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THE ORIGIN OF COPPER IN COSMOS

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ABSTRACT

Copper appears to be the most problematic element in the context of the Galactic chemodynamics. The dependence of the relative-to-iron copper abundance [Cu/Fe] as a function of the metallicity remains a subject of debate. At very low metallicity, the observed copper abundace is also quite low. Several sources of the copper nuclei production have been proposed. Unfortunately, none of them provides an adequate explanation of such a low abundance. It is discussed here that this problem may be related to the LTE assumption used in spectroscopic studies of copper lines. Andrievsky et al. (2018) and Korotin et al. (2018) have shown that copper lines are strongly influenced by NLTE effects. Overionization of the copper neutral atoms leads to a decrease in the overall absorption in Cu I spectral lines, and as a result, LTE analysis yields a copper underabundance (i.e., NLTE corrections are positive). Correct determination of the copper abundance using the NLTE approximation eliminates this problem. Thus, in the low-metallicity regime, copper does not exhibit a significant deficiency and behaves essentially as a primary chemical element. Its cosmic production in the earliest stages of the Galaxy evolution may be associated with explosions of massive stars, such as type II supernovae (core-collapse supernovae) and hypernovae. The main source in this case may be the α-rich freeze-out process during the explosive silicon burning.

Key words: stars: abundances – nuclear reactions, nucleosynthesis, abundances

1 INTRODUCTION

Copper ($Z = 29$) has two stable isotopes: $^{63}_{29}$Cu and $^{65}_{29}$Cu. From the perspective of the Galactic chemical evolution, copper is a highly problematic element. Numerous spectroscopic studies aimed at the copper abundance determination in stars of various metallicities have revealed a very consistent pattern. According to this pattern, as the metallicity of stars decreases, the relative-to-iron ratio [Cu/Fe] also decreases. It should be noted that in these cases, the analysis was based on the assumption of the validity of the local thermodynamic equilibrium (LTE) condition in stellar atmospheres. In the next Section we briefly review some relevant studies.

The above behavior of the [Element/Fe] ratio as a function of [Fe/H] is characteristic of secondary chemical elements, whose nuclei formation depends on the metallicity of the environment. The abundances of primary elements do not exhibit the same dependence as the copper abundance. A number of processes responsible for the production of both secondary and primary elements (e.g., α-elements – neon, magnesium, silicon, sulfur, and others) are discussed in the literature. In particular, the following sources of copper nuclei production have been considered: explosive nucleosynthesis in supernovae (SNe) of type II and hypernovae (HNe), nucleosynthesis in type Ia supernovae, the weak *s*-process in massive stars, the main *s*-process in asymptotic giant branch stars (low-mass, intermediate-mass and more massive), and the *r*-process in massive stars (*s*-process is a slow neutron capture process in which a seed nucleus captures free neutron and undergoes β^--decay before capturing another neutron; *r*-process – the rapid capture of several neutrons by the seed nucleus, followed by β-decays). It should be noted that the certain processes listed here operate effectively at different stages of the Galaxy evolution. In the early stages (corresponding to low metallicity), massive stars should be the main cosmic suppliers of copper.

Helium burning may be responsible for the formation of the most abundant stable isotope $^{63}_{29}$Cu. Reactions between the nuclei of $^{14}_{7}$N and α-particles form nuclei of fluorine isotope $^{18}_{9}$F. After their β^+-decay nuclei of the oxygen isotope $^{18}_{8}$O are formed. Reactions between $^{18}_{8}$O and α-particles produce $^{22}_{10}$Ne nuclei. Subsequent reactions with α-particles lead to the formation of free neutrons in the well known reaction:

$$^{4}_{2}\mathrm{He} + ^{22}_{10}\mathrm{Ne} = ^{25}_{12}\mathrm{Mg} + n$$

Newly formed free neutrons can be captured by seed nuclei (e.g., nuclei of iron-peak elements such as iron, nickel). In the sequence of these reactions, accompanied by β^- decays, progressively heavier nuclei are formed, including those of copper

