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The evolution of C and O abundances in stellar populations

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Abstract. Carbon and oxygen abundances in F and G main-sequence stars ranging in metallicity from [Fe/H] $= -1.6$ to $+0.5$ are determined from a non-LTE analysis of C I and O I atomic lines in high-resolution spectra. Both C and O are good tracers of stellar populations; distinct trends of [C/Fe] and [O/Fe] as a function of [Fe/H] are found for high- and low-alpha halo stars and for thick- and thin-disk stars. These trends and that of [C/O] provide new information on the nucleosynthesis sites of carbon and the time-scale for the chemical enrichment of the various Galactic components.

Keywords. Stars: abundances, Galaxy: disk, Galaxy: halo, Galaxy: evolution

1. Introduction

Recent ΛCDM, hydrodynamical simulations of the formation of the Galaxy (e.g. Zolotov *et al.* 2010; Font *et al.* 2011; McCarthy *et al.* 2012) predict the existence of two populations of halo stars. The first one is formed *in situ* in merging and dissipating gas clumps, whereas the other one is *accreted* from satellite galaxies. For the upper end of the halo metallicity distribution, Zolotov *et al.* (2010) find that [α/Fe] in the accreted population decreases with increasing [Fe/H] relative to the near-constant [α/Fe] in the *in situ* population. This is due to a difference in star formation rate (SFR); the chemical enrichment proceeds at a slower rate in satellite galaxies, so that Type Ia SNe start contributing with iron at a lower metallicity.

Evidence for two halo populations† in the solar neighborhood with different [α/Fe] trends has been found by Nissen & Schuster (2010, hereafter NS10). The "high-alpha" stars have [α/Fe] $\simeq 0.3$, similar to thick-disk stars, and extend in metallicity up to [Fe/H] $\simeq -0.4$. The "low-alpha" stars show a declining [α/Fe]-trend from ~ 0.3 dex at [Fe/H] $\simeq -1.6$ to ~ 0.1 dex at [Fe/H] $\simeq -0.8$, which is the maximum [Fe/H] reached by this population. Furthermore, the Toomre diagram shows that the high-alpha stars tend to move on prograde orbits, whereas the low-alpha stars have higher space velocities with respect to the LSR and an excess of retrograde orbits. These data are consistent with a scenario where the high-alpha stars have been formed in dissipational mergers of gas clouds, and the low-alpha stars have been accreted from satellite galaxies.

The high- and low-alpha halo stars also separate in [Na/Fe], [Ni/Fe], [Cu/Fe], and [Zn/Fe], but not in [Mn/Fe] (Nissen & Schuster 2011). Furthermore, the high-alpha stars seem to be on average 2 - 3 Gyr older than the low-alpha stars (Schuster *et al.* 2012).

In this paper we report on carbon and oxygen abundances in the two halo populations and compare with abundances in stars having thin- and thick-disk kinematics.

† Selected as stars having a total space velocity $V_{\rm total} > 180\,{\rm km\,s^{-1}}$ relative to the local standard of rest (LSR).

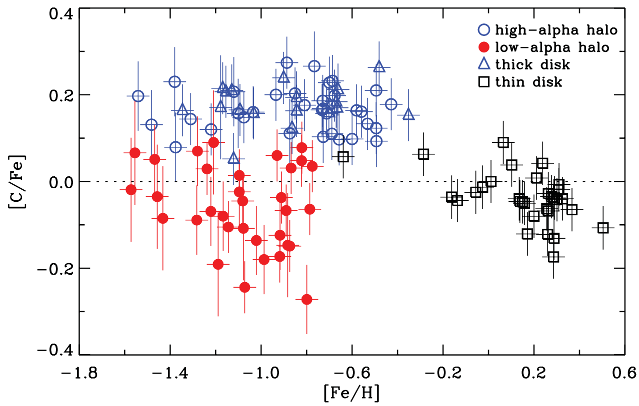

Figure 1. [C/Fe] versus [Fe/H] with the same classification in high- and low-alpha halo and thick-disk stars as in NS10 and with thin-disk stars from Nissen (2013) included.

