NLTE Analysis of Copper Lines in Different Stellar Populations*

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Abstract

The copper abundances of 29 metal-poor stars are determined based on the high-resolution, high-signal-to-noise ratio spectra from the UVES spectrograph at the ESO VLT telescope. Our sample consists of the stars of the Galactic halo, thick- and thin-disk, with [Fe/H] ranging from ~−3.2 to ~0.0 dex. The non-local thermodynamic equilibrium (NLTE) effects of CuI lines are investigated, and line formation calculations are presented for an atomic model of copper including 97 terms and 1089 line transitions. We adopted the recently calculated photoionization cross sections of CuI, and investigated the hydrogen collision by comparing the theoretical and observed line profiles of our sample stars. The copper abundances are derived for both local thermodynamic equilibrium (LTE) and NLTE based on the spectrum synthesis methods. Our results show that the NLTE effects for CuI lines are important for metal-poor stars, in particular for very metal-poor stars, and these effects depend on the metallicity. For very metal-poor stars, the NLTE abundance correction reaches as large as ~+0.5 dex compared to standard LTE calculations. Our results indicate that [Cu/Fe] is under-abundant for metal-poor stars (~−0.5 dex) when the NLTE effects are included.

Key words: Galaxy: evolution – line: formation – line: profiles – stars: abundances – stars: late-type

1. Introduction

The history of the chemical composition of our Galaxy is dominated by the nucleosynthesis occurring in many generations of stars. Metal-poor stars represent one of the main diagnostic tools to probe the early phases of the chemical evolution of our Galaxy. The variation in the elemental abundance ratios derived at different metallicities can be compared with the yields from supernovae (SNe) of different masses to check which ones have contributed to the Galactic chemical enrichment and when. Here, the preliminary result on the iron-group element copper is presented, and the main goal is to better constrain its nucleosynthetic origin.

Several sources of Cu have been discussed: (i) in massive stars the weak s-process operates during core-helium and carbon-shell hydrostatic burning phases, as well as in explosive complete Ne burning phase (Woosley & Weaver 1995; Limongi & Chieffi 2003; Pignatari et al. 2010); (ii) in low-mass stars the main s-process occurs during the asymptotic giant branch (AGB; Arlandini et al. 1999); and (iii) in long-lived type Ia supernovae explosive nucleosynthesis happens (Iwamoto et al. 1999; Travaglio et al. 2004; Fink et al. 2014).

From the observational point of view, Cu abundances have been discussed by Gratton & Sneden (1988) and Sneden & Crocker (1988), who found a secondary-like process for Cu (one requiring iron seeds from previous stellar generations, giving rise to an enrichment proportional to the iron content; also see Sneden et al. 1991). Further abundance determinations for this element in halo and disk stars were provided by Primas et al. (2000), and their results can be represented by a flat distribution, [Cu/Fe] = −0.75 ± 0.2 dex, for low-metallicity stars up to [Fe/H] < −1.8, followed by a linear increase with a slope close to 1 in the metallicity range −1.5 < [Fe/H] < −1 (Reddy & Lambert 2008; Ishigaki et al. 2013). While for the Galactic disk stars, there is a bending of the [Cu/Fe] distribution, and a distinct and separated trends are seen between thick- and thin-disk stars (see also Mishenina et al. 2002; Reddy et al. 2003; Yan et al. 2015; Zhao et al. 2016; Delgado Mena et al. 2017; Mikolaitis et al. 2017). For very low-metallicity stars, Cu abundances have been derived by Bihain et al. (2004) and Lin et al. (2008) under the assumption of LTE from the ultraviolet (UV) lines of CuI at 3247.53 and 3273.95 Å, taking the effects of hyperfine structure (HFS) and isotopic splitting into account, and they found a plateau ([Cu/Fe] ≈ −0.98 dex) at [Fe/H] < −2.5. The copper abundances for the bulge stars have been derived by Johnson et al. (2014), and it is found that the trend of [Cu/Fe] ratios with [Fe/H] in the bulge is very different from the Galactic thin- and thick-disk stars. In the bulge, the Cu abundance increases monotonically from [Cu/Fe] = −0.84 dex in the most metal-poor stars to [Cu/Fe] ≈ +0.40 dex in the most metal-rich stars (McWilliam 2016). The copper abundance in globular clusters has been discussed in detail by Simmerer et al. (2003), who derived the copper abundances of 117 giants in 10 globular clusters (M 3, M 4, M 5, M 10, M 13, M 17, NGC 7006, NGC 288, and NGC 362), and noted that the copper abundances in globular clusters appear to follow the trends found in the field. Similar conclusions have been reported for M 28(Villanova et al. 2017), M 80 (Carretta et al. 2015), NGC 4833 (Carretta et al. 2014), and NGC 5897 (Koch & McWilliam 2014). While it is reported that the copper abundances in the massive Galactic globular cluster ω Centauri fall below the corresponding mean ratio in the field stars by roughly 0.5 dex (Smith et al. 2000; Cunha et al. 2002; Pancino et al. 2002), this may also be the case in the globular cluster Ruprecht 106 (Villanova et al. 2013). Shetrone et al. (2003) measured Cu abundances in a total of 12 stars across 4 dwarf spheroidal galaxies, e.g., Sculptor, Fornax, Carina, and Leo I, and all but one of the stars were below [Fe/H] < −1.0. Their results indicate that the [Cu/Fe] ratio is constant ([Cu/Fe] ~ −0.7) for [Fe/H] < −1.0, while...