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and others (e.g., Zn, and heaver nuclei, if the neutron concentration is sufficient). In this scenario, copper will behave as a secondary element. Thus, copper can be produced by n-capture in the process of He burning in hydrostatic equilibrium (Woosley & Weaver 1995). The pure α-process (consecutive captures of the He nuclei) has the following form:

$$^{4}_{2}\mathrm{He} + ^{12}_{6}\mathrm{C} = ^{16}_{8}\mathrm{O} + \gamma$$

$$^{4}_{2}\mathrm{He} + ^{16}_{8}\mathrm{O} = ^{20}_{10}\mathrm{Ne} + \gamma$$

$$. \quad . \quad .$$

$$^{4}_{2}\mathrm{He} + ^{48}_{24}\mathrm{Cr} = ^{52}_{26}\mathrm{Fe} + \gamma$$

$$^{4}_{2}\mathrm{He} + ^{52}_{26}\mathrm{Fe} = ^{56}_{28}\mathrm{Ni} + \gamma$$

Romano & Matteucci (2007) and Romano et al. (2010) have also concluded that copper is mainly produced in massive stars during the helium burning and carbon burning in the hydrostatic regime. The presence of free neutrons and their high flux ensure that the conditions for the s-process are met. According to Woosley & Weaver (1995) and Limongi & Chieffi (2003) this is also possible in the explosive neon burning.

Explosive burning in the silicon shell of a type II SN (at the final stages of the massive star evolution), is accompanied by a high temperature of the environment through which the shock wave propagates (conditions: temperature above 5×10^9 K, density is about $10^6 - 10^7$ g cm^{-3}). Under these conditions, the high-energy γ-quanta are produced. They can cause the photo-disintegration of silicon nuclei converting them into protons, neutrons, and α-particles. The subsequent expansion of the shell and plasma cooling create favorable conditions for the reassembly of α-particles, forming increasingly heavier nuclei, as shown by the formulas above. This process is described by the α-rich freeze-out phenomenon (Truran & Arnett 1971, Woosley & Hoffman 1992, Howard et al. 1993). Due to the very high concentration of the α-particles, and high temperature, the nuclei lying slightly outside the region of the most stable nuclei with the highest binding energy per nucleon (Fe, Ni) can also be formed, for example, zinc nuclei, $^{60}_{30}$Zn. In the explosive silicon burning shell the concentration of neutrons is high. The captures of free neutrons by seed nuclei and β-decays lead, in particular, to the formation of copper nuclei.

In the case of a gradual decrease of the fraction of unassembled α-particles and a large excess of neutrons, α-rich freeze-out undergoes in the r-process (Woosley & Hoffman 1992, Woosley & Weaver 1995, Umeda & Nomoto 2002). This is another option of the copper nuclei production in massive stars that explode as supernovae.

Massive stars (hypernovae and supernovae) should be the only source of copper production in the early Galaxy. Over time, the less massive and long-lived stars begin to play a role in the chemical evolution of the Galaxy. Among them there are the stars which explode as supernovae of type Ia (Iwamoto et al. 1999), and intermediate- and low-mass stars that become the asymptotic giant branch objects at the advanced stages of their evolution (Gallino et al. 1998). The latter sources make a minor contribution to the formation of copper nuclei through the s-process (Bisterzo et al. 2004). The s-process operates at a neutron concentration significantly lower than in the r-process. In lower-mass stars, the main source of free neutrons is the reaction:

$$^{4}_{2}\mathrm{He} + ^{13}_{6}\mathrm{C} = ^{16}_{8}\mathrm{O} + n$$

$^{13}_{6}$C nuclei originate in the intermediate zone of low-mass stars during the asymptotic giant branch phase, where the hydrogen burning (CNO cycle) zone interacts with a zone enriched in helium nuclei. In massive stars and intermediate-mass stars, the internal temperature is higher, and the reactions between helium and neon nuclei lead to the production of the free neutrons, as shown above, in reactions between $^{4}_{2}$He and $^{22}_{10}$Ne nuclei.

Since the primary source of copper in the very early Galaxy was very massive stars exploding as supernovae and hypernovae, when the metallicity [Fe/H] was less than –3 dex, then the following question arises: why is the copper abundance (namely, [Cu/Fe]) so low in the old, low-metallicity stars, which have survived to the present day due to their low masses? Let us consider the observational data on the copper abundance in old (low-mass and metal-deficient) stars of our Galaxy.

