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Cu and Zn in different stellar populations:

inferring their origin

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Abstract. We analyse recent high-resolution spectroscopic observations of Cu and Zn for stars of different stellar populations and metallicities, using the best available stellar nucleosynthesis expectations. The observations include unevolved stars of the Galactic halo, thick-disk and thin-disk, bulge-like stars and stars of Ω Cen, globular clusters and Dwarf Spheroidal systems. Most cosmic Cu and half the Zn are synthesised in massive stars during the hydrostatic He-burning and C-burning phases by the weak *sr-process*, which depends linearly on metallicity. A minor primary contribution for Cu derives from explosive nucleosynthesis in SNe II. A large primary contribution to Zn (as ^{64}Zn) is ascribable to the α-rich freezout in ν-winds or to SNe II with large explosion energies (hypernovae). AGB stars and type Ia supernovae do not contribute appreciably to either Cu or Zn.

1. Introduction

Earlier spectroscopic abundances of Cu and Zn in Galactic field stars of different metallicity were reanalysed by Sneden et al. (1991) and implemented with a new sample of mild-resolution spectroscopic data. The analysis demonstrated that these two close-by elements (with atomic charges Z = 29 and 30, respectively), situated in the tail of the iron peak group, show a quite different behaviour with metallicity. Zinc shows a flat trend: [Zn/Fe] $\approx$ 0; while copper increases with increasing metallicity, with a possible linear trend: [Cu/Fe] $\approx$ +0.38 [Fe/H] $\pm$ 0.15. The nucleosynthetic origin of the Cu and Zn isotopes derives from different sources, (i) the weak *s*-process occurring in massive stars in hydrostatic condition during the He burning and C burning phases, (ii) the main *s*-process occurring in low mass asymptotic giant branch (AGB) stars, (iii) explosive nucleosynthesis in short-lived massive stars ending as SNe II and (iv) explosive nucleosynthesis in long-lived type Ia supernovae.

The weak *s*-process in massive stars depends on metallicity. There neutrons are released mainly by the ^{22}Ne(α,n)^{25}Mg reaction, where the large abundance of ^{22}Ne during core He burning derives from the original CNO nuclei transmuted into ^{14}N in the H burning ashes followed by double α-capture on ^{14}N in the early phases of He burning. From previous studies (e.g. Prantzos et al. 1990; Raiteri et al. 1993), only about 20%