* Based on data obtained from ESO Science Archive and the Subaru telescope.
the metal-rich Fornax star has a Cu enhancement. McWilliam & Smecker-Hane (2005) derived Cu abundances for 14 red giants in the Sagittarius dwarf spheroidal galaxy (Sgr), and noted that compared to Milky Way stars, the [Cu/Fe] ratio of Sgr stars is deficiency by ~0.5 dex (also see Carretta et al. 2010; McWilliam et al. 2013). On the other hand, Sbordone et al. (2007) found that the [Cu/Fe] deficiencies increase with increasing [Fe/H], such that the [Cu/Fe] ratio of Sgr stars is near ~1 dex around the solar iron abundance. Johnson et al. (2006) derived the Cu abundances of 10 red giant stars in 4 old globular clusters in the Large Magellanic Cloud (LMC), and found that their behavior follows that of the stars in ω Cen with similar [Fe/H]. Pompéia et al. (2008) found that in the inner disk LMC stars, the copper distribution is, flat with a mean value of [Cu/Fe] = −0.68 dex, while around the higher metallicity range the LMC stars present a clear under-abundance with respect to the Galactic disk. Colucci1 et al. (2012) determined detailed abundances of 22 elements, including copper, for eight clusters in LMC, and they also noted the depleted [Cu/Fe] at high metallicity. Very recently, Sakari et al. (2017) investigated two stars in the LMC globular cluster NGC 1718 and ascertained that these two stars are strongly deficient in copper.

It was noted by Bonifacio et al. (2010) that the Cu I resonance lines are not reliable abundance indicators, and departures from LTE should be taken into account to properly describe these lines for both dwarfs and giants. Recently, Roederer et al. (2014) found a large difference of copper abundance (~0.56 dex) derived from Cu I resonance and Cu II lines (also see Roederer & Lawler 2012), and thus suggested that Cu I lines may not be formed in LTE. Clearly, more work is needed to better understand the formation of Cu I lines in cool stars.

The present work is based on a sample of metal-poor stars and aims to explore their [Cu/Fe] abundance ratios by applying full spectrum synthesis based on level populations calculated from the statistical equilibrium equations. In Section 2 we provide the observational techniques, while the atmospheric models, stellar parameters, and atomic data are described in Section 3. The copper atomic model and the NLTE effects are discussed in Section 4. The results and comparisons with other works are illustrated in Section 5. The discussion is given in Section 6, and the conclusions are presented in Section 7.

2. Observations

Our aim is to derive the copper abundances for a sample of metal-poor stars using high-resolution and high-signal-to-noise ratio spectra with the two Cu I near-UV resonance lines included. The spectra of 26 metal-poor stars were observed with the UVES échelle spectrograph mounted at the ESO VLT during two observation runs: 2000 April 8–12 and 2001 April 10–12 (programme IDS 65.L-0507 and 67.D-0439). The wavelength ranges of the spectra are from 3050 to 3850 Å, with a resolution power (R) of 48,000 for the blue arm, and from 4800 to 6800 Å with R ~ 55,000 for the red arm. We use also high-quality observed spectra from the ESO UVESPOP survey (Bagbulu et al. 2003) for Procyon, HD 84937 and HD 122563. Finally, for G 64-12 we use the spectrum from the High Dispersion Spectrograph at the Nasmyth focus of the Subaru 8.2 m telescope (Noguchi et al. 2002).

