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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

[^0]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 buildup 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 $\mathrm{Ap}(\mathrm{SrCrEu})$ 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 $\mathrm{Ap}(\mathrm{SrCrEu})$ stars. More than 40 roAp stars were discovered before 2008 (Bruntt et al. 2008) in the effective temperature range of $7000 \lesssim T_{\text {eff }} \lesssim 10000 \mathrm{~K}$. 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 $10000 \lesssim T_{\text {eff }} \lesssim 20000 \mathrm{~K}$. 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
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 $\sigma$ OriE 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 16000 K . He-rich stars are mostly slow rotators ( 99.5 per cent of those stars have $v \sin i<130 \mathrm{~km} \mathrm{~s}^{-1}$, 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. ${ }^{1}$ In the Appendix, we give also 'multiplicity' information (binarity, belonging to a cluster, etc.) of these stars according to Simbad ${ }^{2}$ archive. In Section 3, we present comparison results with previous compilations (see Paper I, Paper II, and Smith 1996).

[^1]
## 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 ( $T_{\text {eff }} \leq 10300 \mathrm{~K}$, 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 30000 K according to Zboril \& North (2000), all others He-w stars being cooler than $T_{\text {eff }} \approx 18500 \mathrm{~K}$. 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 ${ }^{3}$ (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

[^2]

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 $(0.05<p$-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 Herich (He-r) stars. Statistically significant correlations are shown in boldface ( $p$-value $\leq 0.05$ ), marginal ones are underlined ( $0.05<p$-value $<0.06$ ).

