be considered for atmospheres (some of them are not yet included in numerical models simulating the abundance stratification build-up).

As a good example of the interest in using observed abundance correlation with effective temperature, it is common to cite the trend of Mn overabundances found by Smith & Dworetzky (1993) for HgMn stars. It was previously predicted by the theoretical study of manganese NLTE radiative acceleration by Alecian & Michaud (1981). This trend has been identified as to be due to Mn stratification process in optically thin layers, above  $\tau \approx 1$ , where diffusion time-scales are much shorter than stellar evolution time as shown by Alecian, Stift & Dorfi (2011). These authors have also shown that abundance stratification in atmospheres can rapidly adjust to changes in atmospheric parameters (in less than 10–1000 yr according to the element). Therefore, the trend found for Mn is not due to secular evolution: even if the effective temperature changes with the star age, the spread of  $T_{\text{eff}}$  is mainly due to the variety of stellar masses for which stratification of abundances can occur. However, this does not mean that secular evolution as found by Bailey et al. (2014) does not affect the observed abundance peculiarities. For instance, considering the atmospheric abundance evolution with time observed by Bailey et al. (2014) for many elements, one may expect that the shape of abundance peculiarity trends should be different comparing stellar clusters having different ages. On another hand for instance, one expects that a young HgMn stars with  $T_{\text{eff}}$  slightly hotter than 10 000 K may become Am stars during their evolution on the main sequence (as suggested by Michaud et al. 2015, section 9.1.1).<sup>7</sup> The situation is different when one considers the gravity, which spreads from 3.4 to 4.6 in dex. Because these different  $\log g$  are due to stellar evolution on the main-sequence. This is what we mean by writing in Section 1 that correlation with gravity may show an effect of evolution. Most of published discussions confronting theoretical models for atmospheres and observations have been done considering *equilibrium solutions* of equations for abundance stratifications.<sup>8</sup> However, as did also in Bailey et al. (2014), we draw the reader’s attention on the limits of this approach.<sup>9</sup> Indeed, equilibrium solution for a given element corresponds to the maximum abundance that can be supported by the radiation field in each layer. The stratification build-up is actually complex and several numerical simulations carried out by Stift & Alecian (2016), and more recently by Alecian & Stift (2019) have shown that stratification build-up converge rather to stationary solutions quite different from equilibrium ones, especially when a stellar mass-loss (or a wind) is assumed. In addition, one has to consider for ApBp stars the existence of a strong magnetic field that always affects strongly atomic diffusion velocities (as well

by its strength than by its orientation). Observations of Bailey et al. (2014) show quite well that abundance peculiarities are correlated with the magnetic field intensity. Notice that the first 3D simulations in magnetic atmospheres have been carried out by Alecian & Stift (2017) in equilibrium hypothesis (same studies for non-equilibrium hypotheses are in progress). It is clear that correlation with stellar parameters as shown in this work and others cannot reveal this complex reality, except through the well-known dispersion of abundances from star to star that may be easily noticed in Fig. 1 or 2.

## 6 CONCLUSIONS

In this work, we present adjunction to our data base (discussed in Paper II) of 88 CP stars with their fundamental parameters and chemical abundances. As in Paper II, these data have been obtained by compiling the data obtained through high-resolution spectroscopy and published by various authors. The adjunction consists in 20 He-weak and 28 He-rich stars. We have also updated the CP-type of 40 ApBp stars that are actually roAp stars. This new compilation allows us to compare the abundance peculiarities observed for these CP-types to those of the types considered in Paper II.

