

OPEN CLUSTERS AND FIELD CEPHEIDS IN THE GALACTIC DISK – CONTRADICTIONS IN PROPERTIES

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ABSTRACT. The comparative analysis of the abundances of α -process elements, elements of the rapid and the slow neutron capture and iron in the open stellar clusters, field Cepheids, and also in red giants and dwarfs of the thin disk has been performed. The found distinctions and the revealed regularities are attracted for clarification of the history of star formation in the thin disk of the Galaxy.

Key words: cepheids, open clusters, galactic disk

Introduction

Both classical Cepheids and the open stellar clusters are typical representatives of the thin galactic disk, therefore the chemical composition of the atmospheres of these objects can be used for the analysis of stages of formation and evolution of this subsystem. This is due to the difference of times of entering of chemical elements produced in the various processes of nuclear synthesis in previous generations of stars into the interstellar medium, out of which more young Cepheids and open clusters were later formed. To now sufficient amount of precision astrometric and spectroscopic data are collected to make statistical comparison of chemical properties of classical Cepheids and open clusters in our Galaxy for the testing of degree of homogeneity of these populations.

Initial data

We have restricted the use of the abundances of only those chemical elements which, according to modern views, have almost no changes related to the nuclear processes in the atmospheres of the studied stars. In particular such elements are α -elements (O, Mg, Si, and Ca), iron-peak elements (Fe), elements of the slow (Ba, La, and Ce) and of the rapid neutron capture (Eu) (see rationale for choosing below). We have used homogeneous data on the abundances for 221 Cepheids from the papers of one group of authors (see Andrievsky et al., 2013 and references therein to earlier papers). http://www.multitrans.ru/c/m.exe?a=110&t=3501211_2_1&sc=41 Determination accuracy of the abundances for the elements having more than 10 lines (e.g., iron) reaches 0.05-0.10 dex, whereas the error increase to 0.15-0.20 dex in case of five lines or less. We calculated the ages of these stars from the formula

$\log t = 8.50 - 0.65 \log P$, where t is the age in years, and P is the Cepheid period in days (Efremov, 2003).

The abundances of the listed chemical elements in 77 open clusters were taken from 72 papers published between 1994 and 2013. The most probable number of the measured stars in the cluster is equal to four, whereas the abundances received by one star and in one paper are defined only for four clusters. We averaged data from different sources in inverse proportion to the declared errors. External convergences of the relative abundances of all elements range within $\sigma_{[el/Fe]} = 0.08-0.15$ dex.

For comparison, we have involved data on the abundances of the same elements in 212 dwarfs and in 171 ascending-branch giants and the clump-giants which are close to the evolutionary status of Cepheids received by group of authors, using a similar technique (Mishenina et al., 2006; 2007; 2013). The errors in determining the abundances of all the elements in these stars do not exceed 0.15 dex. The uniformity of approaches to determining the abundances of chemical elements in the Cepheids, dwarfs and giants is provided by using everywhere the unified system of solar oscillator strengths, the uniform list of spectral lines and the uniform grid of the atmospheric models of Kurucz.

Dependences of the relative abundances of the various chemical elements on metallicity

According to modern views, the basic processes of nuclear synthesis, which produced isotopes of all chemical elements, take place in stars of a certain masses. In particular, the bulk of α -elements are synthesized in the interiors of massive ($M > 10M_{\odot}$) stars in the late stages of their evolution and are ejected into the interstellar medium as a result of outbursts as Type II supernovae. At that only oxygen and magnesium are produced exclusively in these stars, while the others α -elements can be synthesized in SNe Ia in small amounts. At the same time, for dwarfs of the disk, the relative abundances of two more α -elements, silicon and calcium, change with increasing metallicity like oxygen and magnesium, i.e. the contribution to their abundance from SNe Ia is insignificant (Mishenina et al., 2013). The abundances of these elements are practically unchanged in the atmospheres of stars in advanced stages of evolution too, that is, in the red giants and the red clump-

giants, in which the helium is burning in core (see Mishenina et al., 2006). The abundances in the atmospheres of Cepheids also don't undergo significant changes (Kovtyukh et al., 2005). We have used the abundances only four α -elements, namely O, Mg, Si and Ca, to study.