The spectra were reduced with the standard ESO MIDAS package including location of échelle orders, wavelength calibration, background subtraction, flat-field correction, and order extraction.

3. Method of Calculation

3.1. Model Atmospheres

In this analysis the line-blanketed 1D LTE MAFAGS opacity sampling model atmospheres are adopted (Grupp 2004; Grupp et al. 2009), and the convection according to Canuto & Mazzitelli (1992) is used. For stars with [Fe/H] < −0.6 the enhanced α-element (O, Mg, Si, and Ca) by 0.4 dex were used for individual models. As usual, the mixing length parameter l/Hp = 0.5 is adopted.

3.2. Stellar Parameters

We employed the stellar parameters determined by Tan et al. (2009) for most of our program stars, except G 20-24 and G 183-11; the surface gravities of these two stars have been revised using the parallaxes from Gaia DR1 (Gaia Collaboration et al. 2016). For HD 61421, HD 84937, and HD 122563 the parameters were taken from Mashonkina et al. (2011), while for G 64-12 they were taken from Shi et al. (2009). We also adopted the parameters from Mashonkina et al. (2017) for HD 122563. In these works the wings of the Balmer lines have been used to derive the effective temperatures, and the HIPPARCOS parallaxes are adopted to determine the surface gravities. The iron abundances have been determined with the Fe II lines, and the microturbulence velocities are estimated by requesting that the iron abundance derived from Fe II lines should not depend on equivalent widths. The uncertainties for the temperature, surface gravity, metal abundance and microturbulence velocity are generally considered to be ±80 K, 0.1 dex, 0.1 dex and 0.2 km s⁻¹, respectively.

3.3. Atomic Line Data

The relevant line data with their final solar fit (Shi et al. 2014) gf values are presented in Table 1. The collisional broadening through van der Waals interaction with hydrogen atoms are calculated according to Anstee & O’Marra (1991, 1995) tables, and the HFS was included in our analysis with the data taken from Biehl (1976). Following Asplund et al. (2009) the isotopic ratio of ⁶⁰Cu/⁶⁴Cu is adopted as 69%:31%.

4. NLTE Calculations

4.1. Atomic Model

Our copper model atom contains all the important Cu I levels (including 96 Cu I terms) and the Cu II ground state, and is
well-known metal-poor star with high-temperature among our sample, while HD 122563 is a typical cool metal-poor giant star. The departure coefficients for the investigated levels of Cu I and the Cu II ground state are presented in this figure, and it is clear that the number densities of the Cu I levels begin to underpopulate outside layers with log $\tau_{5000} \sim 0.5$ due to overionization for both stars. An obvious overpopulate of the level $5s^2\,^2S$ for HD 122563, which is due to over-recombination, can be seen in the range of $-0.5 > \log \tau_{5000} > -2.0$.

Note that the NLTE effects of Cu I lines are evident in our abundance determination, and as expected, there is an inclination that the effects tend to be large for more metal-poor stars, very similar phenomenon is discovered for sodium (Shi et al. 2004). Compared to their NLTE counterparts, the substantially lower LTE results can be found clearly, and the differences can be larger than 0.50 dex for extreme metal-poor stars. We display the copper abundance differences between LTE and NLTE calculations as functions of temperature, metal abundance, and surface gravity for our sample stars in Figure 2, respectively. The average NLTE effects are $+0.27$, $+0.09$, and $+0.07$ dex for the halo, thick-, and thin-disk stars.

Our results indicate that departures from the LTE of the copper level populations seem to be larger for more metal-poor stars, and there is a clear tendency in which the NLTE effects increase with decreasing metallicity, which can explain the large Cu abundance difference derived from Cu I and Cu II lines for stars of [Fe/H] $\sim -2.3$ e.g., the Cu abundances derived from Cu I resonance lines are about 0.56 dex lower than that from the Cu II lines found by Roederer et al. (2014).

5. Results

5.1. Stellar Copper Abundances

The copper abundances of our program stars are derived with the spectral synthesis method, and the synthetic spectra are convolved with Gauss broadening profiles in order to fit the observed spectral lines. Figures 3 and 4 show the fitting line profiles for HD 122563 and G 64-12, respectively. It is found that the abundance differences are small for the NLTE results with a line to line abundance scatter between 0.01 and 0.11 dex, while it is larger for the LTE result. In Table 2 we present the final LTE and NLTE copper abundance results.