For each CP-type, we applied Spearman’s rank correlation test on the chemical abundances according to physical parameters (effective temperature, surface gravity, and projected rotation velocity). We have found that there are significant correlations for effective temperature and surface gravity and a few ones with rotation velocity in He-rich stars. As we mentioned in Paper II, all these correlations could help in identifying which of the physical parameters could have a significant effect on abundance stratification process in these stars. Among the limits of such a study, we would like to point out that an important source of errors on abundances published in the literature is the fact that abundance determinations are generally done assuming homogeneous distribution of elements in CP stars atmospheres, although CP stars (except for AmFm or possibly He-r stars) have certainly strongly stratified abundances in their atmospheres and inhomogeneous horizontal distributions of elements in magnetic cases. Our statistical results are consistent with the important role of radiative accelerations in roAp and He-weak stars. We may also question the existence of a distinct He-weak CP type. He-rich stars appear to be clearly different from other main-sequence CP-types stars. This could be possibly due, as proposed by the unified model (Vauclair 1975), to the competition between a strong mass-loss (increasing with  $T_{\text{eff}}$ ) with atomic diffusion. However, this unified model still needs to be confirmed by numerical simulations.

In addition, we tried to apply AD test to only single and binary-type stars but possibly because of the lack of data we could not get any relation between abundance anomalies and multiplicity. We are convinced that more stars in the data base should present better results about correlations. Therefore, large catalogues such as the one of *Gaia* mission will have a significant impact in near future.

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<sup>7</sup>During evolution,  $T_{\text{eff}}$  decreases and that may trigger the appearance of a superficial convection zone which characterizes the structure of AmFm stars. HgMn stars are considered to be the continuation of the AmFm group to hotter effective temperatures. Both groups are non-magnetic.

<sup>8</sup>These solutions assume that stratification build-up reaches a state such that atomic diffusion fluxes are zero everywhere in the atmosphere (see the detailed discussion in Stift & Alecian 2016).

<sup>9</sup>To consider equilibrium, solution was justified, because stationary solutions for atmospheres may be obtained only through very heavy numerical calculations that are achieved only very recently by solving the time-dependent continuity equation for concentrations in optically thin media.