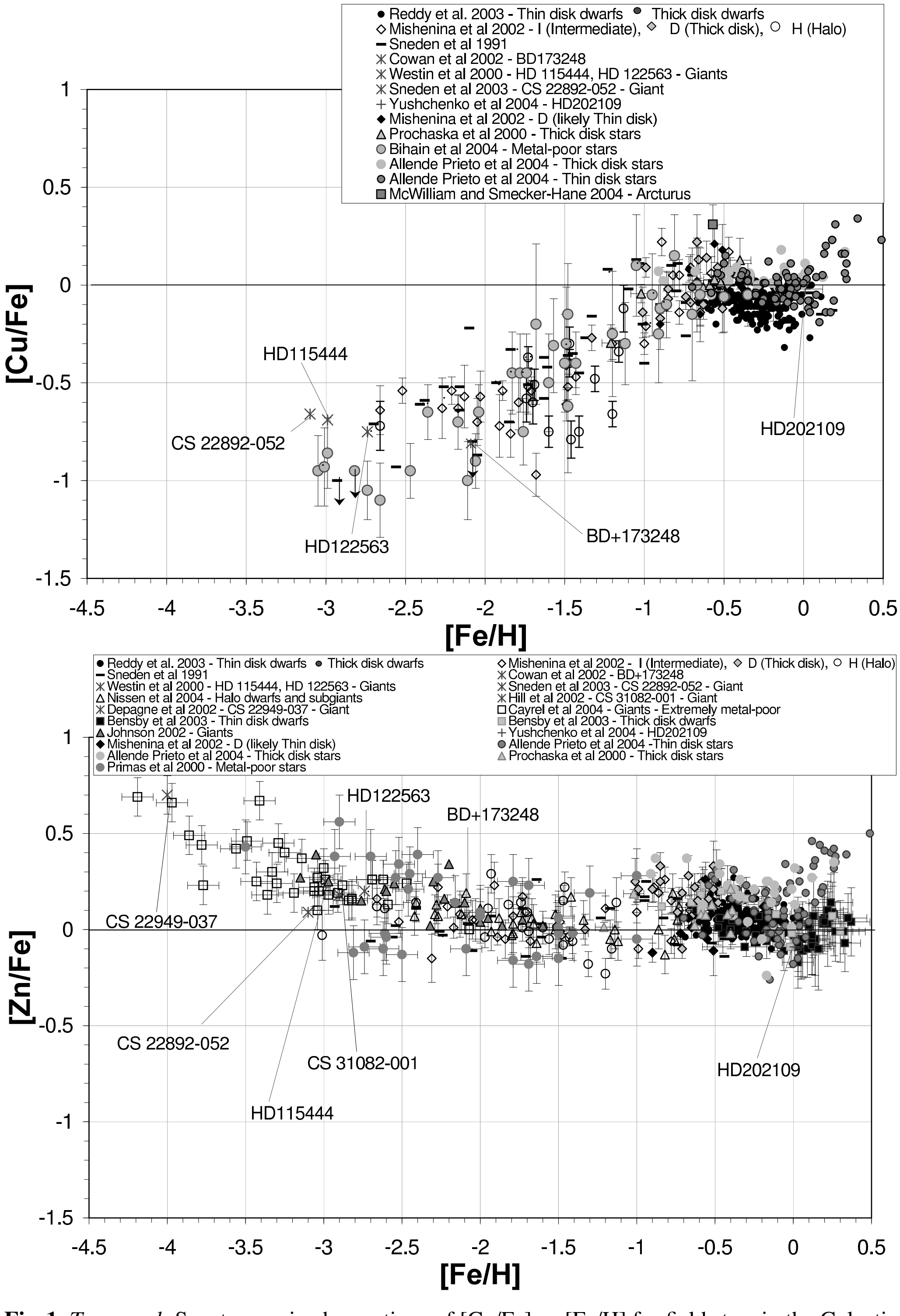

Fig. 1. *Top panel:* Spectroscopic observations of [Cu/Fe] vs [Fe/H] for field stars in the Galactic Halo, thick-disk, thin-disk. *Bottom panel:* The same for [Zn/Fe] vs [Fe/H].