2 LTE COPPER ABUNDANCE RESULTS

A good overview of copper abundance determinations in stars of different types and populations published published before 2004 is presented in Bisterzo et al. (2004). Here we will mention only a few papers from that period and briefly touch on more recent ones. Halo and disk stars were studied by Sneden et al. (1991). It was found that the relative copper abundance [Cu/Fe] varies linearly with metallicity: the lower the metallicity, the lower the copper abundance. A fairly large sample of metal-poor stars in the metallicity range [–3;–0.5] dex was studied by Mishenina et al. (2002). As in the above-mentioned work, the authors focused, in particular, on the copper abundance determination. As a result, a clear tendency of the relative copper abundance decrease with metallicity decreasing (in the range of [Cu/Fe] from zero to ≈ -1 dex) was found. To explain this dependence, the authors proposed that massive stars (which are considered the most efficient suppliers of many chemical elements in the early stages of the chemical evolutions of galaxies) produce only a small amount of the copper nuclei. A similar observational conclusion was reached by Simmerer et al. (2003), where the copper abundance in the giants from ten globular clusters and the halo field were compared. The relative copper abundance [Cu/Fe] shows similar trends for cluster and halo stars. Reference should also be made to Bihain et al. (2004), where the copper abundance was determined for a sample of FGK stars with [Fe/H] values ranging from –3 dex to approximately solar value. The result was expected, the copper abundance [Cu/Fe] gradually decreases from about solar value to –1 dex when the metallicity reaches [Fe/H] ≈ -3 dex. Cohen et al. (2008) determined LTE abundance of copper in several extremely metal-poor giant stars. For this purpose, the near-UV resonance lines of Cu I near 3250 Å were used. Combining these new data on abundances with the results of Mishenina et al. (2002) and Simmerer et al. (2003), cited above, the authors concluded that starting from the solar [Cu/Fe] ratio, the relative copper abundance gradually decreases to [Fe/H] ≈ -1.5 dex, reaching [Cu/Fe] ≈ -0.7 dex (but with a large scatter), and then this ratio reaches (very) roughly a plateau value in the range ≈ -0.9 to –0.6 dex.

A very interesting paper was published by Roederer & Barklem (2018). The authors analyzed the lines of neutral and ionized copper in a sample of six metal-poor stars (iron abundance ranges from about –2.5 to –1 dex). The temperatures and gravities of the studied stars are in the ranges ($\approx 5770 - 6500$) K and ($\approx 3.6 - 4.5$) dex, respectively. Since the program stars are metal-deficient, some of the copper lines in the visual part of the spectra are very weak. The authors used the spectra in ultraviolet and visible ranges obtained with the help of space and ground-based telescopes. The following copper lines were used: Cu I (5218.20, 5105.54, 3273.96, 3247.54) Å, Cu II (2126.04, 2104.80, 2054.98, 2037.13) Å. The main result for the copper abundance was the following: for stars with metallicity less than –1.8 dex, the difference in the copper abundance inferred from the Cu II lines was 0.36 ±0.06 dex greater than the abundance derived from the Cu I lines. This is clear evidence that the Cu I lines are very strongly influenced by NLTE effects in the low-metallicity regime. Recently Sneden et al. (2023) published LTE results on the copper abundance in 37 main-sequence (turn-off) very metal-poor stars ([Fe/H] less than –2 dex). The authors showed that in this metallicity range [Cu/Fe] values are scattered within the range from –0.5 to –0.9 dex.

Timmes et al. (1995) performed a numerical analysis of the chemical evolution of the seventy-six stable isotopes of elements from hydrogen to zinc, using the SNe of type II models with various masses ranging from 11 to 40 $M_\odot$ and five fixed values of metallicities. The results were compared with the stellar LTE abundances inferred from observations (metallicity from –3 to 0 dex). In particular, for copper, these authors failed to reproduce the LTE elemental abundance results in their calculations. To achieve reasonable agreement with observations they had to reduce the iron yield from type II SNe by a factor of two, which was, in fact, not sufficiently justified. Apparently, the LTE results once again emphasize that for some unknown reason copper is underproduced in the early Galaxy.