## REFERENCES

- Adelman S. J., Caliskan H., Cay T., Kocer D., Tektanali H. G., 1999, *MNRAS*, 305, 591
- Alecian G., 2015, *MNRAS*, 454, 3143
- Alecian G., Michaud G., 1981, *ApJ*, 245, 226
- Alecian G., Stift M. J., 2017, *MNRAS*, 468, 1023
- Alecian G., Stift M. J., 2019, *MNRAS*, 482, 4519
- Alecian G., Stift M. J., Dorfi E. A., 2011, *MNRAS*, 418, 986
- Alentiev D., Kochukhov O., Ryabchikova T., Cunha M., Tsymbal V., Weiss W., 2012, *MNRAS*, 421, L82
- Allende Prieto C., Lambert D. L., 1999, *A&A*, 352, 555
- Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, *ARA&A*, 47, 481 (AGS09)
- Bailey J. D., Landstreet J. D., Bagnulo S., 2014, *A&A*, 561, A147
- Balmforth N. J., Cunha M. S., Dolez N., Gough D. O., Vauclair S., 2001, *MNRAS*, 323, 362
- Berger J., 1956, Contribution de l'Institut d'Astrophysique de Paris Series A, 217
- Briquet M., Aerts C., Lüftinger T., De Cat P., Piskunov N. E., Scuflaire R., 2004, *A&A*, 413, 273
- Bruntt H. et al., 2008, *MNRAS*, 386, 2039
- Carrier F., North P., Udry S., Babel J., 2002, *A&A*, 394, 151
- Castelli F., 1998, *CoSka*, 27, 192
- Castelli F., Parthasarathy M., Hack M., 1997, *A&A*, 321, 254
- Castro N. et al., 2017, *A&A*, 597, L6
- Catanzaro G., Frasca A., Molenda-Žakowicz J., Marilli E., 2010, *A&A*, 517, A3
- Cowley C. R., Hartoog M. R., Aller M. F., Cowley A. P., 1973, *ApJ*, 183, 127
- Cowley C. R., Elste G. H., Urbanski J. L., 1978, *PASP*, 90, 536
- Cowley C. R., Ryabchikova T., Kupka F., Bord D. J., Mathys G., Bidelman W. P., 2000, *MNRAS*, 317, 299
- Cunha M. S., Alentiev D., Brandão I. M., Perraut K., 2013, *MNRAS*, 436, 1639
- Deutsch A. J., 1947, *ApJ*, 105, 283
- Drake N. A., Nesvacil N., Hubrig S., Kochukhov O., de La Reza R., Polosukhina N. S., Gonzalez J. F., 2005, in Hill V., Francois P., Primas F., eds, IAU Symp. Vol. 228, From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution, Cambridge Univ. Press, Cambridge. p. 89
- Elkin V. G., Kurtz D. W., Freyhammer L. M., Hubrig S., Mathys G., 2008, *MNRAS*, 390, 1250
- Elkin V. G., Kurtz D. W., Mathys G., Freyhammer L. M., 2010, *MNRAS*, 404, L104
- Elkin V. G., Kurtz D. W., Shibahashi H., Saio H., 2014, *MNRAS*, 444, 1344
- Engmann S., Cousineau D., 2011, *J. Appl. Quant. Methods*, 6, 1
- Feigelson E. D., Babu G. J., 2012, *Modern Statistical Methods for Astronomy*, Cambridge Univ. Press, Cambridge
- Fossati L., Bagnulo S., Monier R., Khan S. A., Kochukhov O., Landstreet J., Wade G., Weiss W., 2007, *A&A*, 476, 911
- Fossati L., Folsom C. P., Bagnulo S., Grunhut J. H., Kochukhov O., Landstreet J. D., Paladini C., Wade G. A., 2011, *MNRAS*, 413, 1132
- Freyhammer L. M., Elkin V. G., Kurtz D. W., Mathys G., Martinez P., 2008, *MNRAS*, 389, 441
- Gelbmann M. J., 1998, *CoSka*, 27, 280
- Gelbmann M., Ryabchikova T., Weiss W. W., Piskunov N., Kupka F., Mathys G., 2000, *A&A*, 356, 200
- Gerbaldi M., Floquet M., Faraggiana R., van't Veer-Menneret C., 1989, *A&AS*, 81, 127
- Ghazaryan S., Alecian G., 2016, *MNRAS*, 460, 1912 (Paper I)
- Ghazaryan S., Alecian G., Hakobyan A. A., 2018, *MNRAS*, 480, 2953 (Paper II)
- Glagolevskij Y. V., Leushin V. V., Chuntunov G. A., Shulyak D., 2006, *Astron. Lett.*, 32, 54
- Glagolevskij Y. V., Leushin V. V., Chuntunov G. A., 2007, *Astrophys. Bull.*, 62, 319
- Groote D., Kaufmann J. P., Lange A., 1982, *A&AS*, 50, 77
- Hack M., Castelli F., Polosukhina N. S., Mavanushenko V. P., 1997a, *Astron. Astrophys. Trans.*, 13, 283