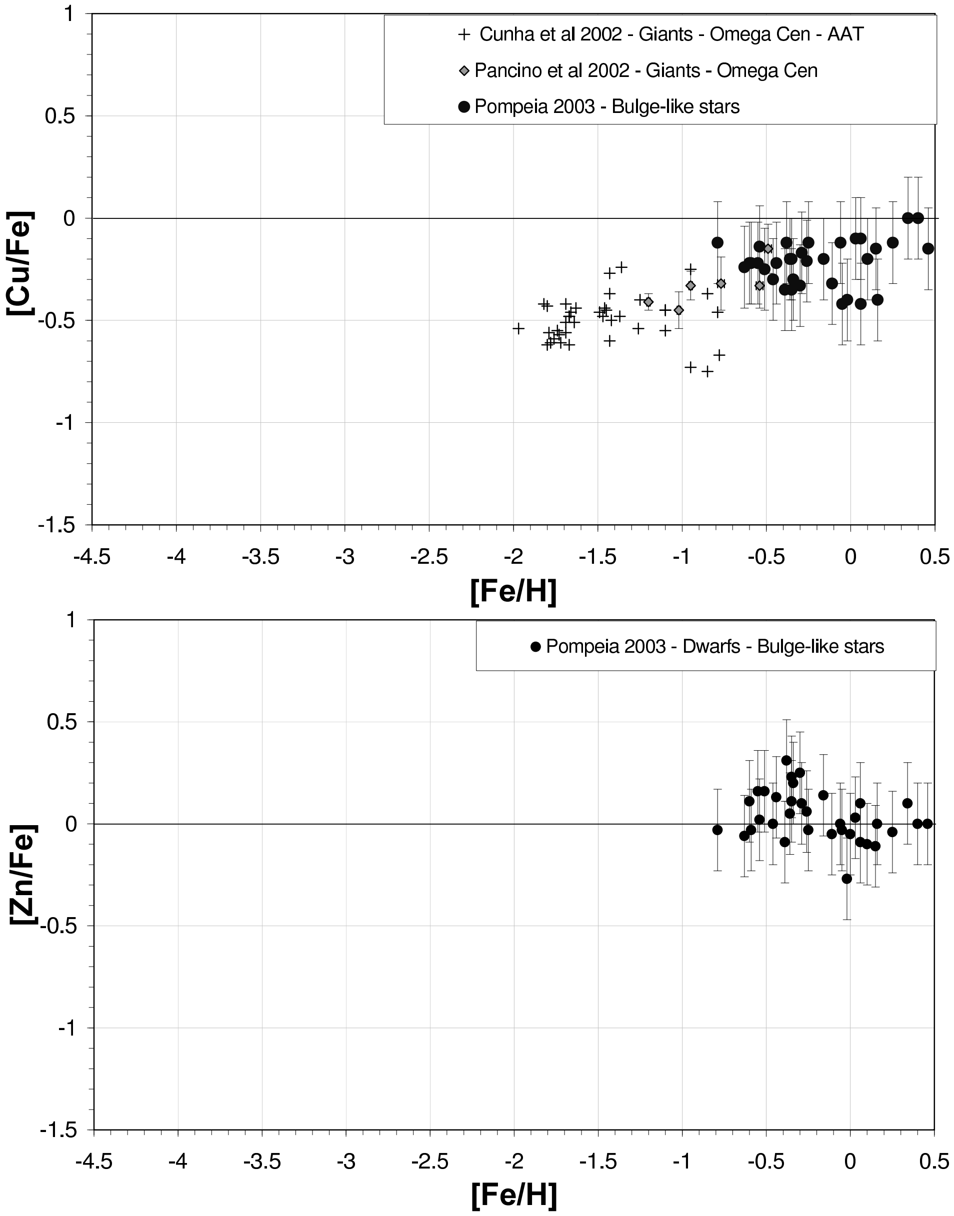

Fig. 2. *Top panel:* Spectroscopic observations of [Cu/Fe] vs [Fe/H] for Ω Cen and for Bulge-like stars. *Bottom panel:* Spectroscopic observations of [Zn/Fe] vs [Fe/H] for Bulge-like stars.

of solar Cu and 10% of solar Zn could be attributed to the weak *s*-process in massive stars. The main *s*-process operating in low-mass AGB stars does not contribute more than 5% to the production of Cu and Zn isotopes (Arlandini et al. 1999; Travaglio et al. 2004). Explosive nucleosynthesis in supernovae may provide a primary-like contribution to the various isotopes. However nucleosynthesis calculations for type Ia supernovae provide a negli-