As noted by Bihain et al. (2004) and Cayrel et al. (2004), the abundances derived from the spectra of metal-poor stars may be overestimated if the continuum scattering is included as an additional opacity source in the spectral synthesis code. The overestimation is especially high for lines with $\lambda < 4000$ Å, where continuum scattering becomes important relative to continuous absorption. Based on our spectrum synthesis modeling code SIU, which can treat continuum scattering properly, we evaluated the influence on the derived Cu abundances for the only giant, HD 122563. The determined Cu abundance lowers by about 0.3 dex compared to the abundance derived without the continuum scattering considered, while there is no impact on the derived Cu abundances for the dwarfs, e.g., HD 84937 and G 64-12. We found a much lower correlation of Cu abundance with wavelength when the continuum scattering is included, and a similar behavior was found by Cayrel et al. (2004) and Lai et al. (2008).
5.2. Comparison with other Work

Some groups have determined copper abundances for metal-poor stars based on both LTE and NLTE analyses. We compare our results with those from the previous works, and discuss the reasons for the differences.

Nissen & Schuster (2011). Nissen & Schuster (2011) adopted a LTE line formation for a sample of α-rich and
| Name       | $T_{\text{eff}}$ | log g | [Fe/H] | $\zeta$ | 3247 | 3273 | 5105 | 5218 | 5220 | 5700 | 5782 | [Cu/Fe]       |
|------------|-----------------|-------|--------|--------|------|------|------|------|------|------|------|--------------|---------------|
| CD −30° 18140 | 6195            | 4.15  | −1.87  | 1.5    | −0.87| −0.90| ...  | ...  | ...  | ...  | ...  | −0.89 ± 0.015 |
| CD −57° 1633  | 5915            | 4.23  | −0.91  | 1.2    | −1.92| −1.81| −0.81| −0.68| ...  | ...  | ...  | −0.70 ± 0.010 |
| G 13-009     | 6270            | 3.91  | −2.28  | 1.5    | −0.95| −0.90| ...  | ...  | ...  | ...  | ...  | −0.87 ± 0.050 |
| G 020-024    | 6190            | 3.90  | −1.92  | 1.5    | −0.99| −0.92| ...  | ...  | ...  | ...  | ...  | −0.68 ± 0.020 |
| G 64-12      | 6407            | 4.40  | −3.12  | 2.5    | −0.90| ...  | ...  | ...  | ...  | ...  | ...  | −0.96 ± 0.035 |
| G 183-011    | 6190            | 4.09  | −2.08  | 1.5    | −0.97| −0.88| ...  | ...  | ...  | ...  | ...  | −0.62 ± 0.050 |
| HD 61421     | 6510            | 3.96  | −0.03  | 1.8    | ...  | ...  | −0.14| −0.17| −0.15| ...  | −0.18 | −0.16 ± 0.015 |
| HD 76932     | 5890            | 4.12  | −0.89  | 1.2    | −0.22| −0.25| −0.26| −0.23| ...  | ...  | ...  | −0.24 ± 0.032 |
| HD 84937     | 6350            | 4.09  | −2.15  | 1.7    | −0.92| −0.94| ...  | ...  | ...  | ...  | ...  | −0.68 ± 0.005 |
| HD 97320     | 6030            | 4.22  | −1.20  | 1.3    | −0.19| −0.18| −0.29| −0.15| ...  | ...  | ...  | −0.97 ± 0.020 |
| HD 97916     | 6350            | 4.11  | −0.88  | 1.5    | −0.34| −0.36| −0.35| ...  | ...  | ...  | ...  | −0.45 ± 0.015 |
| HD 103723    | 6005            | 4.23  | −0.82  | 1.3    | −0.57| −0.43| −0.51| −0.51| ...  | ...  | ...  | −0.35 ± 0.007 |
| HD 106038    | 5990            | 4.43  | −1.30  | 1.2    | −0.47| −0.38| −0.40| −0.36| ...  | ...  | ...  | −0.41 ± 0.018 |
| HD 111980    | 5850            | 3.94  | −1.11  | 1.2    | −0.32| −0.28| −0.38| −0.40| ...  | ...  | ...  | −0.35 ± 0.045 |
| HD 113679    | 5740            | 3.94  | −0.70  | 1.2    | −0.06| −0.08| −0.06| −0.12| −0.03| ...  | ...  | −0.07 ± 0.024 |
| HD 121004    | 5720            | 4.40  | −0.73  | 1.1    | −0.12| −0.12| −0.12| −0.14| −0.02| ...  | ...  | −0.10 ± 0.034 |
| HD 122196    | 5975            | 3.85  | −1.74  | 1.5    | −1.13| −1.09| ...  | ...  | ...  | ...  | ...  | −0.04 ± 0.026 |
| HD 122563    | 4600            | 1.60  | −2.50  | 1.9    | −1.25| −1.18| −1.15| ...  | ...  | ...  | ...  | −1.11 ± 0.020 |
| HD 126681    | 5595            | 4.53  | −1.17  | 0.7    | −0.32| −0.24| −0.31| −0.29| ...  | ...  | ...  | −0.29 ± 0.025 |
| HD 132475    | 5705            | 3.79  | −1.50  | 1.4    | −0.51| −0.53| −0.57| ...  | ...  | ...  | ...  | −0.54 ± 0.022 |
| HD 140283    | 5725            | 3.68  | −2.41  | 1.5    | −1.12| −1.09| ...  | ...  | ...  | ...  | ...  | −0.35 ± 0.013 |
| HD 160617    | 5940            | 3.80  | −1.78  | 1.5    | −1.09| −1.00| ...  | ...  | ...  | ...  | ...  | −0.64 ± 0.005 |
| HD 166913    | 6050            | 4.13  | −1.55  | 1.3    | −0.72| −0.68| −0.60| ...  | ...  | ...  | ...  | −0.70 ± 0.020 |
| HD 175179    | 5780            | 4.18  | −0.74  | 1.0    | 0.03 | 0.02 | −0.01| 0.00  | 0.03 | −0.01| ...  | 0.01 ± 0.017 |
| HD 188510    | 5480            | 4.42  | −1.67  | 0.8    | −0.37| −0.41| −0.45| ...  | ...  | ...  | ...  | −0.41 ± 0.027 |
| HD 189558    | 5670            | 3.83  | −1.15  | 1.2    | −0.47| −0.43| −0.42| ...  | ...  | ...  | ...  | −0.44 ± 0.020 |
| HD 195633    | 6000            | 3.86  | −0.64  | 1.4    | −0.12| −0.18| −0.13| −0.13| ...  | ...  | ...  | −0.14 ± 0.020 |
| HD 205650    | 5815            | 4.52  | −1.13  | 1.0    | −0.13| −0.19| −0.17| −0.21| ...  | ...  | ...  | −0.18 ± 0.025 |
| HD 298986    | 6085            | 4.26  | −1.33  | 1.3    | −0.97| −1.00| ...  | ...  | ...  | ...  | ...  | −0.99 ± 0.015 |