- Hack M., Polosukhina N. S., Malanushenko V. P., Castelli F., 1997b, *A&A*, 319, 637
- Hubrig S., Castelli F., González J. F., Elkin V. G., Mathys G., Cowley C. R., Wolff B., Schöller M., 2012, *A&A*, 542, A31
- Hunger K., Groote D., 1999, *A&A*, 351, 554
- Hunger K., Groote D., Heber U., 1991, in Michaud G., Tutukov A. V., eds, IAU Symp. Vol. 145, Evolution of Stars: the Photospheric Abundance Connection, Kluwer Academic Publishers, Dordrecht. p. 173
- Joshi S., Ryabchikova T., Kochukhov O., Sachkov M., Tiwari S. K., Chakradhari N. K., Piskunov N., 2010, *MNRAS*, 401, 1299
- Kato K.-I., Sadakane K., 1999, *PASJ*, 51, 23
- Kılıçoğlu T., Monier R., Richer J., Fossati L., Albayrak B., 2016, *AJ*, 151, 49
- Kochukhov O., 2003, *A&A*, 404, 669
- Kochukhov O., Bagnulo S., 2006, *A&A*, 450, 763
- Kochukhov O., Tsymbal V., Ryabchikova T., Makaganyk V., Bagnulo S., 2006, *A&A*, 460, 831
- Kochukhov O., Ryabchikova T., Bagnulo S., Lo Curto G., 2008, *A&A*, 479, L29
- Kochukhov O., Shulyak D., Ryabchikova T., 2009, *A&A*, 499, 851
- Krtićka J., Kubát J., Groote D., 2006, *A&A*, 460, 145
- Krtićka J., Mikulášek Z., Henry G. W., Zverko J., Žižovský J., Skalický J., Zvěřina P., 2009, *A&A*, 499, 567
- Kupka F., Ryabchikova T., Bolgova G., Kuschnig R., Weiss W. W., Mathys G., Le Contel J. M., 1994, in Zverko J., Ziznovsky J., eds, Chemically Peculiar and Magnetic Stars, Astronomical Institute, Slovak Academy of Sciences, Slovak Republic. p. 130
- Kupka F., Paunzen E., Iliev I. K., Maitzen H. M., 2004, *MNRAS*, 352, 863
- Kurtz D. W., 1978, *Inf. Bull. Var. Stars*, 1436, 1
- Kurtz D. W., 1982, *MNRAS*, 200, 807
- Kurtz D. W., Elkin V. G., Mathys G., 2007, *MNRAS*, 380, 741
- Kurtz D. W. et al., 2011, *MNRAS*, 414, 2550
- Landstreet J. D., 1988, *ApJ*, 326, 967
- LeBlanc F., 2010, *An Introduction to Stellar Astrophysics*, Wiley
- Martinez P., Kurtz D. W., Heller C. H., 1990, *MNRAS*, 246, 699
- Matthews J. M., Kurtz D. W., Martinez P., 1999, *ApJ*, 511, 422
- Michaud G., 1970, *ApJ*, 160, 641
- Michaud G., Alecian G., Richer J., 2015, *Atomic Diffusion in Stars*, Astronomy and Astrophysics Library, Springer International Publishing, Switzerland
- Mon M., Hirata R., Sadakane K., 1981, *PASJ*, 33, 413
- Nesvacil N., Shulyak D., Ryabchikova T. A., Kochukhov O., Akberov A., Weiss W., 2013, *A&A*, 552, A28
- Netopil M., Paunzen E., Hümmelich S., Bernhard K., 2017, *MNRAS*, 468, 2745
- Niemczura E. et al., 2015, *MNRAS*, 450, 2764
- Norris J., 1971, *ApJS*, 23, 193
- Osmer P. S., Peterson D. M., 1974, *ApJ*, 187, 117
- Polosukhina N. et al., 2004, in Zverko J., Ziznovsky J., Adelman S. J., Weiss W. W., eds, IAU Symp. Vol. 224, The A-Star Puzzle, Cambridge Univ. Press, Cambridge. p. 665
- Przybilla N. et al., 2016, *A&A*, 587, A7
- Rachkovskaya T. M., Lyubimkov L. S., Rostopchin S. I., 2006, *Astron. Rep.*, 50, 123
- Ryabchikova T., 1998, *CoSka*, 27, 319
- Ryabchikova T. A., Romanovskaya A. M., 2017, *Astron. Lett.*, 43, 252
- Ryabchikova T. A., Adelman S. J., Weiss W. W., Kuschnig R., 1997a, *A&A*, 322, 234
- Ryabchikova T. A., Landstreet J. D., Gelbmann M. J., Bolgova G. T., Tsymbal V. V., Weiss W. W., 1997b, *A&A*, 327, 1137
- Ryabchikova T. A., Savanov I. S., Hatzes A. P., Weiss W. W., Handler G., 2000, *A&A*, 357, 981
- Ryabchikova T. A., Savanov I. S., Malanushenko V. P., Kudryavtsev D. O., 2001, *Astron. Rep.*, 45, 382