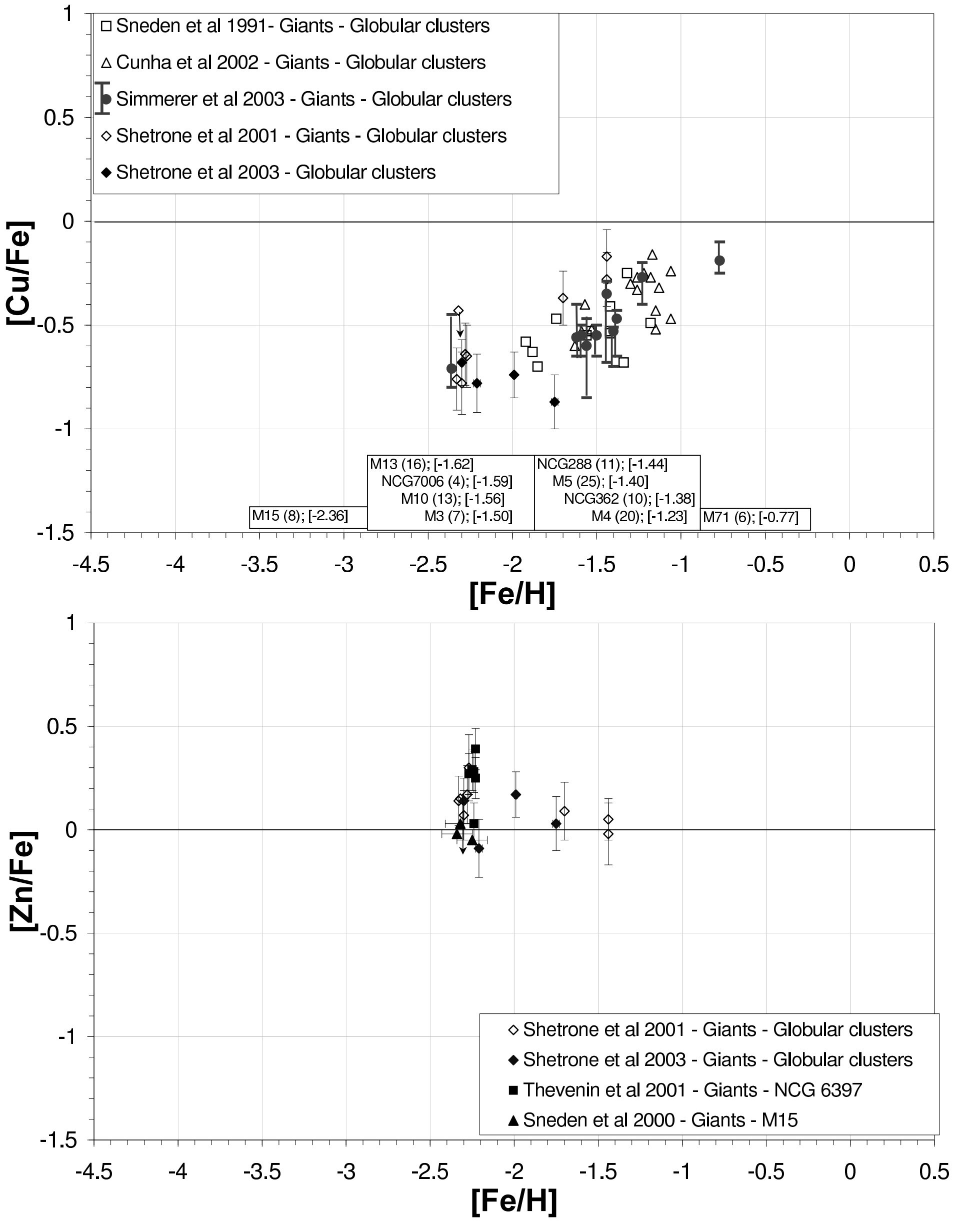

Fig. 3. *Top panel:* Spectroscopic observations of [Cu/Fe] vs [Fe/H] for giants stars in different globular clusters. The name of the cluster, the metallicity and the number of stars observed for each cluster are reported in the bottom inset of the panel. *Bottom panel:* The same for [Zn/Fe].

gible contribution to Cu and Zn (Thielemann, Nomoto and Yokoi 1986). As for massive stars, in the early nineties, full stellar evolutionary and nucleosynthesis calculations including Cu and Zn isotopes were not yet available although a consistent primary production of Zn, in the form of ^{64}Zn, in the α-rich freezout neutrino winds, was predicted by Woosley and

