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## ► To cite this version:

S. Ghazaryan, G. Alecian. Statistical analysis from recent abundance determinations in HgMn stars. Monthly Notices of the Royal Astronomical Society, 2016, 460 (2), pp.1912-1922. 10.1093/mnras/stw911 . hal-02338640

**HAL Id: hal-02338640**

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Submitted on 17 Mar 2023

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# Statistical analysis from recent abundance determinations in HgMn stars

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Accepted 2016 April 15. Received 2016 April 15; in original form 2015 December 29

## ABSTRACT

To better understand the hot chemically peculiar group of HgMn stars, we have considered a compilation of a large number of recently published data obtained for these stars from spectroscopy. We compare these data to the previous compilation by Smith. We confirm the main trends of the abundance peculiarities, namely the increasing overabundances with increasing atomic number of heavy elements, and their large spread from star to star. For all the measured elements, we have looked for correlations between abundances and effective temperature ( $T_{\text{eff}}$ ). In addition to the known correlation for Mn, some other elements are found to show some connection between their abundances and  $T_{\text{eff}}$ . We have also checked if multiplicity is a determinant parameter for abundance peculiarities determined for these stars. A statistical analysis using a Kolmogorov–Smirnov test shows that the abundances anomalies in the atmosphere of HgMn stars do not present significant dependence on the multiplicity.

**Key words:** stars: abundances – stars: chemically peculiar – stars: statistics.

## 1 INTRODUCTION

HgMn stars constitute a subgroup of hot chemically peculiar (CP) ApBp stars. They are characterized by strong overabundances of various heavy elements, generally up to about 2 dex (as Mn), and even up to about 5 dex (as for Hg). There is not confirmed detection of magnetic fields in HgMn stars, so they are considered as non-magnetic stars, which is not the case for the other ApBp stars. They are typically found in the spectral-type range from nearly A2 to B5, and have luminosity types from V to IV. Their effective temperatures are in the range of 10 000 to 16 000 K (see the review by Smith 1996b).

Abundance anomalies found in main-sequence CP stars are due to atomic diffusion processes (Michaud 1970). According to their atomic properties, elements are more or less pushed upward by the net radiation flux (radiative acceleration), and their concentrations stratify. In hot CP stars, like HgMn stars, abundance stratifications take place in the atmosphere and deeper. In stable atmospheres, elements that are pushed strong enough by radiative forces could leave the star. The elements that would be noticeably overabundant in ‘non-magnetic’ stars would be those for which either radiative accelerations are large in most part of the atmosphere, but decrease at some point above the line-forming region (see Alecian & Michaud 1981, for more details), or if a weak (undetected) horizontal magnetic field forces the diffusion velocity to decrease (Alecian 2013a). Detailed discussion of the physics in play in HgMn stars may be found, for instance, in Alecian et al. (2009), in the book of Michaud,

Alecian & Richer (2015) (Section 8.2), and in Alecian (2015) for ApBp stars including HgMn.

Because radiative accelerations, as diffusion coefficients, depend on local plasma properties (temperature, density, etc.), chemical peculiarities found in the atmospheres of HgMn stars are related to fundamental parameters as effective temperature  $T_{\text{eff}}$  and  $\log g$ .

The abundance anomalies in HgMn stars may be correlated with  $T_{\text{eff}}$ . Alecian & Michaud (1981) have shown that according to their NLTE estimate of radiative accelerations, Mn should accumulate in stars below  $T_{\text{eff}} \approx 16\,000$  K with a cutoff of overabundances below  $T_{\text{eff}} \approx 10\,000$  K due to existence of a superficial convective zone for low effective temperatures. They have also shown that Mn overabundance should increase with  $T_{\text{eff}}$ . This prediction was later confirmed in observed stars by Smith & Dworetzky (1993). Above  $T_{\text{eff}} \approx 16\,000$  K, Mn atoms could leave the star because of the large radiative acceleration. Above  $T_{\text{eff}} \approx 18\,000$  K the large stellar wind velocity prevents manganese to stratify, as for other chemical species.

HgMn stars are marginally in the Slowly Pulsating B stars domain of the HR diagram. According to theoretical models taking into account atomic diffusion in their interiors (Turcotte & Richard 2003; Alecian et al. 2009), HgMn stars should develop SPB type pulsations. However, only few HgMn stars have been found to show photometric variations through the CoRoT satellite observations (Alecian et al. 2009; Morel et al. 2014), and it is not yet established whether these variations are due to pulsations or rotational modulations. To understand the reason of the low occurrence of photometric variability in these stars, one needs to better constrain theoretical models.

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Some HgMn stars have been found to present horizontal inhomogeneous distributions (spots or patches) of some heavy elements (Adelman et al. 2002), with secular variations for some of them (Kochukhov et al. 2007 for Hg; Briquet et al. 2010 variations for Ti, Sr and Y). Such inhomogeneities (including secular variations) are compatible with models of HgMn stars including atomic diffusion provided that a very weak (undetected) magnetic field exists (few Gauss). Indeed, elements with small cosmic abundance (and often with high atomic number) may form clouds in high atmospheric layers, above the layers with homogeneous abundance stratification of other metals (as usually proposed in the classical diffusion model). Notice that for this kind of clouds, atomic diffusion time-scales are compatible with the secular variations observed by Kochukhov et al. (2007) and Briquet et al. (2010) (see detailed discussion in Alecian 2013a,b).

Because atomic diffusion is very sensitive to mixing motions, rotation and binarity are important parameters to be considered in this framework. More than 50 per cent of HgMn stars are members of binary or multiple system, which is larger than for normal stars (Smith 1996b). The question arises of the incidence of multiplicity on the abundance anomalies. It is therefore interesting to consider the statistical distribution of abundances for single HgMn stars versus those discovered in binary or multiple systems.

The purpose of the present work is to collect new observational constraints, useful for theoretical studies, from published abundance determinations in HgMn stars. A review devoted to spectroscopic properties of all observed chemically peculiar stars, including HgMn stars, was done by Smith (1996b) (see also Preston 1974). This author considered most of observations of CP stars before 1993, and one can find a discussion in his paper of various properties of CP stars and a figure showing the distribution of existing measures of chemical abundances in the atmospheres of HgMn stars. There has been no such study after 1996 and before 2013. A new compilation has been realized by Ghazaryan (2013) to check if the distribution of chemical abundances in HgMn stars obtained with modern techniques shows the same trends as in the compilation by Smith (1996b). In the present work we use the compilation of Ghazaryan (2013) as a global survey of abundance anomalies in HgMn stars (Section 2). We look for trends of abundance anomalies versus effective temperature and other fundamental parameters (Section 3), and we proceed to a statistical study of the abundance anomalies with respect to multiplicity (Section 4).

## 2 SAMPLE OF HgMn STARS

The HgMn stars considered in this work are listed in Table A1. This table contains 107 HgMn stars observed spectroscopically by various authors since 1993 and before 2013. Due to the differences of used methods for abundance determination, our sample is heterogeneous and so statistical analysis is difficult, but we have tried to consider as much as possible the published error bars. For a given star and for a given chemical element, abundance values from various papers were preferentially selected from those of papers in which the error bars are given. Notice that these error bars correspond often to the internal error of abundance determination methods rather than real uncertainties on abundances, which should be larger. If the abundance is given for several ions of a given element, we take the average value, and the error is recalculated as a mean square of the errors. If several authors give different abundances of a given element we take the value from the publication where many other elements' abundances are given to have more

homogeneous data set (the details of abundance sources, element per element and for each star are given in the online table.).<sup>1</sup>

In Table A1, we show main stellar parameters available in the literature. In a separate column we also indicate the multiplicity we find from Simbad<sup>2</sup> archive. In Section 4 this indicator will be used to divide our sample into two subsamples to be able to analyse chemical peculiarities according to multiplicity. In the last column of the table we refer to the papers from which we took chemical abundances values, and the main physical parameters.