- Ryabchikova T., Nesvacil N., Weiss W. W., Kochukhov O., Stütz C., 2004, *A&A*, 423, 705
- Ryabchikova T., Leone F., Kochukhov O., 2005, *A&A*, 438, 973
- Ryabchikova T. et al., 2006, *A&A*, 445, L47
- Ryabchikova T., Kochukhov O., Bagnulo S., 2008, *A&A*, 480, 811
- Sadakane K., Takada M., Jugaku J., 1983, *ApJ*, 274, 261
- Saffe C., Levato H., 2014, *A&A*, 562, A128
- Sargent W. L. W., 1964, *ARA&A*, 2, 297
- Savanov I. S., Kochukhov O. P., 1998, *Astron. Lett.*, 24, 516
- Semenko E. A., Sachkov M. E., Ryabchikova T. A., Kudryavtsev D. O., Piskunov N. E., 2008, *Astron. Lett.*, 34, 413
- Shavrina A. V. et al., 2001, *A&A*, 372, 571
- Shavrina A. et al., 2004, in Zverko J., Ziznovsky J., Adelman S. J., Weiss W. W., eds, *IAU Symp. Vol. 224, The A-Star Puzzle*, Cambridge Univ. Press, Cambridge. p. 711
- Shavrina A., Polosukhina N. S., Drake N. A., Kudryavtsev D. O., Gopka V. F., Yushchenko V. A., Yushchenko A. V., 2013a, preprint ([arXiv:1304.4175](https://arxiv.org/abs/1304.4175))
- Shavrina A. V., Khalack V., Glagolevskij Y., Lyashko D., Landstreet J., Leone F., Polosukhina N. S., Giarrusso M., 2013b, *Odessa Astron. Publ.*, 26, 112
- Shultz M. et al., 2015, *MNRAS*, 449, 3945
- Shulyak D., Ryabchikova T., Mashonkina L., Kochukhov O., 2009, *A&A*, 499, 879
- Shulyak D., Ryabchikova T., Kildiyarova R., Kochukhov O., 2010, *A&A*, 520, A88
- Smalley B. et al., 2015, *MNRAS*, 452, 3334
- Smith K. C., 1996, *Ap&SS*, 237, 77
- Smith K. C., Dworetzky M. M., 1993, *A&A*, 274, 335
- Spearman C., 1904, *Am. J. Psychol.*, 15, 72
- Stift M. J., Alecian G., 2016, *MNRAS*, 457, 74
- Takada-Hidai M., Takeda Y., 1996, *PASJ*, 48, 739
- Takada-Hidai M., Sadakane K., Jugaku J., 1986, *ApJ*, 304, 425
- Vauclair S., 1975, *A&A*, 45, 233
- Vilhu O., Tuominen I. V., Boyarchuk A. A., 1976, in Weiss W. W., Jenkner H., Wood H. J., eds, *IAU Colloq. 32: Physics of Ap Stars*, Universitätssternwarte Wien, Austria. p. 563
- Wahlgren G. M., Hubrig S., 2004, *A&A*, 418, 1073
- Weiss W. W., Ryabchikova T. A., Kupka F., Lueftinger T. R., Savanov I. S., Malanushenko V. P., 2000, in Szabados L., Kurtz D., eds, *ASP Conf. Ser. Vol. 203, IAU Colloq. 176: The Impact of Large-Scale Surveys on Pulsating Star Research*. Astron. Soc. Pac., San Francisco, p. 487
- Zboril M., North P., 1998, *CoSka*, 27, 371
- Zboril M., North P., 1999, *A&A*, 345, 244
- Zboril M., North P., 2000, *CoSka*, 30, 12
- Zboril M., Glagolevskij Y. V., North P., 1994, in Zverko J., Ziznovsky J., eds, *Chemically Peculiar and Magnetic Stars*, Astronomical Institute, Slovak Academy of Sciences, Slovak Republic. p. 105
- Zboril M., North P., Glagolevskij Y. V., Betrix F., 1997, *A&A*, 324, 949