It is believed that the synthesis of the bulk of atoms of rapid neutron capture elements takes place directly during outbursts of SNe II with the masses $8 < M/M_{\odot} < 10$. When SNe II explode, some of the atoms of iron-peak elements are also formed. The bulk of elements of iron peak are produced in the explosions of SNe Ia which are the final stage of the evolution of close binary stars with masses $< 8M_{\odot}$.

Chemical elements, which produced in the process of nuclear synthesis in stars of different masses, are ejected into the interstellar medium in different time. So time of the evolution of massive stars (SNe II progenitors), enriching the interstellar medium with α -elements, the r-process elements, and a small amount of iron, is not more than about 30 million years, and the mass explosions of supernovae SN Ia, making the major contribution to the enrichment of the interstellar medium with iron group elements, occur $\approx 1-1.5$ Gyr later. Therefore, the relative abundances of $[\alpha/Fe]$ and $[r/Fe]$ in new generations of stars will decrease at increasing metallicity. Slow neutron capture elements are also produced in stars of different masses. The bulk of them at solar metallicity are produced in the atmospheres of asymptotic giant branch (AGB-stars) with masses $M < 4M_{\odot}$ are brought into the interstellar space through the envelope ejection. According to theoretical calculations, peak of the yield is formed near $[Fe/H] \approx -0.2$ and the ratio $[s/Fe]$ decreases at a further increasing metallicity. Some more amount of atoms of the s-process elements are produced at high temperatures in the interiors of massive stars; this is the weak component of s-process. We used three heavy s-process elements, namely Ba, La and Ce, for the analysis.

We analyze dependences of the relative abundances of four α -elements on metallicity. Dispersions of the relative abundances of oxygen and magnesium for Cepheid are substantially greater than for the other types of stars: $\Delta [O/Fe] = -0.08 \pm 0.02$ and $\Delta [Mg/Fe] = -0.07 \pm 0.02$. Both elements exhibit weak tendencies to decrease of the relative abundances with increasing metallicity ($r = 0.14 \pm 0.07$ and 0.20 ± 0.07 respectively, at $P_N < 5\%$). For dwarfs and giants, analogous dependencies are narrower; slopes are larger; and correlations are much more significant. The relative abundances of silicon and calcium in Cepheids steadily decrease with a small spread at increasing metallicity in the same way as the other two types of stars ($r = 0.4 \pm 0.1$ and 0.3 ± 0.1 respectively, at $P_N \ll 1\%$). But as well as for two previous α -elements, both relations lie on $\Delta [Si/Fe] = -0.06 \pm 0.01$ and $\Delta [Ca/Fe] = -0.07 \pm 0.01$ lower than those for giants. To compensate for slightly possible systematic deviations in determinations of the abundances for each element, further we will investigate the behavior of the average abundances of all four α -elements.

Dependences of the abundances of three heavy s-elements, viz. Ba, La and Ce, on the metallicity were investigated as well. The slopes of dependences of $[Ba/Fe]$ on $[Fe/H]$ within the error limits for Cepheids and other stars are the same, but the sequence of Cepheids lies up by $\Delta [Ba/Fe] = +0.12 \pm 0.02$. The values of the relative abundances of these s-elements also decrease at increasing

$[Fe/H]$ (in both cases, $P_N \ll 1\%$). In this case, both elements also show increased abundances in comparison with giants and dwarfs. Moreover, for Cepheids and the giants, the slopes of the dependences of $[La/Fe]$ on $[Fe/H]$ within the errors are the same, and the overabundance for Cepheids is very large ($\Delta [La/Fe] = +0.35 \pm 0.02$). The slope of the dependence of cerium abundance outside the error limits for Cepheids is larger, than for giants; and the overabundance is smaller than for the previous two s-elements on $\Delta [Ce/Fe] = +0.07 \pm 0.02$. For dwarfs, the slopes for all elements even in a limited range of metallicity differ only slightly from zero. Thus, regardless of the method used, the relative abundances of each s-process element in Cepheids always turn out to be enhanced. As all listed elements of slow neutron capture behave in Cepheids in approximately the same way relative to the giants, further we will use the average value for all three heavy elements of s-process.