### 2.1 Comparison with previous compilation

To compare our results with the work done nearly 20 years ago by Smith (1996b), and to reduce the heterogeneity of the data, we scaled them using the solar values given by Asplund et al. (2009). When necessary, we estimated the ratio  $N(A)/N(H)$  assuming standard solar composition for He and metals. Fig. 1 gives all abundances of the present compilation versus atomic numbers. Abundances ( $\epsilon$ ) are given in logarithm of the abundance  $N(A)/N(H)$  divided by the solar one. Detailed values element per element may be found as online data.<sup>3</sup> This figure may be compared with fig. 5 (lower panel) of Smith (1996b).

The comparison of our results with Smith's compilation shows that *helium* is not systematically underabundant in this new compilation. The dispersion of He values is quite large and equal to 3 dex. It comes out that the hotter HgMn stars have stronger He deficits than the cooler HgMn stars (see Dworetsky 2004).

*Berillium* [atomic number=4]<sup>4</sup> and *boron* [5] abundances are available only for HD71066 and  $\chi$  Lupi A (see Yüce, Castelli & Hubrig 2011; Leckrone et al. 1999, respectively). We have not found any other papers providing Be and B abundances. These abundances were observed before 1993, which is the reason why we do not have more Be and B abundances in our compilation.

For a few HgMn stars *carbon* [6] seems overabundant, for others it is underabundant, but mostly the relative amount of carbon in the atmospheres of these stars is normal. In Smith's compilation there is no HgMn star which shows carbon overabundance.

*Nitrogen* [7] underabundance is more pronounced than in Smith's compilation. There are two HgMn stars, HD 168932 and HD 179761, which show nitrogen overabundance in their atmospheres (for more details see Niemczura, Morel & Aerts 2009). It is important to note that the dispersion value of carbon and nitrogen is nearly 3 dex for both of them.

The abundance of *oxygen* [8] in HgMn stars is normal and it is not highly dispersed. This result is in a good agreement with Smith's compilation.

On the average, the *neon* [10] and *sodium* [11] abundances are normal. Just a few per cent of HgMn stars show underabundances of neon. Neon and sodium abundances are absent in Smith's figure.

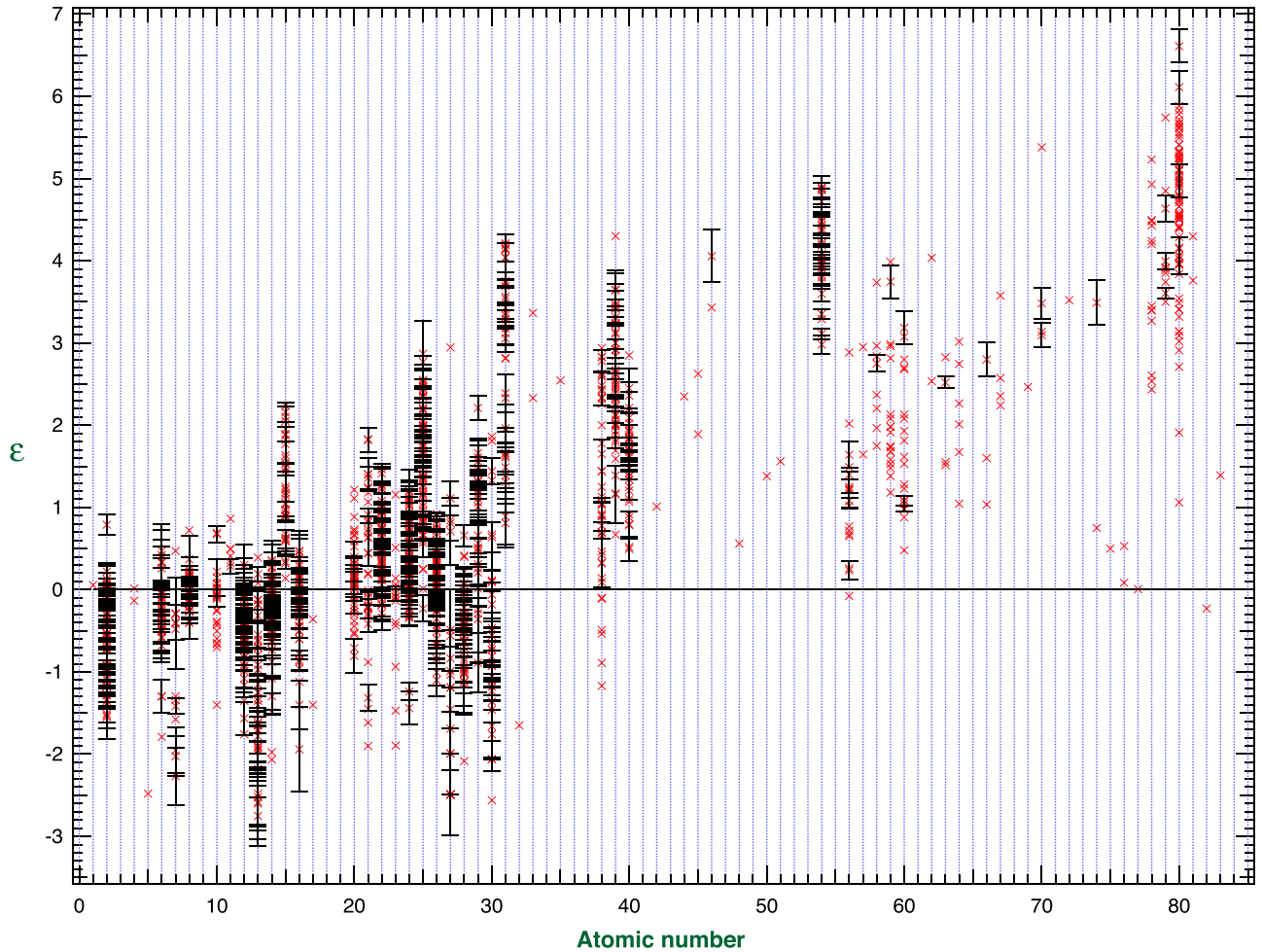
The comparison of the two compilations shows that in our compilation the underabundances of *aluminium* [13] and *silicon* [14] are less pronounced and there is a huge dispersion for these elements as well, nearly 3.2 and 3.6 dex, respectively. Nearly for 75 per cent of

<sup>1</sup> File: abundances\_catalog.pdf and.xlsx.

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

<sup>3</sup> Files: \*\_bar.pdf. In these figures, stars are sorted according to  $T_{\text{eff}}$ , but the x-axis is just an offset by a constant step to avoid an overlapping of error bars. All the stars for which we have not found an error bar are gathered to the left of the figures and represented by a red cross.

<sup>4</sup> For an easy reading of Fig. 1, the atomic number is systematically recalled in this section in brackets beside element names.



**Figure 1.** All the abundances in the present compilation versus atomic number. Abundances ( $\epsilon$  is the logarithm of the abundance divided by the solar one) are taken from the references listed in Appendix A.

HgMn stars silicon abundances are almost solar. The highest overabundance and underabundance values of Si are 1.36 and  $-2.10$  dex for HD 45583 and HD 35548 (see Niemczura et al. 2009 and Smith 1993, respectively). Another element, *magnesium* [12], is mostly underabundant. For a few HgMn stars, the Mg abundances overlay solar value.

*Phosphorus* [15] is overabundant in almost all HgMn stars. It is underabundant only in the atmosphere of 46 Dra B. The exceptional underabundance value of phosphorus goes down to  $-0.4$  dex.