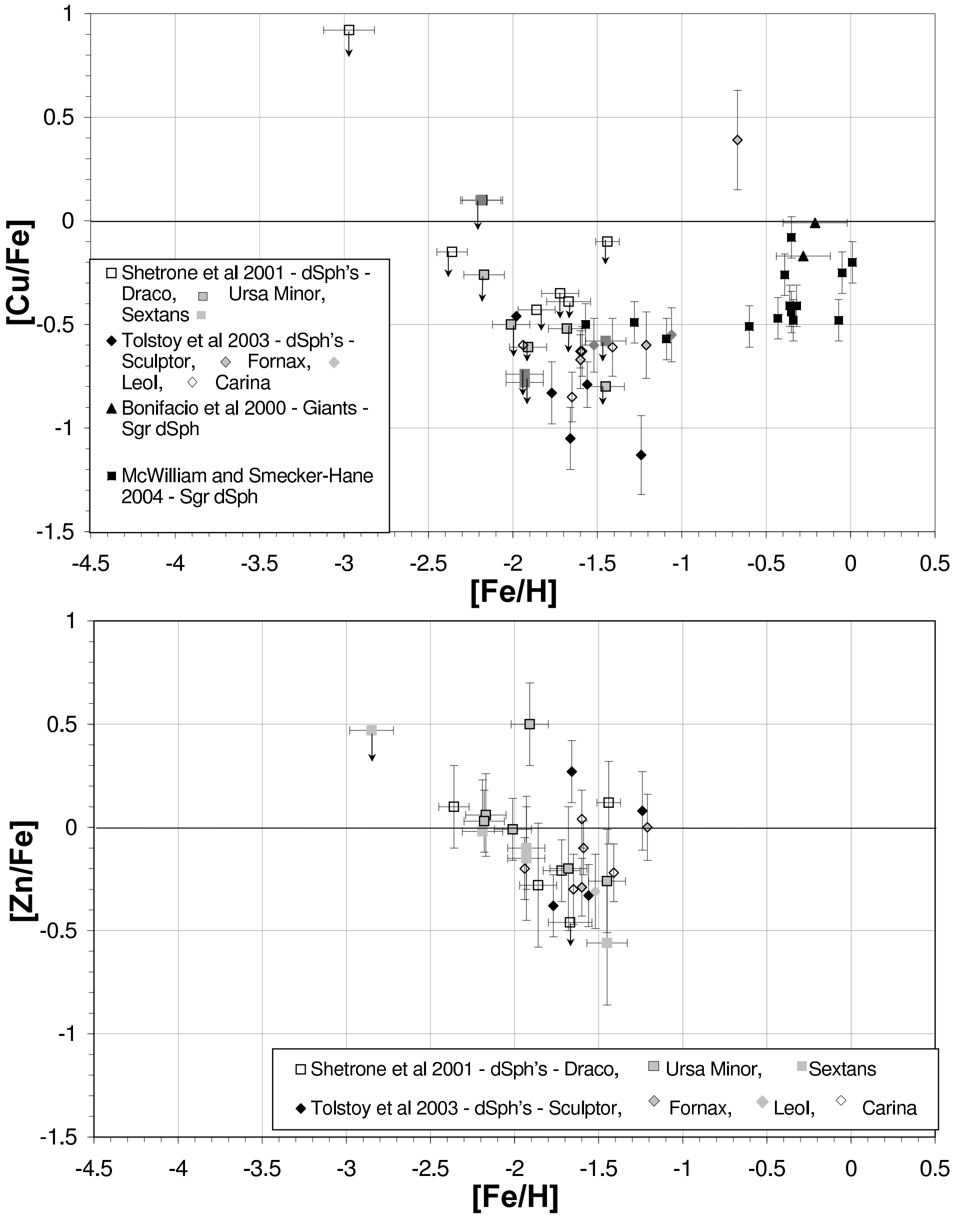

Fig. 4. *Top panel:* Spectroscopic observations of [Cu/Fe] vs [Fe/H] for giants stars of various dSph systems. *Bottom panel:* The same for [Zn/Fe].

Hoffman (1992). All spectroscopic observations and nucleosynthesis prescriptions available at the time were analysed by Matteucci et al. (1993) using a general galactic chemical evolution code. They concluded that to reproduce the observed trends a major contribution by type Ia supernovae had to be hypothesized for both elements.

In this work we analyse more recent high-resolution spectroscopic observations of Cu and Zn for stars of different stellar populations and metallicities, making use of theoretical yields of massive stars for different masses and metallicities by Woosley and Weaver (1995), subsequently upgraded by Woosley et al. (2002), with a full nucleosynthesis network extended up to Pb and Bi. Preliminary results were presented by Bisterzo et al. (2004).