Despite the difference in methods, the slopes of the dependences $\langle [Eu/Fe] - [Fe/H] \rangle$ for all three types of stars are practically the same, exhibiting, on the average, a shift ($\Delta [Eu/Fe] \approx +0.05 \pm 0.01$) in the direction of greater relative abundance in Cepheids in comparison with giants. Thus, the relative abundances of all investigated α -elements in Cepheids show in a varying degrees lower ratios of $[\alpha/Fe]$, than those in other field stars (including the Sun). Instead, the relative abundances of all studied elements of s- and r-processes in Cepheids turn out to be enhanced compared to field stars. Besides all elements show a decrease of the relative abundances with increasing metallicity.

Connection of relative abundances of chemical elements of different processes

The first three panels in Fig. 1 shows the dependence of the relative abundances of the α -elements, rapid and slow neutron capture elements on the metallicity for open clusters, Cepheids, giants and dwarfs. At first we have made the comparative analysis of the behavior of Cepheids versus field stars. For each star, the errors of different signs in the determinations of the abundances of elements produced in a single process are compensated a little at such averaging. As can be seen, the relative abundances of the elements produced in α - and r-processes decrease approximately identically for all objects with increasing metallicity. Besides the sequences for dwarfs and giants are practically the same, while the sequence of α -elements for Cepheids lies outside the 3σ limits lower ($\Delta [\alpha/Fe] = -0.07 \pm 0.01$), than for giants and dwarfs, and the sequence of r-process element lies outside the error limits higher ($\Delta [Eu/Fe] = +0.03 \pm 0.01$). The slope of the dependence of $[s/Fe]$ on $[Fe/H]$ for Cepheids is about the same as that for giants with the same metallicity (i.e. $[Fe/H] > -0.30$). But at that point Cepheids lie much higher ($\Delta [s/Fe] = +0.19 \pm 0.01$). Note that the nature of the dependence of s-elements and the other two types of elements on metallicity is different. If the yield of s-elements decreases at increasing metallicity of their parent stars, then the relative abundances of α -elements and r-process elements decrease in the next more metal-rich generations of stars due to the later onset of the epoch of mass iron ejections during SNe Ia explosions.

Existence of the correlation between the elements of the s- and r-processes surprises. The fact is that, with the solar metallicity, low-mass ($<4M_{\odot}$) AGB-stars contribute mainly to the enrichment of s-process elements. Some of these stars, being close binaries, subsequently explode as a SN Ia, enriching the interstellar medium with iron.

That is, both processes proceed successively in the same stars, and so the relative number of atoms of the s-process elements ejected by them into the interstellar medium seems to should not to depend on metallicity. The existence of correlations most likely stems from the fact that the yield of the relative amount of s-process elements decreases with increasing metallicity of AGB stars in which atmospheres their formation happens. As a result, as shown in the top panels of Fig. 1, dependences of the relative abundances of the s-elements on metallicity for all stars were very similar to the analogous dependences of the relative abundances of α - and r-elements; the reason for their appearance is related to the sequence of enrichment of the interstellar medium with these elements and iron.