Note. The LTE results of each star are shown in the first row, while the NLTE cases are indicated in the second row. The stellar parameter information is described in the text.
moderately metal-poor stars, and they used Cu I λ 5105.5, 5218.2, and 5782.1 Å lines for determining the copper abundances. Their results have been revised by Yan et al. (2016) with the NLTE effects included. Our results are in agreement with theirs: the average difference of the NLTE results is 0.029 ± 0.055 for the 11 stars in common. Compared with Nissen & Schuster (2011), our LTE result is 0.023 ± 0.040 lower than theirs, while it is 0.068 ± 0.042 higher for our NLTE results.

Mishenina et al. (2002, 2011). Their analysis investigated a large number of metal-poor stars, of which five objects are in common with ours, and an average Δ[Cu/Fe] of 0.132 ± 0.139 dex is obtained for both LTE results. It is found that the largest difference (0.47 dex) comes from the metal-poor giant HD 122563, and around a 0.3 dex difference is due to the continuum scattering included in our analysis. Excluding this object, the difference will be reduced to −0.048 dex.

Bihain et al. (2004). The authors determined the copper abundances for 38 FGK stars. Our LTE results are mostly in agreement with theirs. For the eight stars in common, the average difference is −0.12 ± 0.091. The largest difference (0.43 dex) is from the object HD 166913. Both studies have adopted similar stellar parameters, thus it is hard to explain such a large difference in [Cu/Fe] for this star.