3 NLTE COPPER ABUNDANCE RESULTS

A new approach to solving the copper abundance problem arose from the analysis of copper lines within the NLTE approximation. Here, we will mention two relevant papers devoted to the NLTE copper abundance in a sample of the metal-poor stars. Andrievsky et al. (2018) developed the copper atomic model for the NLTE analysis. The sample of stars used by these authors included dwarfs and giants. Eleven program stars have metallicities [Fe/H] from –4.2 to –1.4 dex. The authors used a large number of neutral copper lines. Copper lines have been shown to be susceptible to strong NLTE effects. As an example, this is demonstrated in Fig. 1 for several lines located in the ultraviolet region of the spectrum of the metal-deficient star HD 84937 ([Fe/H] = –2.25 dex), which show an agreement between the observed and calculated NLTE synthetic profiles. In cotrast to the LTE result, which yields a strongly underestimated copper abundance: [Cu/Fe] = –0.83 (Sneden et al. 2016), our NLTE abundance result is [Cu/Fe] = –0.2. Since NLTE effects cause overionization of neutral copper atoms, absorption in the lines is reduced, and, accordingly, the Cu I lines become weaker. As a result, in this case, NLTE abundance corrections to the LTE abundances are positive, i.e., NLTE correction = abundance(NLTE) – abundance(LTE). Fig. 2 shows the obtained NLTE copper abundance in the program stars. For each star, the LTE abundance was also calculated. As can be seen from this Figure, the difference in copper abundances between NLTE and LTE cases is striking. Thus, direct LTE analysis of the equivalent widths of neutral copper lines or fitting their profiles with synthetic spectrum lead to an artificail underestimation of the copper abundance, and this effect becomes increasingly pronounced as the metallicity decreases. At the same time, a detailed analysis using the NLTE approximation yields a radically different result: the relative copper abundance [Cu/Fe] is practically independent of metallicity (namely, [Fe/H]), and the average copper abundance [Cu/Fe] is ≈ -0.2 in the low-metallicity regime.

A similar conclusion was also reached by Korotin et al. (2018). These authors have also analyzed copper lines in a sample of dwarfs with temperatures of 5800 – 6100 K. In addition to neutral copper lines, these authors studied eight ultraviolet lines of ionized copper. The first ionization potential of copper is about 7.73 eV. For effective temperature of about 6000 K, in the atmosphere levels where the weak lines of ionized copper are formed, the dominant ionization stage should be Cu II. Therefore, it can be assumed that the Cu II energy levels will be populated according to the Boltzmann distribution, i.e., the analysis in the LTE approximation can be applied to the lines of this ionization stage. Fig. 3 shows examples of the Cu II lines in the spectra of two program stars HD 94028 and HD 140283. In paper by Korotin et al. (2018), excellent agreement between the abundances derived from the lines of two ionization stages was obtained (the difference is less than 0.1 dex for five of the six stars studied). Fig 4. shows the overall distribution of the relative copper abundance [Cu/Fe] as a funcion of [Fe/H] from the aforementioned two papers. Interestingly, in this nearly flat distribution of the relative copper abundance, a shallow dip can be noted in the metallicity region around –2 dex. This feature can be associated with the onset of the enrichment of the Galactic gas with iron-peak elements. These elements are produced by relatively long-lived stars that explode as SNe of type Ia. This process occurs approximately after a few Gyrs of the Galaxy evolution.

Thus, taking into account the discussion above, it can be argued that from an astrophysical perspective, copper behaves as a primary-like chemical element. Its production in the early Galaxy is controlled by massive stars exploding as SNe and HNe. There is no need to invoke any artificial mechanisms in order to explain the low LTE abundance of this element in the low-metallicity regime. Nevertheless, LTE copper abundance in metal-poor stars is still used in the literature when comparing this value with the predictions of theoretical models of copper yield in the early Galaxy. For example, Kobayashi et al. (2020) recently performed a fit of the modeled [Cu/Fe] behavior to the LTE copper abundance distribution in the metallicity range from –3 to zero dex, but without due consideration of the latest NLTE results.