|  |  | $\epsilon\left(T_{\text {eff }}\right)$ |  | $\epsilon(\log g)$ |  |  |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Elements | $\rho$ | $p$ | $N$ | $\rho$ | $p$ | $N$ | $\rho$ | $p$ | $N$ |  |
|  |  |  | roAp |  |  |  |  |  |  |  |
| Li | 0.23 | 0.452 | 13 | $\mathbf{0 . 6 1}$ | $\mathbf{0 . 0 2 7}$ | $\mathbf{1 3}$ | -0.32 | 0.286 | 13 |  |
| O | $\mathbf{- 0 . 5 8}$ | $\mathbf{0 . 0 0 5}$ | $\mathbf{2 2}$ | 0.23 | 0.299 | 22 | -0.17 | 0.449 | 22 |  |
| Na | $\underline{0.44}$ | $\underline{0.053}$ | 20 | -0.14 | 0.551 | 20 | 0.14 | 0.557 | 20 |  |
| Si | $\mathbf{0 . 3 6}$ | $\mathbf{0 . 0 4 3}$ | $\mathbf{3 2}$ | 0.02 | 0.908 | 32 | 0.02 | 0.931 | 32 |  |
| Ca | $\mathbf{0 . 6 5}$ | $\mathbf{0 . 0 0 0}$ | $\mathbf{3 3}$ | -0.01 | 0.976 | 33 | 0.11 | 0.545 | 33 |  |
| Sc | 0.20 | 0.377 | 22 | $\mathbf{0 . 4 2}$ | $\mathbf{0 . 0 4 9}$ | $\mathbf{2 2}$ | -0.22 | 0.321 | 22 |  |
| Ti | $\mathbf{0 . 7 3}$ | $\mathbf{0 . 0 0 0}$ | $\mathbf{2 8}$ | 0.19 | 0.331 | 28 | -0.13 | 0.495 | 28 |  |
| V | -0.19 | 0.409 | 21 | $\mathbf{0 . 5 4}$ | $\mathbf{0 . 0 1 2}$ | $\mathbf{2 1}$ | -0.01 | 0.969 | 21 |  |
| Cr | $\mathbf{0 . 8 1}$ | $\mathbf{0 . 0 0 0}$ | $\mathbf{3 6}$ | -0.27 | 0.114 | 36 | 0.19 | 0.276 | 36 |  |
| Mn | $\mathbf{0 . 5 9}$ | $\mathbf{0 . 0 0 3}$ | $\mathbf{2 4}$ | -0.11 | 0.614 | 24 | -0.09 | 0.677 | 24 |  |
| Fe | $\mathbf{0 . 8 2}$ | $\mathbf{0 . 0 0 0}$ | $\mathbf{3 6}$ | -0.06 | 0.729 | 36 | -0.03 | 0.864 | 36 |  |
| Ni | $\mathbf{0 . 7 6}$ | $\mathbf{0 . 0 0 0}$ | $\mathbf{2 4}$ | 0.27 | 0.197 | 24 | 0.092 | 0.669 | 24 |  |
| La | $\mathbf{0 . 4 6}$ | $\mathbf{0 . 0 2 0}$ | $\mathbf{2 5}$ | 0.14 | 0.499 | 25 | 0.10 | 0.632 | 25 |  |
| Eu | 0.24 | 0.174 | 33 | $\mathbf{0 . 3 5}$ | $\mathbf{0 . 0 4 8}$ | $\mathbf{3 3}$ | -0.30 | 0.095 | 33 |  |
| Tb | $\mathbf{- 0 . 5 3}$ | $\mathbf{0 . 0 3 6}$ | $\mathbf{1 6}$ | -0.21 | 0.431 | 16 | -0.18 | 0.493 | 16 |  |
| Dy | -0.10 | 0.698 | 18 | $\mathbf{- 0 . 5 6}$ | $\mathbf{0 . 0 1 5}$ | $\mathbf{1 8}$ | -0.43 | 0.075 | 18 |  |
| Yb | $\mathbf{0 . 6 2}$ | $\mathbf{0 . 0 1 4}$ | $\mathbf{1 5}$ | -0.29 | 0.289 | 15 | 0.02 | 0.955 | 15 |  |
|  |  |  |  |  | $H e-w$ |  |  |  |  |  |
| Fe | $\mathbf{0 . 5 5}$ | $\mathbf{0 . 0 4 3}$ | $\mathbf{1 4}$ | 0.19 | 0.525 | 14 | -0.26 | 0.399 | 13 |  |
|  |  |  |  |  | $H e-r$ |  |  |  |  |  |
| He | $\mathbf{0 . 4 6}$ | $\mathbf{0 . 0 1 9}$ | $\mathbf{2 6}$ | $\mathbf{- 0 . 4 0}$ | $\mathbf{0 . 0 4 3}$ | $\mathbf{2 6}$ | -0.44 | $\underline{0.051}$ | $\underline{20}$ |  |
| C | -0.29 | 0.138 | 27 | $\mathbf{- 0 . 4 4}$ | $\mathbf{0 . 0 2 2}$ | $\mathbf{2 7}$ | -0.02 | 0.923 | 22 |  |
| N | $\mathbf{- 0 . 4 1}$ | $\mathbf{0 . 0 3 8}$ | $\mathbf{2 6}$ | $\mathbf{0 . 3 9}$ | $\mathbf{0 . 0 4 8}$ | $\mathbf{2 6}$ | 0.23 | 0.311 | 22 |  |
| O | -0.12 | 0.635 | 18 | $\mathbf{0 . 5 6}$ | $\mathbf{0 . 0 1 6}$ | $\mathbf{1 8}$ | $\mathbf{0 . 5 5}$ | $\mathbf{0 . 0 3 4}$ | $\mathbf{1 5}$ |  |
| Mg | $\mathbf{- 0 . 2 3}$ | 0.358 | 18 | 0.32 | 0.201 | 18 | $\mathbf{0 . 6 3}$ | $\mathbf{0 . 0 1 1}$ | $\mathbf{1 5}$ |  |

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). ${ }^{4}$ Following Paper II, we have applied the well-known Anderson-Darling (AD) test ${ }^{5}$ 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

[^3]

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 11000 K , slightly shifted towards 11300 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 ${ }^{6}$ ) has $T_{\text {eff }}=10300 \mathrm{~K}$; 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

[^4]

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 $225 \mathrm{~km} \mathrm{~s}^{-1}$ is outside of the $v \sin i$ histogram).
the $v \sin i$, there is no roAp stars with higher projected velocity than $35 \mathrm{~km} \mathrm{~s}^{-1}$, 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 $20 \mathrm{He}-\mathrm{w}$ 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 $T_{\text {eff }} \lesssim 18000 \mathrm{~K}$ 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 $T_{\text {eff }} \lesssim 18000 \mathrm{~K}$.