Sneden et al. (1991). Using high-resolution, high-signal-to-noise ratio spectra, Sneden et al. (1991) measured the copper abundances of metal-poor stars. We have three stars in common with this work; one is the giant star HD 122563, the others are two dwarf stars, i.e., HD 76932 and HD 188510. For the giant our LTE copper abundance is 0.26 dex lower than theirs, and most of the difference can be explained by the continuum scattering considered in our analysis. The difference in [Cu/Fe] is 0.04 dex for HD 76932, while it is 0.29 for HD 188510. For the later object the large difference may be due to the different stellar parameters adopted in each work.

Reddy et al. (2006). Based on the high-resolution, high-signal-to-noise ratio spectra of 176 nearby thick-disk candidate stars, they derived the abundance ratios of [Cu/Fe]. The results of Reddy et al. (2006) are very much in agreement with ours; the average difference between our LTE results and theirs is 0.06 ± 0.04 for the two common stars.

Andrievsky et al. (2018). Recently, Andrievsky et al. (2018) investigated the NLTE effects of copper lines in very metal-poor stars. We have three objects in common with theirs, i.e., HD 84937, HD 122563, and HD 140283. For HD 84937 their NLTE result is 0.25 dex higher than ours, while it is 0.38 for HD 140283. For the giant star HD 122563, their [Cu/Fe] is 0.69 dex higher. We note that they have not considered the impact of the continuum scattering, which will result in a ~0.3 dex difference, while the rest may be due to their large NLTE effects. Similar large NLTE corrections have been found when the hydrogen collisions have not been included ($S_H = 0.0$), and/or the broadening and the exact wavelengths of the two strong Cu I resonance UV lines at 3247 and 3273 Å have not been considered properly.

Roederer & Barklem (2018). Very recently, Roederer & Barklem (2018) tested the copper abundances in late-type stars using ultraviolet Cu II lines, and showed that LTE underestimates the copper abundance determined from Cu I lines, namely the [Cu/H] ratios determined from Cu II lines are 0.36 ± 0.06 dex higher than those determined from Cu I lines for their metal-poor samples. For the four common stars the average difference between their [Cu/Fe] ratios and ours is −0.095 ± 0.025, while it is 0.005 ± 0.125 between their [Cu II/Fe] ratios and our NLTE results. The difference of [Cu I/Fe] for the two works is due to the lower log gf values for the two resonance lines (about 0.15 dex lower) adopted by us.

6. Discussion

Following Nissen & Schuster (2010) we classified our samples as halo (h), thick-disk or halo (tk/h), thick-disk (tk), and thin-disk (tn) stars, and presented in Table 3. In Figure 5 we plotted the Toomre diagram of our program stars. The behavior of [Cu/Fe] with the stellar metallicity [Fe/H] holds information about the chemical evolution of our Galaxy. Figures 6 and 7 display the trend of the [Cu/Fe] ratio (calculated in LTE and NLTE) with the metal abundance for all stars investigated in this paper, respectively. One important feature that we can find from Figure 7 is that the [Cu/Fe] ratios decrease with decreasing metallicity for [Fe/H] from −1.0 to −2.5, and they may increase for more metal-poor stars. While Andrievsky et al. (2018) suggested that the trend for the [Cu/Fe] ratio is constant, this is due to their very large NLTE effects (~1 dex) for very metal-poor stars. Another important feature that can be seen from this figure is that there is a group of stars with clear low [Cu/Fe] ratios compared with other samples with similar metallicity, and it is interesting to discuss the behavior of this group of stars. It was first noted by Nissen & Schuster (2011) that the low-α members show systematic low copper abundances (also see Yan et al. 2016), and in our sample there are four such type objects from their work, i.e., CD −57° 1633, HD 103723, HD 122196, and HD 298986. The [Cu/Fe] ratios of these four stars are obviously lower.

In order to investigate the behavior of α-elements for our sample stars, we derived the LTE and NLTE Mg, Si, and Ca abundances of those objects based on the atomic models of magnesium (Zhang et al. 2017), silicon (Zhang et al. 2016), and calcium (Mashonkina et al. 2017), and the detailed information on abundance and kinematics was listed in Table 3. This table shows that, besides the above four low copper abundance stars, the ratios of both [Mg/Fe] and [α/Fe] (the average of Mg, Si and Ca abundances) for the other four halo stars (i.e., CD −30° 18140, HD 122563, HD 140283, and HD 160617) are also lower compared to other normal stars with similar metallicity, which can also be clearly seen in the plots of [Mg/Fe] and [α/Fe] versus metallicity in Figure 8. For the two very metal-poor stars, HD 140283 and HD 122563, Siqueira-Mello et al. (2015) revealed that both are excellent samples of abundances dominated by the weak r-process.