## APPENDIX

This table shows the main physical parameters of the 88 CP stars added or updated in our catalogue (see [Paper II](#)). The complete data (including other physical parameters and detailed abundances are available as online data).

- (i) Column 1: the star identification, HD number if available. (*Star id*)
- (ii) Column 2: another usual identification taken from Simbad archive. (*Other id*)
- (iii) Column 3: the CP type: roAp, He-w, He-r. (*CP type*)
- (iv) Column 4: The multiplicity indicator (*Mult.*) for each star is given by the numbers 1 to 6, which have following meaning:
  - (a) 1: single star,
  - (b) 2: star in double system,
  - (c) 3: star in cluster,
  - (d) 4: spectroscopic binary,
  - (e) 5: star in multiple system, and
  - (f) 6: eclipsing binary.
- (v) Column 5–7: effective temperature (K), gravity, projected rotation velocity ( $\text{km s}^{-1}$ ) if available, using usual symbols.
- (vi) Column 8: References of publications (listed below the table) from which the physical parameters and chemical abundances of those stars are compiled.

**Table A1.** CP stars and their fundamental parameters.

Star id	Other id	CP type	Mult.	$T_{\text{eff}}$ (K)	$\log g$	$v \sin i$	References
HD 201601	$\gamma$ Equ	roAp	2	7750	4.2	4.5	70,81,144,165,183
HD 203932	<i>BI Mic</i>	roAp	1	7450	4.3	12.5	70,149
HD 24712	<i>DO Eri</i>	roAp	1	7250	4.3	7.0	40,70,169
HD 217522	HIP 113711	roAp	1	6750	4.3	12.0	70
HD 166473	TYC 7900-2776-1	roAp	1	8000	4.4	18.0	70,166
HD 128898	$\alpha$ Cir	roAp	2	7900	4.2	12.5	23,70,98
HD 204411	HR 8216	roAp	3	8400	3.5	5.4	39,96,152
HD 69013	TYC 5996-1937-1	roAp	1	7500	4.5	4.0	67,156
HD 96237	TYC 6640-1026-1	roAp	1	7800	4.43	6.0	67,156
HD 118022	HR 5105	roAp	1	9950	4	10.0	72,156
HD 188041	HR 7575	roAp	1	8800	4	4.0	72,89,151,156
TYC 3545-2756-1	KIC 10195926	roAp	1	7200	3.6	21.0	56,103
HD 101065	HIP 56709	roAp	1	6622	4.06	3.5	40,155,165,170
HD 103498	HR 4561	roAp	2	9500	3.6	12.0	88
HD 115226	HIP 64883	roAp	1	7640	4	27.5	97
HD 178892	HIP 94155	roAp	2	7700	4	9.0	153
HD 92499	HIP 52218	roAp	1	7810	4	2.0	53,67
HD 143487	TYC 7329-1814-1	roAp	4	6930	4	2.0	53,67
HD 65339	53 Cam	roAp	1	8500	4	13.0	72,105
HD 154708	HIP 84017	roAp	4	6800	4.11	6.0	81
HD 184471	HIP 96177	roAp	1	7500	4	10.0	150,195
HD 42659	HIP 29635	roAp	4	8100	4.2	19.0	150,195
HD 176232	10 Aql	roAp	1	7550	4	4.0	44,124,149,151,160
HD 122970	HIP 68790	roAp	1	6930	4.4	5.5	40,93,149,155,195
HD 137949	33 Lib	roAp	1	7750	4.5	2.0	151,165
HD 12098	Renson 3085	roAp	2	7800	4.3	10.0	151,167
HD 60435	HIP 36537	roAp	2	8100	4.2	12.0	134,151,164
HD 75445	HIP 43257	roAp	1	7700	4.3	2.0	151
HD 116114	HIP 65203	roAp	1	8000	4.1	3.0	102,151
HD 137909	$\beta$ CrB	roAp	1	8000	4.3	3.0	32,78,79,100,151,183
HD 110066	HR 4816	roAp	1	9000	4.3	9.0	146,151
HD 225914	KIC 4768731	roAp	1	8100	4	15.0	130,172
HD 177765	TYC 6882-1808-1	roAp	2	8000	3.8	2.5	14
HD 965	TYC 4664-318-1	roAp	1	7500	4	3.0	155,167
HD 134214	TYC 5592-971-1	roAp	1	7315	4.45	2.0	155,165
HD 213637	TYC 6391-745-1	roAp	4	6400	3.6	3.5	93
HD 3980	TYC 8469-1595-1	roAp	1	8100	4	16.5	47,52
HD 9996a	HR 465a	roAp	4	10 300	3.7	2.0	38,39
HD 115708	TYC 1996-1624-1	roAp	1	7550	4	11.0	162
HD 83368	HIP 47145	roAp	2	7750	4	35.0	134,164
HD 318101	TYC 7380-116-1	He-w	3	15 400	4	31.0	205
HD 61556	HR 2949	He-w	2	18 500	4.1	61.0	206
HD 5737	$\alpha$ Scl	He-w	1	13 600	3.2	17.0	182,207
HD 123182	TYC 8268-3344-1	He-w	3	10 800	4.25	81.0	209
TYC 3128-248-1	HIP 93941	He-w	1	19 300	3.8	10.0	210
HD 177410	HR 7224	He-w	1	14 500	4.2		211
HD 37058	TYC 4774-927-1	He-w	3	17 000	3.8	25.0	212
HD 212454	HR 8535	He-w	1	14 400	3.83	40.0	157,182,212
HD 224926	29 Psc	He-w	1	14 000	3.85	68.0	212
HD 30122	HR 1512	He-w	1	15 200	3.52	30.0	213
HD 21699	HR 1063	He-w	3	16 000	4.15	35.0	214
HD 217833	HR 8770	He-w	2	15 450	3.88	35.0	157,182,214
HD 120709	3 Cen A	He-w	2	17 500	3.8	20.0	215,217
HD 131120	HR 5543	He-w	2 or 5	18 250	4.1		216
HD 105382	HR 4618	He-w	2	17 400	4.18		216
HD 138769	d Lup	He-w	2	17 500	4.22		216
HD 37752	HR 1951	He-w	1	15 700	3.9		157,182
HD 44953	HR 2306	He-w	2	17 000	4.1		157,182
HD 23408	20 Mon	He-w	3	12 600	3.2	45.0	218
HD 149363	TYC 5060-966-1	He-w	1	30 000	4	95.0	221