### 5.3 He-rich stars

Considering the histograms for the $28 \mathrm{He}-\mathrm{r}$ 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 $16000 \lesssim T_{\text {eff }} \lesssim 26000 \mathrm{~K}$, with a moderate peak around 23000 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 homogenously distributed. Stronger is the mass-loss rate, faster is the replacement of the superficial matter by the deeper one. So, a strong mass-loss imped 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 (Krtička, Kubát \& Groote 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 $\mathrm{He}-\mathrm{r}$ ).

### 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 \& Dworetsky (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 $10-1000 \mathrm{yr}$ 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 occurs. 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 10000 K may become Am stars during their evolution on the main sequence (as suggested by Michaud et al. 2015, section 9.1.1). ${ }^{7}$ 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. ${ }^{8}$ However, as did also in Bailey et al. (2014), we draw the reader's attention on the limits of this approach. ${ }^{9}$ 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

[^5]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 mainsequence 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 binarytype 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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## 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 ( $\mathrm{km} \mathrm{s}^{-1}$ ) 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. | $T_{\text {eff }}(\mathrm{K})$ | $\log g$ | $v \sin i$ | References |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| HD 201601 | $\gamma$ Equ | roAp | 2 | 7750 | 4.2 | 4.5 | 70,81,144,165,183 |
| HD 203932 | BI Mic | roAp | 1 | 7450 | 4.3 | 12.5 | 70,149 |
| HD 24712 | DO Eri | 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 | $\beta$ Cr B | 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 | 10300 | 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 | 15400 | 4 | 31.0 | 205 |
| HD 61556 | HR 2949 | He-w | 2 | 18500 | 4.1 | 61.0 | 206 |
| HD 5737 | $\alpha \mathrm{Scl}$ | He-w | 1 | 13600 | 3.2 | 17.0 | 182,207 |
| HD 123182 | TYC 8268-3344-1 | He-w | 3 | 10800 | 4.25 | 81.0 | 209 |
| TYC 3128-248-1 | HIP 93941 | He-w | 1 | 19300 | 3.8 | 10.0 | 210 |
| HD 177410 | HR 7224 | He-w | 1 | 14500 | 4.2 |  | 211 |
| HD 37058 | TYC 4774-927-1 | He-w | 3 | 17000 | 3.8 | 25.0 | 212 |
| HD 212454 | HR 8535 | He-w | 1 | 14400 | 3.83 | 40.0 | 157,182,212 |
| HD 224926 | 29 Psc | He-w | 1 | 14000 | 3.85 | 68.0 | 212 |
| HD 30122 | HR 1512 | He-w | 1 | 15200 | 3.52 | 30.0 | 213 |
| HD 21699 | HR 1063 | He-w | 3 | 16000 | 4.15 | 35.0 | 214 |
| HD 217833 | HR 8770 | He-w | 2 | 15450 | 3.88 | 35.0 | 157,182,214 |
| HD 120709 | 3 Cen A | He-w | 2 | 17500 | 3.8 | 20.0 | 215,217 |
| HD 131120 | HR 5543 | He-w | 2 or 5 | 18250 | 4.1 |  | 216 |
| HD 105382 | HR 4618 | He-w | 2 | 17400 | 4.18 |  | 216 |
| HD 138769 | d Lup | He-w | 2 | 17500 | 4.22 |  | 216 |
| HD 37752 | HR 1951 | He-w | 1 | 15700 | 3.9 |  | 157,182 |
| HD 44953 | HR 2306 | He-w | 2 | 17000 | 4.1 |  | 157,182 |
| HD 23408 | 20 Mon | He-w | 3 | 12600 | 3.2 | 45.0 | 218 |
| HD 149363 | TYC 5060-966-1 | He-w | 1 | 30000 | 4 | 95.0 | 221 |