Detailed modeling of the Galactic chemical evolution for copper has been attempted by many authors (e.g., Sneden et al. 1991; Matteucci et al. 1993; Timmes et al. 1995; Goswami & Prantzos 2000; Kobayashi et al. 2006; Romano & Matteucci 2007; Romano et al. 2010). Sneden et al. (1991) suggested that the copper contributes mainly from the weak s-process; however, Raiteri et al. (1992) argued that a large fraction is from long-lived type Ia supernovae (also see Matteucci et al. 1993; Mishenina et al. 2002). Based on Woosley & Weaver’s (1995) metallicity-dependent yields, Timmes et al. (1995) calculated the behavior of [Cu/Fe] as a function of metallicity, and their result predicted that this element may be synthesized in significant amounts by the nuclear burning stages in massive
### Table 3
The LTE and NLTE Magnesium, Silicon and Calcium Abundances of Our Sample Stars

| Name        | [Mg/Fe] LTE | [Mg/Fe] NLTE | [Si/Fe] LTE | [Si/Fe] NLTE | [Ca/Fe] LTE | [Ca/Fe] NLTE | U     | V     | W     | pop* |
|-------------|-------------|--------------|-------------|--------------|-------------|--------------|-------|-------|-------|------|
| HD 122563   | 0.17        |              | 0.26        |              | 0.27        |              | 0.38   | 71.5  | −195.5| −11.2 h |
| HD 97916    | 0.39        |              | 0.39        |              | 0.44        |              | 160.3 | −206.0| 397.0 h |
| G 13-009    | 0.13        |              | 0.19        |              | 0.30        |              | −93.1 | −264.4| 81.4 h |
| HD 020-024  | 0.39        |              | 0.34        |              | 0.31        |              | 160.3 | −206.0| 64.3 h |
| HD 64-12    | 0.13        |              | 0.28        |              | 0.31        |              | −50.0 | −317.0| 397.0 h |
| HD 183-011  | 0.26        |              | 0.36        |              | 0.27        |              | 0.40   | 53.5  | −379.0| −31.6 h |
| HD 61421    | 0.04        |              | 0.15        |              | 0.01        |              | 0.00   | −12.6 | 7.0   | 6.4 tn |
| HD 76932    | 0.33        |              | 0.32        |              | 0.25        |              | 0.26   | 0.3   | −41.0 | 77.0 tk |
| HD 84937    | 0.28        |              | 0.37        |              | 0.35        |              | 0.41   | 226.0 | −237.5| −8.4 h |
| HD 97320    | 0.39        |              | 0.36        |              | 0.17        |              | 0.23   | 80.0  | −11.0 | −30.0 tk |
| HD 97916    | 0.39        |              | 0.42        |              | 0.40        |              | 0.25   | 117.7 | 15.9  | 96.1 tk |
| HD 103723   | 0.13        |              | 0.19        |              | 0.14        |              | 0.16   | −72.0 | −193.0| 58.0 h |
| HD 106038   | 0.24        |              | 0.75        |              | 0.16        |              | 0.22   | 25.2  | −264.3| 26.2 h |
| HD 111980   | 0.35        |              | 0.47        |              | 0.31        |              | 0.34   | 239.0 | −174.0| 57.0 h |
| HD 113679   | 0.42        |              | 0.41        |              | 0.35        |              | 0.33   | −96.0 | −278.0| 3.0 h |
| HD 121004   | 0.36        |              | 0.40        |              | 0.40        |              | 0.17   | 70.0  | −242.0| 105.0 h |
| HD 122196   | 0.11        |              | 0.18        |              | 0.17        |              | 0.24   | −160.9| −139.4| 23.5 tk/h |
| HD 122563   | 0.17        |              | 0.25        |              | 0.24        |              | 0.17   | 139.0 | −233.0| 26.0 h |
| HD 126681   | 0.36        |              | 0.46        |              | 0.35        |              | 0.35   | −15.0 | −28.0 | −64.0 tk |
| HD 132475   | 0.34        |              | 0.55        |              | 0.25        |              | 0.32   | 44.0  | −371.0| 60.0 h |
| HD 140283   | 0.13        |              | 0.16        |              | 0.08        |              | 0.25   | 30.0  | 147.0 | −320.5 h |
| HD 160617   | 0.18        |              | 0.26        |              | 0.21        |              | 0.32   | 68.2  | −209.5| −85.7 h |
| HD 166913   | 0.30        |              | 0.40        |              | 0.39        |              | 0.35   | −44.3 | −44.5 | 67.6 tk/h |
| HD 175179   | 0.45        |              | 0.41        |              | 0.36        |              | 0.34   | 96.0  | −102.0| −19.0 tk |
| HD 188510   | 0.36        |              | 0.37        |              | 0.38        |              | 0.36   | 141.1 | −109.4| 71.6 tk/h |
| HD 189558   | 0.34        |              | 0.42        |              | 0.40        |              | 0.30   | 89.0  | −109.0| 48.0 tk |
| HD 195633   | 0.19        |              | 0.25        |              | 0.22        |              | 0.11   | 12.0  | −15.7 | −3.5 tn |
| HD 205650   | 0.26        |              | 0.36        |              | 0.23        |              | −114.0| −71.0 | 18.0 tk |
| HD 298986   | 0.06        |              | 0.21        |              | 0.20        |              | 0.19   | 250.1| −138.0| 163.3 h |