*Sulphur* [16] is underabundant in most HgMn stars. The largest deficiency of sulphur appears in the atmosphere of HD 55362 (see Niemczura et al. 2009) and reaches  $-2.0$  dex.

*Chlorine* [17] abundances are available only for two targets – HD 46886 and  $\chi$  Lupi A – and are equal to  $-0.36$  and  $-1.40$  dex, respectively (see Leckrone et al. 1999; Niemczura et al. 2009). Because of the lack of abundance values one cannot speak about dispersion of this element from star to star.

The dispersion of Ca [20], Sc [21] and V [23] is large, nearly 3 dex or slightly more.

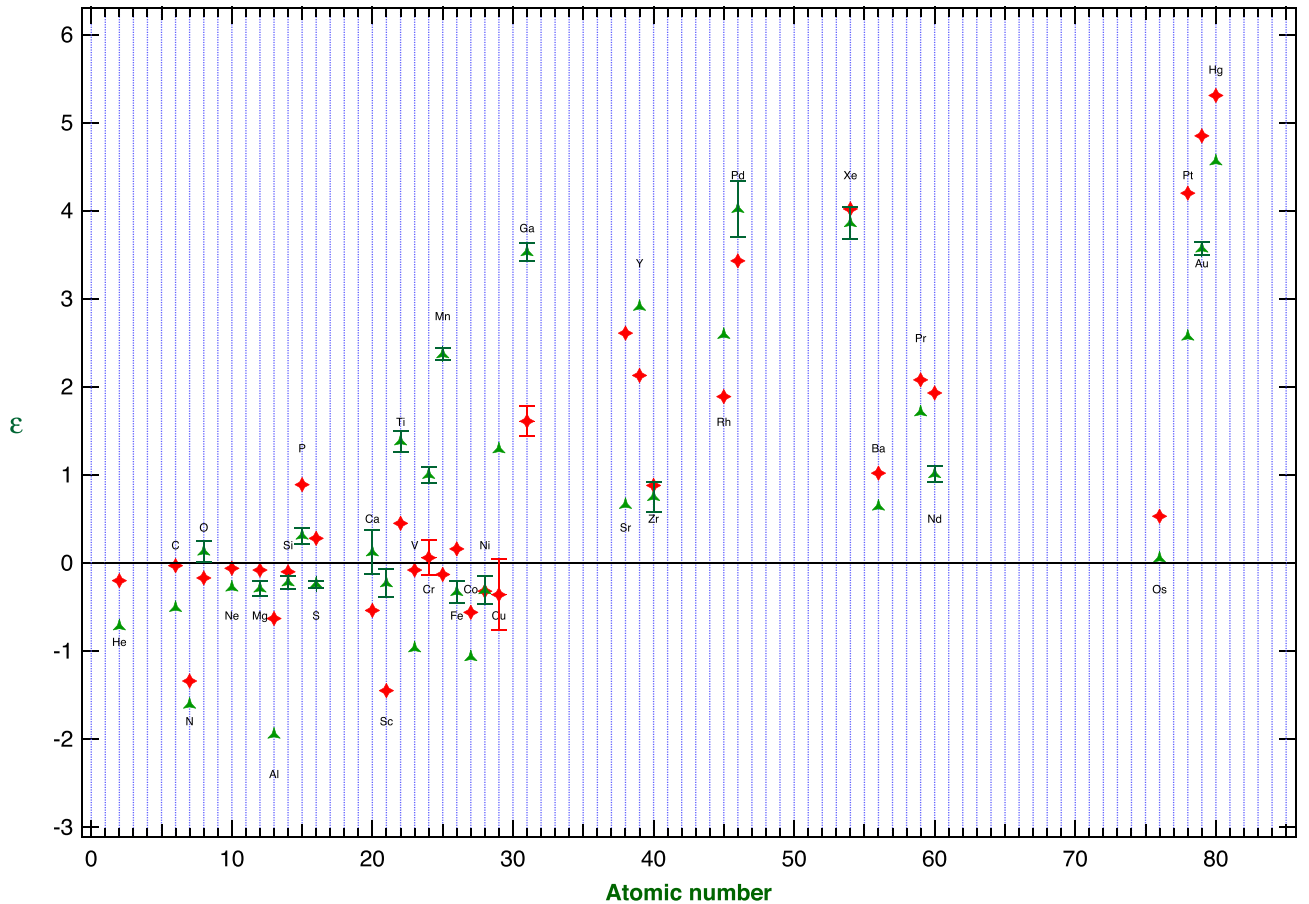
*Titanium* [22] is mostly overabundant in HgMn stars. However, it is underabundant in the atmospheres of some HgMn stars. The overabundances of titanium in this compilation are slightly larger than the Smith’s one.

The iron-peak elements (Cr [24], Mn [25], Fe [26], Co [27], and Ni [28]) are broadly scattered around the solar one. It is worth-

while to note that in two stars ( $\chi$  Lupi A and 36 Lyn) manganese is underabundant, which is not usual for HgMn stars. These observational results seem to confirm Cowley’s (1980) suggestion that there is a separate group of hot, mild HgMn stars, which are difficult to identify by usual classical observational techniques. The total range in iron abundance determined in this HgMn sample is around 2.5 dex, which is greater than that measured for any other group of chemically peculiar stars (see Ptitsyn & Ryabchikova 1980). HgMn stars are generally Co-deficient, although there are some examples with overabundances. An unusual overabundance is determined in the atmosphere of HD 143807 (see Ryabchikova 1998) which needs further detailed investigations. The HgMn stars are generally Ni-deficient, although there are some examples with abundances higher with respect to the Sun (see Smith & Dworetsky 1993). Although the high dispersion of iron-peak elements, heavy elements are more overabundant in the atmospheres of HgMn stars.

*Copper* [29] is overabundant in most HgMn stars and is underabundant only in few cases. *Zinc* [30] is typically deficient in those stars, despite the fact that in some cases it is overabundant with respect to solar values or essentially equal to solar abundances (see Smith 1994).

*Gallium* [31] is overabundant in HgMn stars. In both compilations Ga abundances are larger than in the Sun. In this sample, gallium overabundance reaches to 4.4 dex which is a bit different from Smith’s compilation (4 dex).



**Figure 2.** Abundances (relative to the Sun) for two HgMn stars: HD 175640 and  $\chi$  Lupi A. The green triangles are for HD 175640, and the red crosses are for the abundances of  $\chi$  Lupi A. The abundances are obtained from Castelli & Hubrig (2004), Yüce et al. (2011), Dworetzky et al. (2008a), Dolk, Wahlgren & Hubrig (2003), Dworetzky (2004) (for HD 175640), Dworetzky et al. (2008b), Catanzaro, Leone & Leto (2003), Jomaron et al. (1999), Ryabchikova (1998), Leckrone et al. (1999), Pintado & Adelman (1996), Adelman et al. (2004), Wahlgren et al. (2000), Dolk et al. (2002), Dworetzky & Budaj (2000), and Smith (1994) (for  $\chi$  Lupi A).

Yttrium [39], zirconium [40] and cerium [58] are overabundant in all HgMn stars. Strontium [38] is overabundant in nearly all HgMn stars as well. Just in a few cases it seems deficient in those stars. It is important to note that all these abundances are broadly scattered above the solar abundances.

In our compilation xenon [54], barium [56], lanthanum [57], holmium [67], praseodymium [59] and neodymium [60] overabundances have nearly the same values as in Smith's compilation. Thulium [69], platinum [78], gold [79] and mercury [80] overabundances are smaller in Smith's compilation than in ours. In Smith's compilation platinum tend to solar abundance but in our sample it is broadly overspread with respect to solar values. Mercury abundance, which is among the main characterizing quantities of those stars, reach up to 6.7 dex in the atmosphere of HR 8937 (see Saffe, Núñez & Levato 2011).