2. Copper.

The available high-resolution spectroscopic data of [Cu/Fe] for field Galactic stars by Prochaska (2000), Mishenina et al. (2002), Reddy et al. (2003) are reported in Figure 1 (top panel). Also reported are data of the previous sample of stars at mild resolution by Sneden et al. (1991). Data for a few very metal-poor and very *r*-process enriched stars are labeled with the name of the star (HD 115444, Westin et al. 2000; BD +17 3248, Cowan et al. 2002; CS 22892-052, Sneden et al. 2003). We have further included data for the very metal-poor and non *r*-process rich star HD 122563 (Westin et al. 2000) and for the *s*-rich Ba star of close to solar metallicity HD 202109 (Yushchenko et al. 2004). The new high-resolution spectroscopic data can be represented for low metallicity stars up to [Fe/H] ≈ -1.8 by a flat distribution [Cu/Fe] $= -0.75 \pm 0.2$ followed by a linear increase with a slope close to 1 in the metallicity range $-1.5 <$ [Fe/H] < -1. Then, for stars belonging to the Galactic disk, there is a bending of the [Cu/Fe] distribution towards a slightly decreasing distribution. Actually, distinct and separated trends are seen between thick-disk stars (Mishenina et al. 2002) and thin-disk stars (Reddy et al. 2003). The above spectroscopic observations can be understood in the frame of a galactic chemical evolution model (GCE, Timmes et al. 1995), with SNe II yields for different masses and metallicities by Woosley and Weaver (1995). In the the O-rich zone the release of α particles during convective shell C burning and the higher temperature ensures the residual ^{22}Ne, left behind at core He exhaustion, is fully consumed. The neutron density reaches quite high values, up to a few 10^{12} cm^{-3}. In these conditions many branchings along the *s*-path are open and a much larger network than usually assumed in classical *s*-process calculations has to be introduced. We define this neutron capture process as the *weak sr-process*. According to the analysis by Bisterzo et al. (2004), the production factors of the two Cu isotopes, ^{63,65}Cu, in the O-rich outer regions of exploding massive stars, are very similar to each other. The high neutron density released during the hydrostatic convective shell C-burning phase, as well as the explosive nucleosynthesis occurring in the outer He shell, induced by the passage of the shock front, concur to make the final production of these two elements very similar. A small primary yield of ^{63,65}Cu, 5 to 10% of solar Cu, derives from explosive nucleosynthesis in the inner regions, from the radiogenic decay of ^{63,65}Zn. The bending of the [Cu/Fe] trend in the disk is the result of the progressive contribution of Fe to the interstellar medium by type Ia supernovae. AGB stars provide a marginal contribution to solar Cu (main *s*-component), of 5% (Travaglio et al. 2004). Summing up, solar copper is mostly the outcome of the weak *sr*-process in massive stars, with no need for an extra contribution by type Ia supernovae. In Figure 2 (top panel) spectroscopic data of [Cu/Fe] bulge-like stars (Pompeia 2003, corrected by adding +0.12 dex to all data) and in Ω Cen (Cunha et al. 2002, Pancino et al. (2002) are reported. The bulge-like stars show a constant trend: [Cu/Fe] $= -0.13 \pm 0.20$, in the whole range spanned by the sample stars, -0.8 $<$ [Fe/H] $< +0.5$, compatible with the Galactic disk behaviour. An intense star burst on short time scales, (see diskussion in Pompeia et al. 2003) may explain the results. As to Ω Cen, a flatter distribution than for unevolved Galactic stars of similar metallicity is apparent. In the range $-2.0 <$ [Fe/H] < -0.8 we find [Cu/Fe] $\approx -0.50 \pm 0.2$, followed by an increase for the most metal-rich stars in the sample at [Fe/H] ≈ -0.50 (Pancino et al. 2002). This behaviour can be understood by a multimodal star burst and by partial retention of type I supernova ejecta by the less intense gravitational potential well of the system. Figure 3 (top panel) shows the Cu spectroscopic data for stars belonging to different globular clusters (Sneden et al.

1991; Shetrone et al. 2001; Cunha et al. 2002; Simmerer et al. 2003; Shetrone et al. 2003). For globular clusters of low metallicity, up to [Fe/H] ≈ -1.8, the distribution is possibly flat, with [Cu/Fe] = -0.65 ± 0.15. For the globular clusters of higher metallicities a linear increase is evident, in agreement with field stars of similar metallicity. This trend may imply that globular clusters condensed from the Galactic interstellar medium progressively polluted by the previous Galactic stellar generations. Figure 4 (top panel) shows the Cu data for stars in different dSph systems. Data for stars belonging to the Draco, Ursa Minor and Sextans dSph systems are from Shetrone et al. (2001), data for Sculptor, Fornax, Leo I, Carina dSph systems are from Tolstoy et al. (2003) and data for the Sgr dSph System are from Bonifacio et al. (2000) and McWilliam and Smecker-Hane (2004). The data by Shetrone et al. (2001) are only upper limits. Despite the limited number of observations, there is no contradiction of the increasing trend of [Cu/Fe] shown by Galactic field stars, as inferred from stars in the Sgr dSph system (Bonifacio et al. 2000, 2004; McWilliam and Smecker-Hane 2004).