Note. 
* Following the Nissen & Schuster (2010) classifications as halo (h), thick-disk or halo (tk/h), thick-disk (tk), and thin-disk (tn) stars.

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**Figure 5.** Ternary diagram of our program stars. The different symbols correspond to different stellar populations: the thin-disk (equilateral triangle), thick-disk (filled circle), thick/halo (filled square), and halo (Eight pointed star).

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**Figure 6.** [Cu/Fe] ratios under the LTE condition as a function of [Fe/H] for selected stars. The symbols are the same as in Figure 5.

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stars, which was confirmed by Romano & Matteucci (2007) with a comprehensive study of copper evolution in different systems. In Figure 9 we plot the predicted [Cu/Fe] ratios as a function of [Fe/H] from Romano et al. (2010) with our NLTE results. In their model 1, the Woosley & Weaver (1995) case B yields for normal SNe II have been adopted and provide the best fit to the observed [Cu/Fe] versus [Fe/H] trend, even for the lowest metallicities, which means that copper is mainly produced by massive type II SNe. Models 4 and 5 of Romano et al. (2010) were computed adopting the Kobayashi et al. (2006) yields with $\xi_{\text{HN}} = 0$ and 1, respectively. Although
model 4 can reproduce the [Cu/Fe] ratio for metal-rich stars, it underestimates the copper abundance for the very metal-poor region. Both models 1 and 5 are indistinguishable from the observational data alone, though their model 1 can reproduce our results.

7. Conclusions

We have determined copper abundances for 29 metal-poor stars spanning the metallicity range $-3.2 < \text{[Fe/H]} < -0.7$. Using MAFAGS’s LTE model atmospheres the copper abundances were obtained with both the near-UV and optical lines. Our results are derived for both LTE and NLTE based on the line-fitting method. We draw the following conclusions:

1. The [Cu/Fe] ratios are under-abundant for metal-poor stars, and there is an indication that [Cu/Fe] decreases with decreasing metallicity within $-2.0 < \text{[Fe/H]} < -0.7$. Meanwhile, it may increase for very metal-poor stars with $\text{[Fe/H]} < -3.0$, which needs to be confirmed with more objects.

2. Our NLTE result confirms that the low-$\alpha$ sample stars also have the lower copper abundance found by Nissen & Schuster (2011).

3. The NLTE effects of Cu I lines are sensitive to the metallicity, and they increase with decreasing metallicity. The NLTE effects can reach $\sim 0.5$ dex for very metal-poor stars, which can explain the large difference in copper abundance derived from Cu II and Cu I resonance lines noted by Roederer et al. (2014) and Roederer & Barklem (2018). It must also be noted that the NLTE effects are different from line to line, and the weak lines are less sensitive to NLTE effects, while the strong resonance 3247 and 3273 Å lines show large NLTE effects.

4. Compared with model 1 of Romano et al. (2010) our results suggest that, similar to $\alpha$ elements, copper is mainly produced by massive type II SNe.

Our results indicate that it is important to perform NLTE abundance analyses for Cu I lines for very metal-poor stars.

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