One should mention that there are elements (Ge [32], As [33], Br [35], Mo [42], Ru [44], Rh [45], Pd [46], Cd [48], Sn [50], Sm [62], Os [76], Sb [51], Pr [59], Eu [63], Gd [64], Dy [66], W [74], Re [75], Ir [77], Au [79], Tl [81], Pb [82], and Bi [83]) that are not present in Smith's compilation. Among these elements only germanium and lead are underabundant, the others are overabundant in the atmospheres of HgMn stars. The abundances of praseodymium, gadolinium and dysprosium are given for dozens of HgMn stars while the other rare earth abundances are available for one or two targets. Germanium, molybdenum, ruthenium, cad-

mium, tin, antimony, europium, tungsten, ruthenium, iridium, lead and bismuth abundances are given for  $\chi$  Lupi A only (see Leckrone et al. 1999). Bromine abundance is available for HD 175640 (see Castelli & Hubrig 2004), while the arsenic abundance is given for HD 71066 (see Yüce et al. 2011) and  $\chi$  Lupi A only (see Leckrone et al. 1999). The abundances of rhodium, osmium and palladium are determined in the atmospheres of HD 175640 and  $\chi$  Lupi A (see Castelli & Hubrig 2004; Leckrone et al. 1999, respectively), the thallium abundance in  $\chi$  Lupi A only (see Leckrone et al. 1999). Samarium abundance is determined in the atmospheres of HD 158704 and HD 193452 (see Hubrig, Castelli & Mathys 1999).

The compilation confirms that the overabundances in the atmospheres of HgMn stars increase for heavy elements with atomic number. The large scatter of the abundances is comparable to that we find in Smith's compilation (1996b), despite the progress in measurement techniques. We think that this scatter is not only due to the heterogeneity of the data since it exists even between stars analysed by the same authors (as e.g. for Hg in Smith 1996a, or Fe in Niemczura et al. 2009), but also likely due to errors of measures since for any of the elements, abundance anomalies extend over three or four orders of magnitude. To illustrate this scatter from star to star, we have chosen two HgMn stars (HD 175640 and  $\chi$  Lupi A), which were measured by different techniques and different methods, and we have plotted them in the same plot (see Fig. 2). As we can see, both stars show very different patterns of abundances. The



large scatter of abundances of heavy elements in the atmospheres of HgMn stars supports the idea that the abundance stratifications are affected by several physical processes among which are the unstable scenario of abundance stratifications build-up proposed by Alecian (1998) and Alecian, Stift & Dorfi (2011).

### 3 ABUNDANCES VERSUS FUNDAMENTAL PARAMETERS

#### 3.1 Abundances versus effective temperatures

Our purpose in this section is to look for correlations between abundances and  $T_{\text{eff}}$  as the one found by Smith & Dworetsky (1993) for manganese. Such a correlation has been theoretically predicted for Mn by Alecian & Michaud (1981) who have shown that the maximum abundance of manganese which can be supported by the radiation field should increase with  $T_{\text{eff}}$  until a cutoff temperature (around 16 000–18 000 K). The measures of Smith & Dworetsky (1993) have shown that the Mn overabundances are limited by an envelope which follows this theoretical prediction. To find such a correlation for other elements could bring significant constraints for theoretical studies.

In this section we consider the same abundance data that are shown in Fig. 1, but element per element and with respect to the effective temperatures  $T_{\text{eff}}$  listed in Table A1 (see also Fig. 3). Figs 4, 5 and 6 show the case of phosphorus, sulphur, and copper with their error bars and star's number for those having error bars (from first column of Table A1). The plots for the other elements are given in online figures.<sup>5</sup>

Fig. 3 shows a condensed view of our full data set in the form of 35 panels (for 35 elements). Elements for which the abundances are determined in less than 5 stars in our compilation are not shown. For the sake of clarity, star numbers are not given in this plot. A quick look on this figure allows us to see elements for which a correlations seem to exist. First, we found the same trend for Mn as the one found by Smith & Dworetsky (1993). One star departs from this well-marked trend. It is the coolest star of our sample, star No. 1 of the Platais open cluster (star number 78 of Table A1) analysed by Usenko et al. (2001). This star has stronger overabundance of Mn than expected according to its  $T_{\text{eff}}$  (10000 K). Strong overabundance of P is also noticeable in Fig. 4 (first point at the left of the figure). This star is also very unusual for the HgMn group because of its high overabundance of He. Usenko et al. (2001) assume that the overabundance of He may be due to light induced drift process (LID process; suggested by Atutov & Shalagin 1988); however, this is unlikely because the LID process could be invoked only to explain isotopic anomaly (high  $^3\text{He}/^4\text{He}$  ratio) and not for global He overabundances (LeBlanc & Michaud 1993). So, this star is either an abnormal case, or possibly its  $T_{\text{eff}}$  is incorrect. It deserves certainly further studies.

Sr, S and possibly Mg seem to have decreasing abundances with increasing  $T_{\text{eff}}$ . Besides the known correlation for Mn, and if one excludes the case of the star 78 (Platais 1 No.1), abundances of P, Ti, V, Xe and possibly Ca, Sc, Ba seem to increase with  $T_{\text{eff}}$ .

Some elements (N, Co, Cu, Zn) possibly show bi-modal behaviour of their abundances. For Cu, for which the detailed data are shown in Fig. 6, it seems to be a first group of stars with increasing overabundances ( $10\,000 < T_{\text{eff}} < 14\,000$  K) and a second group ( $13\,000 < T_{\text{eff}} < 15\,000$  K) with underabundances for the cooler members and overabundances above  $T_{\text{eff}} \approx 14\,500$  K. According to

the available data, no one of these two groups can be related to multiplicity. Also, one cannot exclude that such bi-modal behaviours may be due selection bias.

#### 3.2 Abundances versus $\log g$ and $v \sin i$

We have looked also for a possible connection of abundances with  $\log g$  and  $v \sin i$ . However, no clear dependence of abundances with these parameters is revealed, except perhaps for Hg with respect to  $\log g$ . We have plotted a second degree polynomial fit shown in Fig. 7. Indeed, a maximum of Hg abundances seems to exist around  $\log g \approx 3.9$ . Considering dependences on  $v \sin i$ , it is even less conclusive, since abundances appear very scattered around the average values of abundances, and without any significant structure. Points are just more gathered around low velocities, which is expected since low rotational velocity is among the required conditions to suppress mixing processes and to allow atomic diffusion to be efficient in the atmospheres of HgMn stars. Notice that Fossati et al. (2007, 2008) have found trends of abundances with  $v \sin i$  for Am stars. However, although abundance peculiarities of Am stars are also due to atomic diffusion, these stars are cooler than HgMn stars and have a superficial convection zone. So, element stratifications do not occur in the atmospheres of Am stars, contrarily to what happens in HgMn stars. Because the depth of the superficial convection in Am stars is closely related to rotation history of individual Am stars (Richer, Michaud & Turcotte 2000), it is not surprising that correlation with  $v \sin i$  was found for these stars.