4 DISCUSSION

As seen in previous discussion, the LTE copper abundance in the low-metallicity stars may provide an incorrect evidence that copper behaves as a secondary element. Sneden et al. (2016) presented the LTE abundances in metal-poor star HD 84937. The most noticeable deviation from the solar [Element/Fe] ratio is observed only for copper. The resulting copper abundance (relative to iron abundance) [Cu/Fe] = –0.83 dex, which is a very low value. Other chemical elements, whose abundances were determined in this star, do not show such a remarkable underabundance. It should be noted that Andrievsky et al. (2018) analyzed several metal-deficient stars using the NLTE approximation. This star was among the sample stars. Due to the very low metallicity of this star, the copper lines in the visual region of the spectrum are very weak. The only option is to use the near-UV doublet lines of Cu I. The authors showed that these lines suffer from strong NLTE effects. Moreover, the far-UV lines are also strongly affected by the NLTE effects. The NLTE corrections are large and positive. This means that the LTE copper abundance inferred from Cu I lines is significantly underestimated. This is demonstrated by Fig. 2 for all stars of the sample. At the same time, as shown by Korotin et al. (2018), the ultraviolet line profiles of the ionized copper are well reproduced in LTE. The NLTE copper abundance inferred from Cu I UV lines in metal-poor stars agrees very well with LTE abundance derived from Cu II lines. This result was confirmed by Xu et al. (2022). These authors used their own NLTE model of copper atom for analysis of six metal-poor stars ([Fe/H] ranges from –2.59 to –0.95).

The nearly flat distribution of the relative copper abundance presented by Korotin et al. (2018) and Caliskan et al. (2025) exhibits a shallow dip, visible in the metallicity region around [Fe/H] ≈ -2 dex. This feature may be related to the onset of enrichment of the Galactic gas with iron-peak elements. These elements are produced by relatively long-lived stars that explode as type Ia SNe. This process occurs after approximately a few Gyrs of the Galaxy evolution. The gradual increase in the relative copper abundance up to the solar ratio [Cu/Fe] toward solar metallicity ([Fe/H] ≈ 0 dex) may be due to the increasing efficiency of the weak *s*-process in massive stars, the progenitors of type II SNe. At this stage of the Galaxy evolution, the abundance of iron-peak elements in the interstellar medium is gradually increases due to type I SNe activity. The greater the proportion of iron-peak elements in massive stars, progenitors of type II SNe, the greater the number of seed nuclei, which is necessary for more efficient neutron capture processes and, in particular, copper production.

Faroqui et al. (2025) discussed the origin of the chemical elements through the lens of the Galactic archaeology. They gathered data on the elemental abundances in stars with metallicity [Fe/H] lower than –2 dex, as these stars are bearing the imprints of primordial nucleosynthesis in the Galaxy. The abundances of 34 chemical elements from lithium to lead were considered. Although copper was mentioned in this interesting study, its abundance in the first Galactic low-mass stars was not discussed because the LTE abundance of this element was found to be too low for the metallicity considered. In fact, the theoretical models failed to predict such a low ratio [Cu/Fe] (see, Fig. 3 of this paper). However, it should be emphasized that theoretical models of Woosley & Heger (2007), after analyzing the evolution of the stars in the mass range from 12 to 120 $M_\odot$, showed that the expected [Cu/Fe] ratio should be in the range from –0.4 to +0.6 dex, with a maximum probablity of production of about +0.4 dex. This expectation appears to significantly exceed the abundance obtained from LTE analysis ([Cu/Fe] = –0.83 for metallicity –2.25; star HD 84937, see discussion above).

5 CONCLUSION

This brief note was intended to attract the attention of specialists working in the field of chemodynamic models of the early Galaxy, when massive SNe of type II and HNe contaminated their environment with certain chemical elements, to the copper problem. Copper is the most problematic element from the perspective of the Galactic chemodynamics. Currently, the dependence of the relative-to-iron copper abundance [Cu/Fe] as a function of the metallicity (namely, [Fe/H]) is still a subject of debate. The observed copper abundance at the very low metallicity is quite low. None of the proposed sources of the copper nuclei production can explain such a low abundance. The problem is apparently related to the LTE assumption used in the spectroscopic analysis of Cu I lines. Studies by Andrievsky et al. (2018) and Korotin et al. (2018) have shown that copper lines are strongly influenced by NLTE effects. Overionization of the copper neutral atoms