Table A1 – continued

Star id	Other id	CP type	Mult.	$T_{\text{eff}}$ (K)	log $g$	$v \sin i$	References
TYC 8976-5133-1	CPD-622124	He-r	3	23 650	3.95	75.0	219
TYC 8613-98-1	CPD-573509	He-r	3	23 750	4.05	35.0	220
HD 92938	HR 4196	He-r	3	16 000	4	125.0	221,222,226
HD 96446	TYC 8627-156-1	He-r	1	23 000	4	0.0	221,222,226
HD 133518	TYC 8305-2754-1	He-r	1	20 000	4	0.0	221,222,226
HD 145939	DM-134383	He-r	1	18 000	4	55.0	221
HD 149257	TYC 8325-1455-1	He-r	3	25 000	3	40.0	221,226
TYC 9280-38-1	DM-692698	He-r	1	25 000	4	30.0	221,226
HD 164769	TYC 6850-1755-1	He-r	1	23 000	4	105.0	221
HD 168785	TYC 7393-979-1	He-r	1	23 000	4	14.0	221,226
HD 186205	TYC 1057-69-1	He-r	1	17 000	4	5.0	221
TYC 7972-666-1	DM-4314300	He-r	1	22 000	4	2.0	221
HD 36485	HR 1851	He-r	4	18 400	4.41	54.0	222,224,225
HD 37017	HR 1890	He-r	4	19 200	4.45	80.0	222,224,225
HD 37479	HR 1932	He-r	3	22 200	4.53	100.0	222,224,225
HD 37776	HR 26742	He-r	1	21 800	4.52	75.0	222,224,225
HD 260858	TYC 741-818-1	He-r	1	19 200	4.22	47.0	222,224,225
HD 264111	TYC 156-966-1	He-r	1	23 200	4.54	75.0	222,224,225
TYC 6532-2200-1	HIP 34781	He-r	1	22 700	4.53	45.0	222,224,225
HD 58260	HIP 35830	He-r	3	19 000	4.02	45.0	222,224,225
HD 60344	HIP 36707	He-r	1	21 700	4.48	55.0	222,224,225
HD 64740	HR 3089	He-r	1	22 700	4.50	130.0	222,224,225
HD 66522	HIP 39246	He-r	1	18 800	4.39	0.0	222,225,226
TYC 8152-1868-1	LS 1169	He-r	1	22 000	4.52	80.0	222,225,227
HD 108483	HR 4743	He-r	2 or 5	19100	4.25	130.0	222,224,225
HD 1224448	TYC 8264-3162-1	He-r	1	22000	3.70		225
HD 169467	$\alpha$ Tel	He-r	1	16600	4.05		226
HD 68450	HR 3219	He-r	3	32100	3.55		226