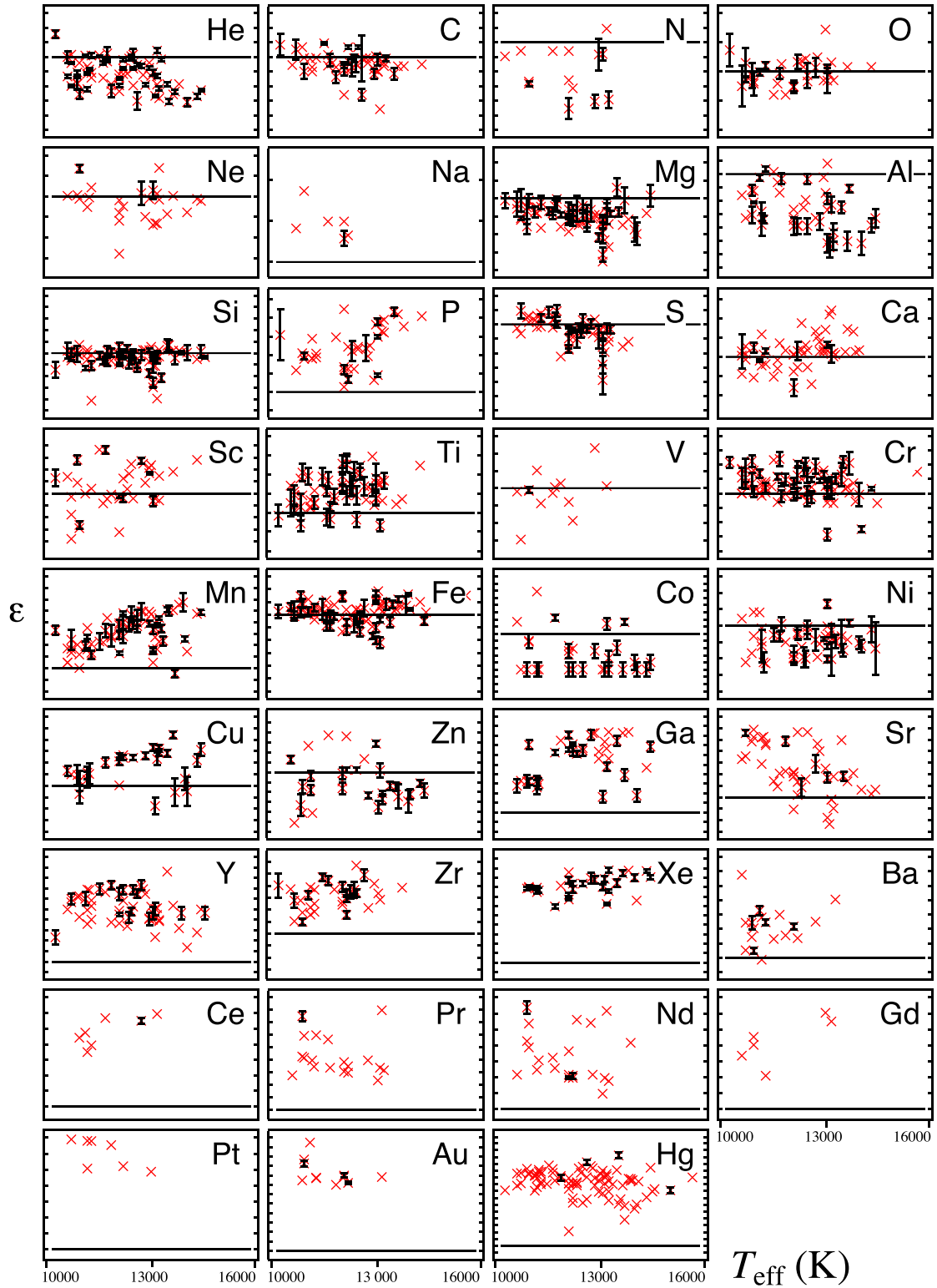
### 4 SEARCH OF A CORRELATION WITH MULTIPLICITY IN HG MN STARS

As we mentioned in previous sections, abundance peculiarities in HgMn stars, as plotted in Fig. 1, are highly scattered even if the general trend is clearly dominated by overabundances for heavy elements. This is not specific to HgMn stars but common to all chemically peculiar stars of the main sequence. Such a scatter may be understood in the framework of the models including atomic diffusion processes. For instance, it may be due to the abundance stratification build-up processes in the atmospheres (Alecian et al. 2011) or related to a variety of weak mixing processes (strong mixing being incompatible with abundance stratifications). Despite this observational fact, it is possible to find some trends as for the one of manganese. We already mentioned that more than 50 per cent of HgMn stars are members of binary or multiple system, which is larger than for normal stars (Smith 1996b). In Table A1, we have indicated those stars which are known to be binary or member of multiple system, so there is an opportunity to check if this parameter may be related to the abundance anomalies.

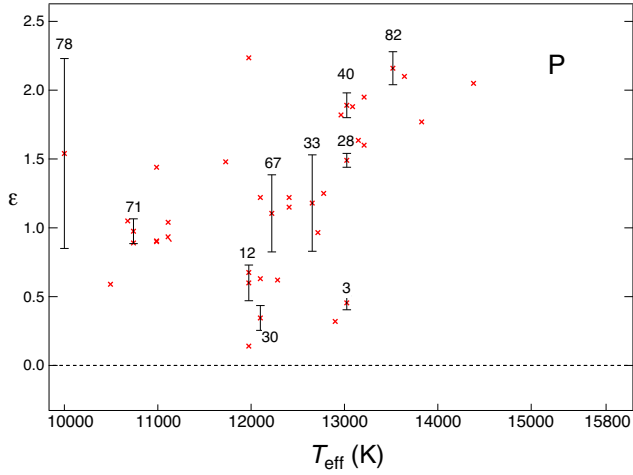
We can distinguish two groups in our sample: the first one forms a subsample of single stars (47 stars), the second one gathers those observed in binary systems or in multiple systems (60 stars). We use *Kolmogorov–Smirnov* test (P.C. Gregory 2005) to compare the two samples. This non-parametric well-known test allows us to check if two independent samples are formed according to different undetermined physical processes. As a non-parametric statistic, it is valid for any underlying distribution (see Santos et al. 2002); this is why it is a well-fitted one to our data. The *null-hypothesis* is defined as the case where there is not any indication that the two samples are due to different processes. For this statistical work, we use the R project<sup>6</sup> codes (R Core Team 2014).

<sup>5</sup> Files: \*\_teff.pdf.

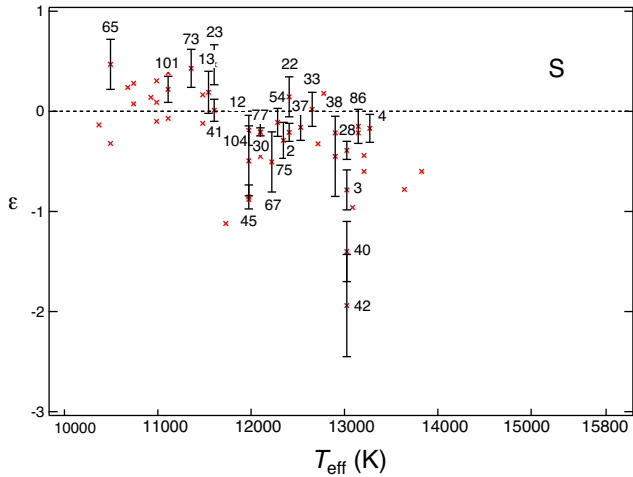
<sup>6</sup> <http://www.r-project.org>



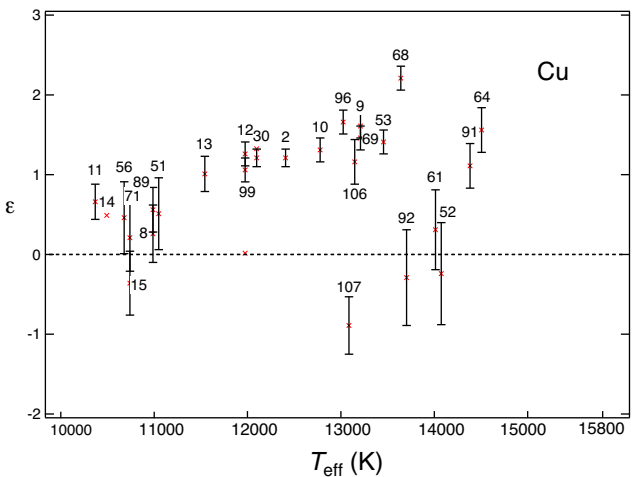
**Figure 3.** Abundances  $\epsilon$  versus  $T_{\text{eff}}$ . The horizontal line is the  $\epsilon = 0$  line (left axis) and ticks are spaced by 0.5 dex. The x-axis (shown below the lower panels) is the effective temperature from 10 000 to 16 000 K in linear scale (same scale as Fig. 4). The purpose of this figure is to have a global quick look of the data; the detailed figures (element per element as in Figs 4–6) are provided as online figures.



