Contrasting copper evolution in ω Centauri and the Milky Way

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ABSTRACT
Despite the many studies on stellar nucleosynthesis published so far, the scenario for the production of copper in stars remains elusive. In particular, it is still debated whether copper originates mostly in massive stars or in Type Ia supernovae. To answer this question, we compute self-consistent chemical evolution models taking into account the results of updated stellar nucleosynthesis. By contrasting copper evolution in ω Cen and the Milky Way, we end up with a picture where massive stars are the major factor responsible for the production of copper in ω Cen as well as the Galactic disc.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – Galaxy: evolution – globular clusters: individual: ω Centauri.

1 INTRODUCTION
Almost two decades ago, Sneden & Crocker (1988) and Sneden, Gratton & Crocker (1991) discussed the possible mechanisms for the synthesis of copper (hereafter Cu) in stars in the light of their high-resolution observations (showing a decline in [Cu/Fe] with decreasing [Fe/H] in Galactic stars), and favoured a secondary origin for Cu through the weak component of the s-process in massive stars.

The s-process has long been thought to contribute to the production of Cu in stars (see e.g. Burbidge et al. 1957). The main s-process, operating in low-mass asymptotic giant branch (AGB) stars, does not contribute more than 5 per cent to the synthesis of Cu isotopes (Raiteri et al. 1993; Travaglio et al. 2004) and will be neglected hereinafter. The weak s-process in massive stars depends on metallicity. This mechanism, in fact, requires neutron fluxes originating mainly from the reaction 22Ne (α, n) 25Mg, where the large abundance of 22Ne during core He burning derives from the original CNO nuclei transmuted into 14N in the H-burning ashes, followed by double α-capture on 14N. The residual 22Ne, left behind at core He exhaustion, is fully consumed in the O-rich zone during convective shell C burning. A small primary yield of Cu, 5 to 10 per cent of its solar abundance depending on the location of the mass cut, derives from explosive nucleosynthesis in the inner regions of core-collapse supernovae (Type II supernovae, SNe II).

In the early 1990s, only 25 per cent of solar Cu was attributed to the weak s-process in massive stars (Raiteri et al. 1993). It was advanced then (Matteucci et al. 1993; Mishenina et al. 2002) that most solar Cu originated in Type Ia supernovae (SNe Ia). Current SN Ia models, however, predict a negligible production of Cu during thermonuclear explosions (Iwamoto et al. 1999; Travaglio, Hillebrandt & Reinecke 2001; Hoffman, Woosley & Weaver 2001; Rauscher et al. 2002), a detailed description of Cu evolution in different Galactic structures is still missing from the literature.

In this Letter, we try to fill in this gap by analysing the evolution of Cu in the framework of detailed Galactic chemical evolution (GCE) models in which Cu originates mostly from (i) massive stars or (ii) SNe Ia. In particular, we contrast the evolution of Cu in the Milky Way with that in the anomalous GC ω Cen. We conclude that scenarios where Cu is produced primarily in SNe Ia are no longer supported by the observations. This imposes strong constraints on the astrophysical processes responsible for the synthesis of Cu in stars.

2 MODELS VERSUS OBSERVATIONS: IMPLICATIONS FOR STELLAR YIELDS AND CHEMICAL EVOLUTION TIME-SCALES
Nowadays, high-resolution spectroscopic data of [Cu/Fe] are available for large samples of field Galactic stars (see Fig. 1, left-hand panel). GCs generally follow the trends defined by halo field giants (Simmerer et al. 2003): a flat distribution, [Cu/Fe] = −0.75 ± 0.2, for low-metallicity stars up to [Fe/H] ≤ −1.8 dex, followed by a linear increase with a slope close to 1 in the metallicity range −1.5 < [Fe/H] < −1 (GC data are not plotted in Fig. 1). At
Figure 1. Left-hand panel: \([\text{Cu/Fe}]\) in Galactic disc and halo stars, as measured by Prochaska et al. (2000, big empty squares), Mishenina et al. (2002, stars), Reddy et al. (2003, small filled squares), Allende Prieto et al. (2004, small filled upside-down triangles), Bihain et al. (2004, big empty triangles) and Reddy, Lambert & Allende Prieto (2006, dots) in the solar neighbourhood. Also shown are \([\text{Cu/Fe}]\) values for the very metal-poor stars BD +17° 3248 (Cowan et al. 2002; big filled square), HD 115444, HD 122563 (Westin et al. 2000; big filled triangles) and the extremely metal-poor giant CS 22892−052 (Sneden et al. 2003; big star) and TP-AGB star CS 30322−023 (Masseron et al. 2006; pentagon). Right-hand panel: \([\text{Cu/Fe}]\) in the globular cluster \(\omega\) Cen. Data from Cunha et al. (2002) and Pancino et al. (2002) (filled circles) have been homogenized as discussed in Romano et al. (2007). Superimposed on the data are our model predictions for \(\omega\) Cen (right-hand panel, thin lines) and for the solar vicinity (left-hand panel, thick lines), in cases where Cu originates mostly from SN explosions (Models 1 and 2, Table 1, long- and short-dashed lines, respectively; both SN II and SN Ia explosions are considered). The effect of completely removing the (primary) explosive SN II contribution is also shown as a dotted line (only in a model for the solar vicinity; left-hand panel, Model 4, Table 1). See the text for details on the different model prescriptions.