Note: **References:** 14: Alentiev et al. (2012), 23: Bruntt et al. (2008), 32: Castelli (1998), 38: Cowley et al. (1973), 39: Cowley et al. (1978), 40: Cowley et al. (2000), 44: Cunha et al. (2013), 47: Drake et al. (2005), 52: Elkin et al. (2008), 53: Elkin et al. (2010), 56: Elkin et al. (2014), 67: Freyhammer et al. (2008), 70: Gelbmann (1998), 72: Gerbaldi et al. (1989), 78: Hack et al. (1997a), 79: Hack et al. (1997b), 81: Hubrig et al. (2012), 88: Joshi et al. (2010), 89: Kato & Sadakane (1999), 93: Kochukhov (2003), 96: Kochukhov et al. (2006), 97: Kochukhov et al. (2008), 98: Kochukhov et al. (2009), 100: Kupka et al. (1994), 102: Kurtz et al. (2007), 103: Kurtz et al. (2011), 105: Landstreet (1988), 124: Nesvacil et al. (2013), 130: Niemczura et al. (2015), 134: Polosukhina et al. (2004), 144: Ryabchikova et al. (1997a), 146: Ryabchikova (1998), 149: Ryabchikova et al. (2000), 150: Ryabchikova et al. (2001), 151: Ryabchikova et al. (2004a), 152: Ryabchikova et al. (2005), 153: Ryabchikova et al. (2006), 155: Ryabchikova et al. (2008), 156: Ryabchikova & Romanovskaya (2017), 157: Sadakane et al. (1983), 160: Savanov & Kochukhov (1998), 164: Shavrina et al. (2001), 165: Shavrina et al. (2004), 166: Shavrina et al. (2013), 167: Shavrina et al. (2013a), 169: Shulyak et al. (2009), 170: Shulyak et al. (2010), 172: Smalley et al. (2015), 182: Takada-Hidai et al. (1986), 183: Takada-Hidai & Takeda (1996), 195: Weiss et al. (2000), 206: Shultz et al. (2015), 207: Saffe & Levato (2014), 209: Fossati et al. (2011), 210: Catanzaro et al. (2010), 211: Krticka et al. (2009), 212: Glagolevskij et al. (2007), 213: Rachkovskaya et al. (2006), 214: Glagolevskij et al. (2006), 215: Wahlgren & Hubrig (2004), 216: Briquet et al. (2004), 217: Castelli et al. (1997), 218: Mon & Hirata (1981), 219: Castro et al. (2017), 220: Przybilla et al. (2016), 221: Zboril & North (2000), 222: Zboril & North (1999), 224: Zboril & North (1998), 225: Zboril et al. (1997), 226: Zboril et al. (1994), 227: Groote et al. (1982).

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