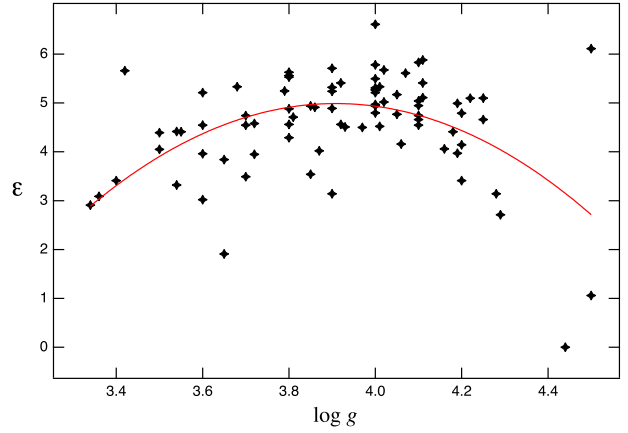
**Figure 4.** Phosphorus abundances with respect to  $T_{\text{eff}}$ . The numbers appearing above or below error bars are the star's number (first column of Table A1).



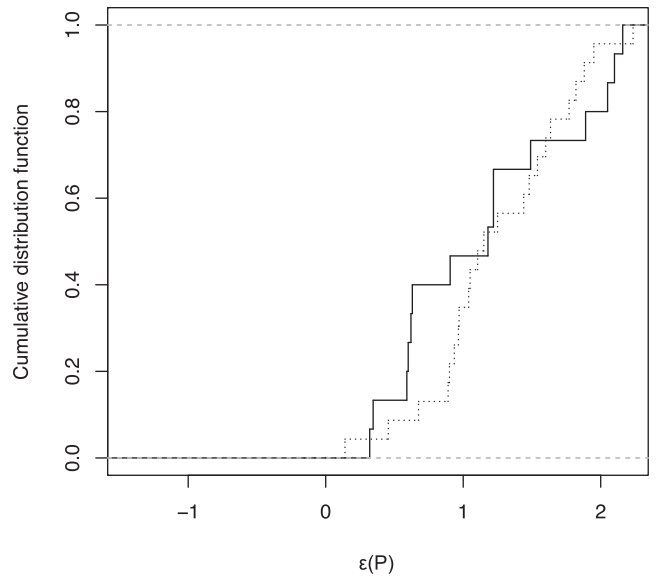
**Figure 5.** Same as Fig. 4, but for sulphur.



**Figure 6.** Same as Fig. 4, but for copper.



**Figure 7.** Mercury abundances versus  $\log g$ . The red curve is a polynomial fit (see text).



**Figure 8.** Cumulative distribution function for the two subsamples versus phosphorus abundances. The continuous curve represents the first group of HgMn stars, and the dotted one the second group, respectively.

The first step consists in calculating the cumulative distribution function for these two samples for each element (subsamples), and to determine a *distance* according to the following formulae (see Feigelson & Babu 2012, for more details):

$$D = \sqrt{(n_s + n_m)/(n_s n_m)} \max_x |F_s(x) - F_m(x)|, \quad (1)$$

where  $x$  represents the logarithmic abundance value ( $\epsilon$ ) of the element,  $F_s(x)$  is the cumulative distribution function of the  $n_s$  stars found as single HgMn stars, and  $F_m(x)$  is the one for the  $n_m$  stars found in multiple systems. Because the abundance of a given element is not known for all the stars of the two samples,  $n_s$  and  $n_m$  are different for each element (one has two subsamples for each element). As an example, such cumulative distribution functions are presented in Figs 8 and 9, for phosphorus and sulphur, respectively, and the two subsamples do not differ significantly.

For each element,  $\mathbb{R}$  application returns the maximum difference  $D$  and a corresponding  $p$ -value, which are presented in Table 1. The  $p$ -value is the probability of rejection of the *null-hypothesis*. Usual criterion to reject the *null-hypothesis* is  $p < 0.05$ . For our list of



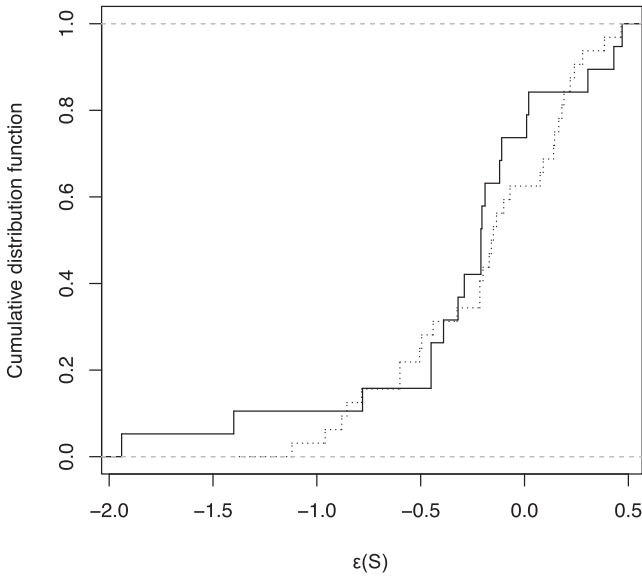


Figure 9. Same as Fig. 8 for sulphur.

**Table 1.** Maximum difference of cumulative distribution functions and  $p$ -values extracted from  $R$ ,  $n_s$  and  $n_m$  values for a given element.

Elements	$D$	$p$ -value	$n_s$	$n_m$
He	0.1883	0.6446	26	38
C	0.2381	0.5044	21	28
O	0.3	0.4234	15	20
Mg	0.2486	0.2611	29	38
Al	0.38	0.097 36	18	25
Si	0.2688	0.1647	31	39
P	0.3113	0.3359	15	23
S	0.2171	0.6278	19	32
Ca	0.1625	0.9042	19	34
Sc	0.2826	0.4904	14	23
Ti	0.2171	0.4974	25	35
Cr	0.145	0.7568	42	44
Mn	0.2033	0.5108	28	39
Fe	0.1396	0.8122	38	46
Co	0.596	0.01566	11	18
Ni	0.1877	0.8069	19	30
Cu	0.2834	0.6568	11	17
Zn	0.2778	0.635	12	18
Ga	0.3147	0.3934	13	22
Sr	0.1743	0.9092	17	27
Y	0.3273	0.1388	20	33
Zr	0.25	0.7168	12	22
Hg	0.1939	0.4433	33	50

HgMn stars, rejection occurs only for Co, but one cannot exclude an observational bias because the error bars are uniformly large for Co (0.5 dex) compared to those of the other elements (see the online data), and because most of the abundances are in same bins for stars in multiple system. For the other 22 elements, including P and S (Figs 8 and 9),  $p$ -value is relatively high, which means that there is no indication that the *null-hypothesis* has to be rejected. So, according to the *Kolmogorov–Smirnov* test applied to our compilation, one cannot conclude that multiplicity is a determinant parameter for chemical abundance anomalies in HgMn stars.