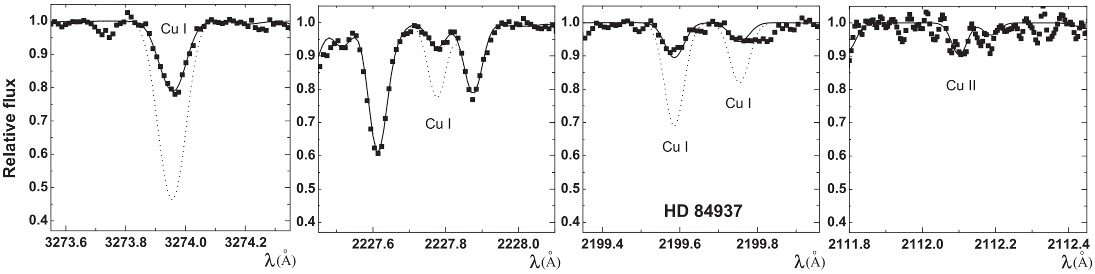

Figure 1. Copper (Cu I and Cu II) line profiles in the spectrum of HD 84937. Observed spectrum – filled squares, NLTE spectrum – continuous line, LTE spectrum calculated with the same abundance that was used for NLTE spectrum generation – dotted line. According to Andrievsky et al. (2018).

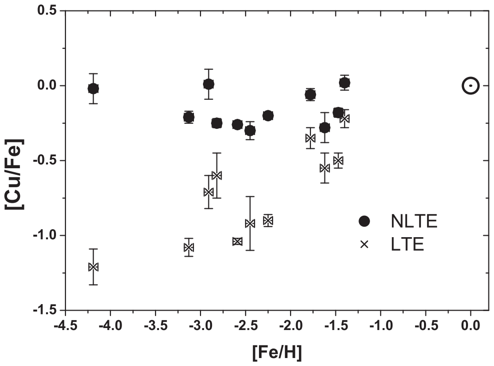

Figure 2. NLTE and LTE copper abundances as a function of [Fe/H] in a sample of stars from Andrievsky et al. (2018). Copper abundance in the Sun is denoted as ⊙.

leads to a decrease in the total absorption in the spectral lines (the NLTE corrections are positive), resulting in a copper deficiency in the LTE analysis. A correctly determined copper abundance with the help of the NLTE approximation eliminates this artificial underabundance. Thus, in the low-metallicity regime, copper behaves mainly as the primary chemical element. Its production may be associated with massive stars exploding as the core-collapse supernovae or hypernovae. The primary source in this case may be the α-rich freeze-out process during the explosive silicon burning. The reassembly of α-particles, the sequential formation of increasingly heavier nuclei, and their interaction with a neutron-rich environment create favorable conditions for the production of copper nuclei.

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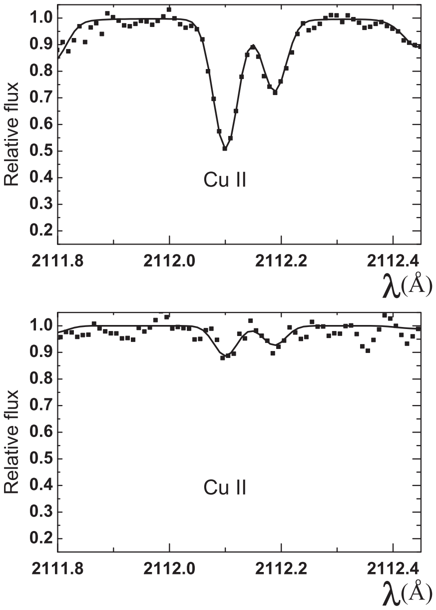

Figure 3. Cu II line profiles in the spectra of HD 94028 (top) and HD 140283 (bottom). Observed spectrum – filled squares, NLTE spectrum – continuous line. According to Korotin et al. (2018).

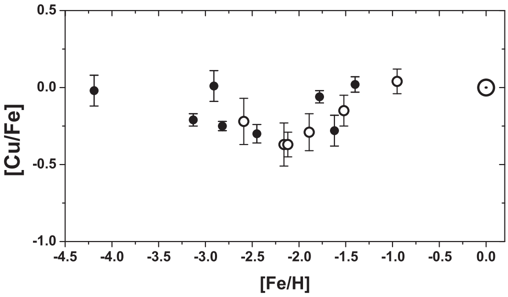

Figure 4. NLTE copper abundance as a function of [Fe/H] in a sample of stars from Andrievsky et al. (2018) and Korotin et al. (2018). Filled circles – abundances in stars obtained in Andrievsky et al. (2018), open circles – abundances obtained in Korotin et al. (2018). Copper abundance in the Sun is denoted as ⊙.

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