The abundances of chemical elements in open clusters

In Fig. 1 dependences of the relative abundances of chemical elements of all three processes of nuclear synthesis on metallicity in the open clusters are also shown. There are notable differences in the behavior of these elements for all types of objects. So, although the average abundances of α -elements in the clusters and field giants are almost the same, but the slope of dependence for the clusters has practically absent. As a result, the relative abundances of α -elements in the clusters with metallicity less than solar value significantly lower than that for the field giants. For clusters, the slope is also absent in dependence of s-process elements on metallicity. But the sequence of clusters is far higher outside the error limits than for field giants. In Fig. 1c europium in clusters shows a very large spread, although the sequences for all objects are parallel. Unfortunately, in young clusters where there are Cepheids, there are no red giants, and it isn't possible to compare the chemical composition of these stars inside the cluster. The correct comparison is possible only after a detailed analysis of the methods for determining the abundances of chemical elements in the clusters by different authors. Therefore we will try to explain only the behavior of the abundances of chemical elements in field Cepheids.

Discussion

The change of the relative abundances of some chemical elements $[e/Fe]$ with increasing metallicity can be interpreted within the framework of chemical evolution of a stellar-gaseous system only in case if the total abundance of heavy elements in it increases on the average with time, that is, if metallicity is the statistical indicator of age. In a recent paper (Marsakov et al. 2011), we made the complete sample of F-G-dwarfs of the thin disk located within 70 pc of the Sun on the basis of the catalog (Holmberg et al. 2009); we showed in it that the interstellar matter in the thin disk demonstrated really on average approximately the same amount of heavy elements ($<[Fe/H] \approx -0.2$) and a low homogeneity within the first few billion years of the formation of the thin disk.

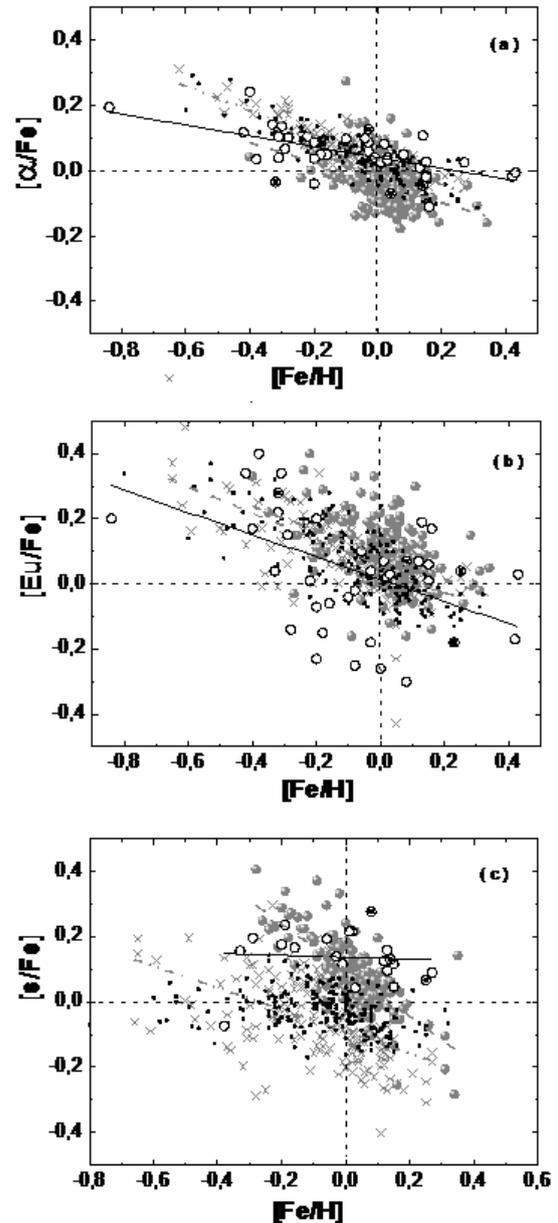


Figure 1: Dependences of the relative abundances of the chemical elements of different processes on the metallicity in open clusters (large open circles), Cepheids (gray filled circles), red giants (gray crosses), and field dwarfs (small dark gray circles). The solid, dashed and dotted inclined lines are the regression for Cepheids, open clusters and giants.