## 5 CONCLUSION

In this work we consider a compilation of the abundances of 61 chemical elements determined for 107 HgMn stars (Ghazaryan 2013), and 35 of them have been determined in more than four stars. All these abundances were published after 1993, and so are not included in the previous compilation by Smith (1996b). Main trends such as increasing overabundances with atomic number and large dispersion from star to star are just confirmed in the new compilation. However, some differences for some elements may be found in the new compilation.

We have also considered the abundances element per element according to parameters such as  $T_{\text{eff}}$ ,  $\log g$  and  $v \sin i$ . Apart from the already known correlation for Mn (Smith & Dworetsky 1993), we have found possible correlations for Sr, S, Mg (decreasing overabundances with  $T_{\text{eff}}$ ), and for P, Ti, V, Xe, Ca, Sc, Ba (increasing overabundances with  $T_{\text{eff}}$ ). On the other hand, we have not found significant connection of abundances with  $\log g$  and  $v \sin i$  except for Hg where a maximum of the overabundances is found at  $\log g \approx 3.9$ . We have also looked for correlations of the overabundances according to the multiplicity using a *Kolmogorov–Smirnov* test. This statistical analysis has not allowed us to conclude that multiplicity is a determinant parameter for chemical abundance anomalies in HgMn stars.

## ACKNOWLEDGEMENTS

This collaboration has been supported by the CNRS and the State Committee for Science of Armenia through the Collaborative Bilateral Research Projects EDC26043. SG would like to express her gratitude to Arthur Hakobyan for valuable discussions.

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

The files `abundances_catalog.pdf` and `abundances_catalog.xlsx` provide (in two different formats) the details of abundance sources, element per element and for each star. The files `*_bar.pdf` are the figures showing abundances element per element (with error bars), see footnote 3. The files `*_teff.pdf` are the abundances plotted vs.  $T_{\text{eff}}$ .

(<http://www.mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stw911/-/DC1>).

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## APPENDIX A

References: (1) Adelman, Philip & Adelman (1996), (2) Adelman et al. (2001a), (3) Adelman et al. (2001b), (4) Adelman et al. (2004), (5) Adelman et al. (2006), (6) Alecian et al. (2009), (7) Anders & Grevesse (1989), (8) Asplund et al. (2009), (9) Bohlender, Dworetsky & Jomaron (1998), (10) Castelli & Hubrig (2004), (11) Catanzaro et al. (2003), (12) Catanzaro & Leone (2006), (13) Catanzaro (2010), (14) Cowley et al. (2007), (15) Dolk et al. (2003), (16) Dolk et al. (2002), (17) Dworetsky & Budaj (2000), (18) Dworetsky (2004), (19) Dworetsky et al. (2008a), (20) Dworetsky et al. (2008b), (21) Fossati et al. (2011), (22) Hubrig et al. (1999), (23) Jomaron, Dworetsky & Allen (1999), (24) Kochukhov et al. (2005), (25) Leckrone et al. (1999), (26) Makaganiuk et al. (2012), (27) Niemczura et al. (2009), (28) Pintado & Adelman (1996), (29) Roby, Leckrone & Adelman (1999), (30) Ryabchikova, Zakharova & Adelman (1996), (31) Ryabchikova (1998), (32) Ryabchikova, Malanushenko & Adelman (1999), (33) Saffe et al. (2011), (34) Savanov & Hubrig (2003), (35) Smith (1993), (36) Smith & Dworetsky (1993), (37) Smith (1994), (38) Smith (1996), (39) Smith 1996a, (40) Smith (1997), (41) Tkachenko et al. (2013), (42) Usenko et al. (2001), (43) Wahlgren et al. (2000), (44) Wahlgren et al. (1998), (45) Wahlgren & Hubrig (2000), (46) Woolf & Lambert (1999a), (47) Woolf & Lambert (1999b), (48) Yüce et al. (2011), (49) Yushchenko et al. (1999), (50) Zavala et al. (2007).

**Table A1.** HgMn stars considered in this work. The first line shows the Sun's references that we used to scale the abundances presented in this paper (see Sec. 2.1).

No.	Stars' names	Multiplicity	$T_{\text{eff}}(K)$	$\log g$	$v \sin i$	$\xi$	References
0	Sun	*	5777	4.44	$1.6 \pm 0.3$	—	7,8
1	$\alpha$ And A	**	13800	3.86	51.00	—	32
2	$\beta$ Scl	*	12400	3.90	25.00	0.0	20,33,35,36,37,38
3	$\beta$ Sco Ea	**or*m	$13000 \pm 800$	$4.20 \pm 0.20$	$5.0 \pm 1.0$	2.0	13
4	$\beta$ Tau	**	13250	3.65	59.00	0.1	5
5	$\gamma$ Cma	$Cl^*$	13600	3.40	—	2.0	46
6	$\gamma$ Crv	*	12125	3.70	32.00	0.0	5,16
7	$\theta$ Hyi	**or*m	14106	3.81	36.00	0.0	15
8	$\iota$ CrB A	$SB^*$	11000	4.00	1.00	0.2	15,17,18,19,20,23,30,31,35,37
9	$\kappa$ Cnc A	$SB^*$	13200	3.70	6.00	0.0	3,15,16,18,19,20,23,29,35,36,37
10	$\mu$ Lep	*XC	12800	3.85	15.5	0.0	3,15,17,18,19,20,29,30,34,36,37
11	$\nu$ Cnc	$SB^*$	10375	3.50	20.00	—	16,17,18,19,23,30,37,38,46
12	$\nu$ Her	$SP^*$	12000	3.80	9.00	0.6	5,16,17,18,19,20,29,35,36,37
13	$\phi$ Her A	$SB^*$	11525	4.05	8.0	0.4	19,20,36,50
14	$\phi$ Phe	*	$10500 \pm 200$	$3.80 \pm 0.10$	$13.62 \pm 0.22$	—	15,18,26
15	$\chi$ Lupi A	$SB^*$	10750	4.00	2.00	—	4,11,16,17,18,19,20,25,26,31,36,37,39,44
16	$\xi$ Cmi	*	13500	3.36	$28.0 \pm 3.0$	1.1	46
17	$\pi$ Boo A	**	12700	4.02	—	—	16,30
18	AV Cep A	$Al^*$	11000	3.60	7.00	$1.7 \pm 0.3$	11
19	AV Scl	$SB^*$	12400	4.00	12.00	—	1,14,15,34
20	BD 0984	$Cl^*$	13975	4.20	$49 \pm 2$	2.0	47
21	HD 122983	*iC	$10700 \pm 200$	$4.00 \pm 0.15$	$35.0 \pm 3.0$	$1.0 \pm 0.2$	21
22	HD 123226	*iC	$12400 \pm 300$	$4.04 \pm 0.10$	$17.0 \pm 1.0$	$0.0 \pm 0.2$	21
23	HD 123269	*iC	$11600 \pm 250$	$3.94 \pm 0.15$	$25.0 \pm 2.0$	$0.0 \pm 0.2$	21
24	HD 124740	$SB^*$	10350	4.00	2.00	0.0	14,15,34
25	HD 158704	**or*m	$13163 \pm 124$	$4.22 \pm 0.05$	2.50	—	22
26	HD 168202	*	10500	4.00	$71.0 \pm 6.0$	2.0	27
27	HD 168733	*	13500	3.30	10.00	0.0	34
28	HD 173673	*	13000	3.80	$29.0 \pm 2.0$	—	27
29	HD 174933	$SB^*$	13100	4.10	2.0	—	45
30	HD 175640	*	12077	3.92	0.50	$< 1.0$	10,15,19,48
31	HD 186774	*	$10380 \pm 270$	$3.75 \pm 0.15$	$19.0 \pm 3.5$	2.0	41
32	HD 209459	*	10350	3.48	4.0	—	45
33	HD 29647	*	12650	4.10	4.00	0.4	3
34	HD 35548	$SB^*$	$11088 \pm 86$	$3.79 \pm 0.05$	1.75	—	15,16,17,18,19,20,35,36,37,38
35	HD 37492 A	$Cl^*$	13325	3.93	$8.5 \pm 1.0$	2.0	47
36	HD 37886	$Cl^*$	12540	4.20	$19 \pm 1$	1.0	47
37	HD 45975	*iC	12500	4.00	$61.0 \pm 3.0$	2.0	27,47
38	HD 46886	*	12900	3.80	$18.0 \pm 1.0$	0.0	27
39	HD 47278	*	11500	4.10	$38.0 \pm 2.0$	2.0	27
40	HD 49886	*	13000	4.00	$11.0 \pm 1.0$	0.0	27
41	HD 53004	*	11600	4.00	$58.0 \pm 8.0$	2.0	27
42	HD 55362	*	13000	4.00	$53.0 \pm 6.0$	2.0	27
43	HD 65949	$Cl^*$	13600	4.00	—	—	14
44	HD 65950	*	12910	4.00	—	—	14
45	HD 71066	**	12000	4.10	1.50	—	48
46	HR 1079	*	12000	4.10	87.6	—	24
47	HR 1185	*iC	13000	4.00	67.0	—	24
48	HR 1445	**	12900	4.00	56.4	—	24
49	HR 1484	*	14600	4.20	63.2	—	24
50	HR 1576	*	13900	4.10	74.6	—	24
51	HR 1800 A	$SB^*$	11050	3.80	3.0	0.5	15,16,17,18,19,20,35,36,37,38
52	HR 2676	*	14050	3.60	21.00	1.0	17,18,19,20,23,35,36,37,38,46
53	HR 2844	$SB^*$	13460	3.80	27.00	0.5	17,18,19,20,23,35,36,37,38,40
54	HR 3273	*	12253	3.42	$20.0 \pm 2.0$	0.3	33
55	HR 3361	$SB^*$	10900	3.87	—	1.0	46
56	HR 4072 A	$SB^*$	10650	3.80	3.20	1.0	11,16,18,19,30,31,35,37,38
57	HR 4089	$SB^*$	15126	4.16	7.00	0.0	15
58	HR 4487	$Cl^*$	11020	3.92	18.00	0.0	14,15
59	HR 4493	*	12500	4.02	$54.0 \pm 3.0$	1.5	46
60	HR 5998	*	15800	4.19	$47.0 \pm 4.0$	1.0	46
61	HR 6000	**	13990	4.29	—	1.5	14,20,35,36,40
62	HR 6532	$SB^*$	11100	3.97	—	1.3	46