3. Zinc.

The [Zn/Fe] versus [Fe/H] trend in field stars of different populations is shown in Figure 1 (bottom panel). To infer the Zn nucleosynthetic origin we need to consider the composite contribution of the various isotopes. The most abundant isotope, ^{64}Zn (48.6% of solar Zn), receives little contribution from the weak *sr*-component; it derives from α-rich freezeout in neutrino winds (Woosley and Hoffman 1992) or from hypernovae, SNe II with large explosion energies (Umeda and Nomoto 2002). All other Zn isotopes belong to the weak *sr*-component, and increase linearly with metallicity. There is no departure from the Galactic trend for the very metal-poor and *r*-process-rich stars labeled in Figure 1, nor for Ba stars enriched in *s*-process elements, like HD 202109 (Yushchenko et al. 2004). AGB stars provide a marginal contribution to solar Zn (main *s*-component), by 3% (Travaglio et al. 2004). Preliminary results by Primas (2000) and the more recent ones by Cayrel et al. (2004) show a linear increase of [Zn/Fe] with decreasing metallicity for [Fe/H] < -3. This indicates a higher Zn efficiency in the more massive SNe II, in the α-rich freezout of ν-winds or in hypernovae. The Zn abundances of bulge-like stars (Pompeia 2003) are reported in Figure 2 (bottom panel). They overlap with spectroscopic observations of Galactic disk stars: the distribution of [Zn/Fe] vs. [Fe/H] is flat and nearly solar. In Figure 3 (top panel) we report the Zn spectroscopic abundance estimates of giant stars in globular clusters (Shetrone et al. 2001; 2003; Thevenin et al. 2001; Sneden et al. 2000). An overlap with field stars of similar metallicity is apparent. The relatively high [Zn/Fe] = 0.39 value of the star A2084 is probably caused by the abundance estimate obtained from a single spectral line. In Figure 4 (bottom panel) we report the Zn abundance estimated for stars of various dSph systems (Draco, Ursa Minor and Sextans dSph systems from Shetrone et al. 2001, Sculptor, Fornax, Leo I, Carina from Tolstoy et al. 2003). Here, a lower [Zn/Fe] value may be inferred as compared with Galactic halo stars of similar metallicity. One should consider that a larger uncertainty affects the abundance estimates of these distant dSph systems.

4. Conclusions

Most cosmic Cu derives from a secondary-like process in massive stars where an efficient weak *sr*-process is driven. A small primary contribution to Cu of about 5% of the solar Cu is produced in massive stars as radioactive decay of ^{63,65}Zn. This primary contribution becomes the dominant contribution at [Fe/H] < -2. AGB stars and SNe Ia contribute little to Cu (as well as to Zn). The observational trend [Cu/Fe] vs [Fe/H] is satisfactorily explained with the above prescriptions. Globular cluster data strictly follow the Cu trend shown by Galactic field stars. Instead, Ω Cen and the bulge-like stars show a more complex trend, possibly related to a different star formation history and partial retention of type I supernova ejecta. The dSph system Sgr, with an ample spread in metallicity, seems to behave similarly. As for zinc, 40 to 50% of the solar abundance is ascribable to the primary contribution to ^{64}Zn from α-rich freezout in ν-winds in type II SNe or in hypernovae, the remaining 50% (accounting for ^{66,67,68,70}Zn) is produced by the secondary weak *sr*-process operating during core He-burning and during the subsequent convective shell C-burning phase in massive stars. The [Zn/Fe] trend with [Fe/H] for bulge-like stars and globular clusters overlaps with spectroscopic observations of Galactic field stars of similar metallicity. For dSph systems more data on [Zn/Fe] are desirable.

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