\([\text{Fe/H}] > -0.8, [\text{Cu/Fe}]\) jumps above the solar value. Then, a ‘bending’ appears for disc stars with \(-0.8 < [\text{Fe/H}] < 0\) (Reddy et al. 2003), although there is a hint that \([\text{Cu/Fe}]\) might start increasing again at higher metallicities (Allende Prieto et al. 2004).

The Galactic GC \(\omega\) Cen stands as a notable exception. The \([\text{Cu/Fe}]\) ratios of its most metal-rich stars are definitely lower than the Galactic trend (Cunha et al. 2002; Pancino et al. 2002; see also Figs 1 and 2), which can be understood as a shift in the \([\text{Cu/Fe}]\) relation to

Figure 2. Same data as in Fig. 1. The \([\text{Cu/Fe}]\) versus \([\text{Fe/H}]\) relation in \(\omega\) Cen is now compared to that for solar neighbourhood stars. Model predictions for \(\omega\) Cen (thin solid line) and the solar vicinity (thick solid line) now refer to the evolutionary picture where most of the solar Cu comes from the weak s-process in massive stars (stellar nucleosynthesis prescriptions as in Model 3, Table 1). See text for details.
Table 1. Prescriptions for stellar Cu production adopted by different GCE models.

| Model | $M_{\text{Cu, weak}}^i$ | $M_{\text{Cu, SN II}}^i$ | $M_{\text{Cu, SNe Ia}}^i$ | Notes |
|-------|----------------|----------------|----------------|-------|
| 1     | Matteucci et al. (1993) | Matteucci et al. (1993) (their model M) | Matteucci et al. (1993) (their model M) | Long-dashed lines in Fig. 1 |
| 2     | Matteucci et al. (1993) | Matteucci et al. (1993) (their model M) | Iwamoto et al. (1999) (their model W7) | Short-dashed lines in Fig. 1 |
| 3     | Nomoto et al. (2007) | Nomoto et al. (2007) | Iwamoto et al. (1999) (their model W7) | Solid lines in Fig. 2 |
| 4     | Matteucci et al. (1993) | 0 | Matteucci et al. (1993) (their model M) | Dotted line in Fig. 1 |

Figure 3. Stellar yields of Cu (in units of solar mass) for solar-metallicity and zero-metallicity massive stars from Matteucci et al. (1993, squares) and Nomoto et al. (2007, dots) as functions of the initial mass of the stars. At solar metallicity (upper panel), the yields comprise a weak s-process component as well as an explosive one, while for $Z = 0$ (lower panel) only the explosive component is present.

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[see Rauscher et al. (2002) for a discussion on this subject]. It is also worth emphasizing how dramatically important the production of Cu from core-collapse SNe is in the very early evolution of the Galactic halo. The SN II contribution sets the level of the ‘plateau’ observed at [Fe/H] = −1.8. This can be clearly seen from Fig. 1 (left-hand panel), where the thick dotted line (Model 4, Table 1) shows the effect of removing any primary Cu production from explosive nucleosynthesis in massive stars from the Milky Way model. In this case, the ‘plateau’ at low [Fe/H] is no longer expected, at variance with the observations, and only the steep rise towards high [Cu/Fe] at high metallicities can be reproduced. Furthermore, notice that when adopting the yields of Nomoto et al. (2007) rather than those of Matteucci et al. (1993), a lower plateau level is obtained (Fig. 2), because of the lower amount of Cu in the ejecta of low-metallicity SNe II predicted by those authors (see Fig. 3, lower panel).

Now we can draw the following conclusions.

(i) After a short phase in which the primary contribution from explosive nucleosynthesis in core-collapse SNe dominates, the evolution of Cu in galaxies of different type is regulated mostly by the weak s-process occurring in massive stars.

(ii) Up-to-date, metallicity-dependent stellar yields of Cu by Nomoto et al. (2007) including both a primary contribution from explosive nucleosynthesis and a secondary contribution from the s-process in massive stars allow us to reproduce very well the observed behaviour of [Cu/Fe] versus [Fe/H] in the solar vicinity as well as in ω Cen.

(iii) When restricting our analysis to a single environment (the solar vicinity), a degeneracy is found in the solution, in the sense that the decline in [Cu/Fe] with decreasing [Fe/H] can be ascribed to either the reduced extent of the weak s-process in massive stars at low [Fe/H], or the delayed Cu production from SNe Ia. Only studying objects that have been chemically enriched along different evolutionary paths allows us to break the degeneracy.

Finally, in Fig. 4 we compare the abundances of Cu measured in a sample of bulge-like stars by Pompéia (2003) with our model predictions for the inner Galaxy (bulge-like stars are thought to originate near the Galactic bulge). A substantial contribution to the Galactic Cu production from SNe Ia (nucleosynthesis prescriptions as in Model 1, Table 1; long-dashed line) is clearly ruled out, while models with a minimum Cu production from SNe Ia can well fit the data (Models 2 and 3, short-dashed and solid lines, respectively). We conclude that the study of Cu abundances in different environments, from both an observational and a theoretical point of view, is of fundamental importance in order to understand the origin of Cu in the Universe.

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