However about 4-5 Gyr ago the mean metallicity began to increase systematically. Therefore it is possible to consider metallicity in the thin disk in the last ~ 5 Gyr as a temporal parameter and to explain observed differences in the relative abundances of α - and r-elements in Cepheids in comparison with other field stars within the framework of chemical evolution of interstellar matter.

The decrease in the relative abundances of the α -elements and r-process elements with metallicity, observed in Fig. 1a,b for Cepheids and field stars, is due to the later ejection of bulk of the iron group atoms into the interstellar medium. As the metallicity in the thin disk is an age indicator and as the

range of ages for the giants and dwarfs are much greater than the evolution time of the progenitors of SN Ia, that such dependences have an evolutionary meaning for these stars. In contrast to dwarfs and giants, Cepheids are very young stars, and dependences of $[\alpha/\text{Fe}]$ on $[\text{Fe}/\text{H}]$ and of $[\text{r}/\text{Fe}]$ on $[\text{Fe}/\text{H}]$ observed for them testify not to their sequential birth, but only to the lack of homogeneity of the chemical composition of the interstellar medium in which star formation took place. From fig. 1a, it can be seen that the correlations are significant, and dependences in both panels are parallel but they are spaced from each other outside the error limits. The parallelism means that all stars were formed from the matter that experienced the same history of enrichment with chemical elements. Apparently, star formation in the past bypassed some regions of interstellar matter, and only then the young stars, which representatives are present Cepheids, were formed out of them. As a result, existence of the dependences for Cepheids testifies to a weak mixing of interstellar matter and "delayed" star formation in some regions, when the stars with different abundances of heavy elements are formed at the same time not far from each other (see also Lepine et al, 2011; Gozha and Marsakov, 2013). Note that stars with ages, typical for Cepheids, are practically absent among our near dwarfs and giants, so a significant gap in ages between the Cepheids and other stars is observed.

Thus, the systematic underabundances of α -elements and overabundances of r -process elements in Cepheids compared to field dwarfs and giants can be explained by the fact that very massive stars stopped to explode as supernovae when the interstellar medium reached about solar metallicity, and as a result the number of atoms of α -elements ejected into the interstellar medium decreased sharply. In view of the fact that high-mass supernovae also produced a significant amount of iron-group elements during their explosions, the $[\text{r}/\text{Fe}]$ ratios increased in the interstellar medium, but the final values of $[\alpha/\text{Fe}]$ nevertheless decreased. Subsequently the Cepheids observed now were formed from this medium. This assumption is supported also by the observational fact, being that all Type II supernovae progenitors investigated in other galaxies do not exceed the maximum of masses ≈ 20 solar masses (see Smartt et al, 2009; Kochanek et al, 2008).

The overabundance of s -process elements in Cepheids can also be explained by the ending of outbursts of massive SNe II, which enriched the interstellar medium also with a significant amount of iron-peak elements except α -elements. But in the atmospheres of massive stars, some amount of the s -elements is also produced in the weak component of the s -process. It is likely that these stars can eject the upper layers of their envelopes even without an explosion like AGB stars, still increasing the relative abundances of the s -elements in the next generation of stars. As a result, the $[\text{s}/\text{Fe}]$ ratios in young stars, Cepheids, could turn out to be enhanced. But the parallelism of dependencies $[\text{s}/\text{Fe}]$ on $[\text{Fe}/\text{H}]$ for the Cepheids and the giants shows that AGB stars, in which $[\text{s}/\text{Fe}]$ ratios in the output depend on their metallicity, remain the main supplier of these elements.

Certainly the expressed assumption can be true only if the discussed distinctions between the relative abundances of various chemical elements in Cepheids, dwarfs and red giants are not due to unrevealed systematic errors in the

determinations of these abundances in Cepheids. Otherwise, it is necessary to reconsider the approach to determining of the chemical element abundances in the evolutionarily advanced stars, namely Cepheids. For testing conclusions of this work, it is desirable to investigate the behavior of the abundances of the same elements in open star clusters, as young as Cepheids.

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