**Table A1** – *continued*

No.	Stars' names	Multiplicity	$T_{\text{eff}}(K)$	$\log g$	$v \sin i$	$\xi$	References
63	HR 6759	<i>SB1</i>	12193	3.54	0.0	—	14,15,16,34
64	HR 6997	<i>SB*</i>	14500	3.90	34.00	1.5	17,18,19,20,23,35,36,37,38,40
65	HR 7018	*	10505	3.90	$(-12.1) \pm 2.6$	0.4	2
66	HR 7028	*	11300	4.01	—	0.0	46
67	HR 7245	<i>SB1</i>	12193	3.54	0.0	—	16,28,45
68	HR 7361	*	13650	3.55	9.00	0.0	3,15,17,18,19,20,35,36,37
69	HR 7664 <i>B</i>	<i>SB*</i>	13200	3.60	8.00	0.8	3,17,18,19,20,35,36,37,40
70	HR 7694 <i>B</i>	<i>SB*</i>	11500	4.07	8.00	0.0	15
71	HR 7775	<i>SB1</i>	10750	4.00	2.0	0.0	9,15,16,18,19,20,30,36,37,43,45
72	HR 7878	★	13010	3.84	5.50	—	34,45
73	HR 8118	*	11381	4.11	$30.0 \pm 1.0$	0.5	33
74	HR 8349	<i>SB*</i>	12975	3.90	—	—	3,30
75	HR 8567	*	12315	3.68	$22.0 \pm 1.0$	0.1	33
76	HR 8723	**	13100	3.60	67.1	—	24
77	HR 8937	*	12088	4.28	$24.0 \pm 2.0$	0.5	20,33,35,36,37,38
78	Platais 1 No.1	<i>*iC</i>	10000	3.50	3.5	—	42
79	TYC 3148 1470 1	*	$10650 \pm 285$	$3.87 \pm 0.14$	$33.0 \pm 5.0$	2.0	41
80	USNO-A2.0 0825-02993210	*	$11750 \pm 500$	$4.00 \pm 0.50$	$50.0 \pm 8.0$	—	6
81	USNO-A2.0 0825-03028353	*	$12500 \pm 500$	$4.50 \pm 0.50$	$50.0 \pm 8.0$	—	6
82	USNO-A2.0 0825-03036752	*	$13500 \pm 500$	$4.00 \pm 0.50$	$35.0 \pm 5.0$	—	6
83	1 Cen	<i>SB*</i>	12900	3.72	—	—	30,46
84	11 Per	*	14550	4.19	$4.8 \pm 0.4$	0.8	46
85	14 Hya	*	12250	3.72	$35.0 \pm 3.0$	2.0	46
86	21 Aql	**	13175	3.27	$17.0 \pm 1.0$	0.0	27
87	21 Peg	*	10350	3.48	4.00	—	45
88	23 Cas	<i>SB*</i>	13200	3.54	$23.0 \pm 2.0$	0.6	46
89	28 Her	*	11000	3.80	8.00	0.0	15,16,18,19,20,23,30,35,36,37,38
90	30 Cap	*	13700	3.34	—	1.0	46
91	33 Gem	<i>Ro*</i>	14400	3.85	19.50	0.5	1,17,18,19,20,34,35,36,37,40
92	36 Lyn	<i>Ro*</i>	13700	3.65	49.00	2.0	18,35,36,37,38,40
93	38 Dra	*	11500	4.01	$32.0 \pm 4.0$	0.5	46
94	41 Eri A	<i>SB*</i>	12750	4.18	12.00	0.0	14,15
95	41 Eri B	<i>SB*</i>	12250	4.10	12.00	0.0	14,15
96	46 Aql	*	13000	3.65	3.0	0.0	14,15,16,17,19,35,36,37,38,48
97	46 Dra A	<i>SB*</i>	11700	4.11	5.00	—	11,31
98	46 Dra B	<i>SB*</i>	11100	4.11	5.00	—	11
99	53 Tau	<i>SB*</i>	12000	4.50	5.0	0.0	5,17,18,19,20,36,37,40,45
100	56 Aqr	*	11977	4.06	25.00	0.0	15
101	66 Eri A	<i>SB*</i>	11100	4.25	17.00	0.9	11,31,49
102	66 Eri B	<i>SB*</i>	10900	4.25	17.00	0.7	49
103	69 Peg	*	10950	4.05	$35.0 \pm 2.0$	1.0	46
104	74 Aqr A	<i>SB3</i>	12000	3.70	$1.0 \pm 0.5$	0.0	12
105	74 Aqr B	**	11500	3.90	1.00	—	12
106	87 Psc	<i>SB*</i>	13150	4.00	21.0	1.5	12,18,19,20,23,35,36,37,38,40
107	112 Her A	<i>SB*</i>	13100	4.10	6.00	0.0	11,15,16,17,18,19,20,32,35,36,37

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