Table A1 - continued

| Star id | Other id | CP type | Mult. | $T_{\text {eff }}(\mathrm{K})$ | $\log g$ | $v \sin i$ | References |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| TYC 8976-5133-1 | CPD-622124 | He-r | 3 | 23650 | 3.95 | 75.0 | 219 |
| TYC 8613-98-1 | CPD-573509 | He-r | 3 | 23750 | 4.05 | 35.0 | 220 |
| HD 92938 | HR 4196 | He-r | 3 | 16000 | 4 | 125.0 | 221,222,226 |
| HD 96446 | TYC 8627-156-1 | He-r | 1 | 23000 | 4 | 0.0 | 221,222,226 |
| HD 133518 | TYC 8305-2754-1 | He-r | 1 | 20000 | 4 | 0.0 | 221,222,226 |
| HD 145939 | DM-134383 | He-r | 1 | 18000 | 4 | 55.0 | 221 |
| HD 149257 | TYC 8325-1455-1 | He-r | 3 | 25000 | 3 | 40.0 | 221,226 |
| TYC 9280-38-1 | DM-692698 | He-r | 1 | 25000 | 4 | 30.0 | 221,226 |
| HD 164769 | TYC 6850-1755-1 | He-r | 1 | 23000 | 4 | 105.0 | 221 |
| HD 168785 | TYC 7393-979-1 | He-r | 1 | 23000 | 4 | 14.0 | 221,226 |
| HD 186205 | TYC 1057-69-1 | He-r | 1 | 17000 | 4 | 5.0 | 221 |
| TYC 7972-666-1 | DM-4314300 | He-r | 1 | 22000 | 4 | 2.0 | 221 |
| HD 36485 | HR 1851 | He-r | 4 | 18400 | 4.41 | 54.0 | 222,224,225 |
| HD 37017 | HR 1890 | He-r | 4 | 19200 | 4.45 | 80.0 | 222,224,225 |
| HD 37479 | HR 1932 | He-r | 3 | 22200 | 4.53 | 100.0 | 222,224,225 |
| HD 37776 | HR 26742 | He-r | 1 | 21800 | 4.52 | 75.0 | 222,224,225 |
| HD 260858 | TYC 741-818-1 | He-r | 1 | 19200 | 4.22 | 47.0 | 222,224,225 |
| HD 264111 | TYC 156-966-1 | He-r | 1 | 23200 | 4.54 | 75.0 | 222,224,225 |
| TYC 6532-2200-1 | HIP 34781 | He-r | 1 | 22700 | 4.53 | 45.0 | 222,224,225 |
| HD 58260 | HIP 35830 | He-r | 3 | 19000 | 4.02 | 45.0 | 222,224,225 |
| HD 60344 | HIP 36707 | He-r | 1 | 21700 | 4.48 | 55.0 | 222,224,225 |
| HD 64740 | HR 3089 | He-r | 1 | 22700 | 4.50 | 130.0 | 222,224,225 |
| HD 66522 | HIP 39246 | He-r | 1 | 18800 | 4.39 | 0.0 | 222,225,226 |
| TYC 8152-1868-1 | LS 1169 | He-r | 1 | 22000 | 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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[^1]:    ${ }^{1}$ These data, and some more may be also found on the following website http://gradsvp.obspm.fr/CPstars/CPstars_home.html (site maintained by Observatoire de Paris, responsible of this web page: G. Alecian).
    ${ }^{2}$ http://simbad.u-strasbg.fr/simbad/.

[^2]:    ${ }^{3}$ 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.

[^3]:    ${ }^{4}$ 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.
    ${ }^{5}$ 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).

[^4]:    ${ }^{6}$ Notice that the abundances for elements lighter than $Z=46$ are not available for this star except for vanadium.

[^5]:    ${ }^{7}$ 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.
    ${ }^{8}$ 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).
    ${ }^{9}$ 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 timedependent continuity equation for concentrations in optically thin media.