2. Carbon abundances

The abundance of carbon was determined from equivalent widths (EWs) of the high-excitation C I lines at 5052.2 and 5380.3 Å as measured in high-resolution, high-S/N VLT/UVES and NOT/FIES spectra. For each star, a 1D model atmosphere was obtained from the MARCS grid (Gustafsson *et al.* 2008) by interpolating to the stellar values of $T_{\rm eff}$, $\log g$, [Fe/H], and [α/Fe]. The model was used to derive an LTE carbon abundance. Non-LTE corrections from Takeda & Honda (2005) were afterwards applied, but they are small, i.e. less than 0.02 dex.

The atmospheric parameters of the stars were determined spectroscopically by analysing Fe I and Fe II lines relative to the same lines in the spectra of two nearby thick-disk stars, HD 22879 and HD 76932, for which $T_{\rm eff}$ and $\log g$ are well known from colour indices and Hipparcos parallaxes. This enables us to determine very precise differential parameters and abundances for stars that belong to the same region of the HR-diagram as the standard stars. The absolute values may be more uncertain. Thus we have increased the $T_{\rm eff}$ scale by +100 K relative to the scale used in NS10 to take into account the new IRFM $T_{\rm eff}$− colour calibration by Casagrande *et al.* (2010). This has only a small effect on $\log g$, [Fe/H] (derived from Fe II lines), and [α/Fe] (derived from neutral lines), but it has a significant effect on C and O abundances derived from high-excitation atomic lines.

The derived [C/Fe] values are shown in Fig. 1. In addition to stars from NS10, we have included stars with thin-disk kinematics from Nissen (2013), who also used the $\lambda\lambda$5052, 5380 C I lines (measured in high-quality HARPS spectra) to derive C abundances. The error bars shown were estimated by adding, in quadrature, the errors arising from the EWs and those corresponding to the internal uncertainties of $T_{\rm eff}$ and $\log g$. At low metallicity and low [α/Fe], the C I lines are very weak, i.e. $EW \sim 2$ - 4 mÅ only, so the error of [C/Fe] due to the uncertainty of the EW measurements becomes large.

3. Oxygen abundances

Oxygen abundances were determined from equivalent widths of the λ7774 O I triplet lines. The NOT/FIES spectra do not cover this wavelength region and only a few of the UVES spectra have the O I triplet included. We have therefore adopted EW measurements from Ramírez *et al.* (2012), who derived oxygen abundances for a subset of stars from NS10 using high-resolution spectra obtained with the 2.7 m telescope at the McDonald observatory, Keck/HIRES, and the MIKE spectrograph at the Magellan Telescope.

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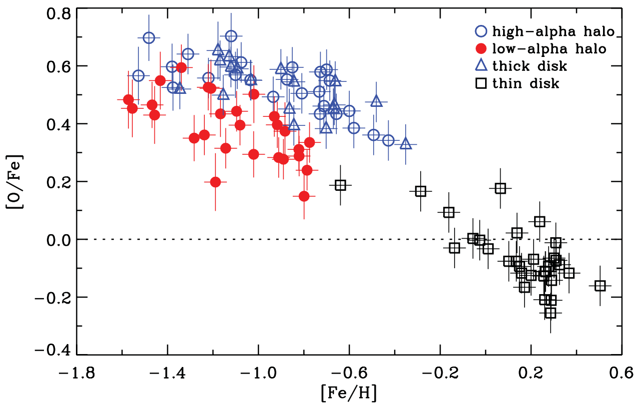

Figure 2. [O/Fe] versus [Fe/H].

For the thin-disk stars we used FEROS spectra obtained with the ESO 2.2 m telescope. Altogether, O I triplet data are available for 101 stars out of the 117 stars for which C I abundances were determined.

In deriving O abundances from the 7774 Å triplet, non-LTE corrections from Fabbian *et al.* (2009a) were applied as described by Nissen (2013). These corrections are important, even for differential determinations in the $T_{\rm eff}$-range of our sample of stars; the correction of [O/H] ranges from about +0.1 dex at 5300 K to −0.1 dex at 6300 K.

The derived [O/Fe] values are shown in Fig. 2. The distribution of stars looks much the same as that obtained by Ramírez *et al.* (2012, fig. 1, lower panel), except that they find a flatter distribution of [O/Fe] for the thick-disk and high-alpha halo stars. This is due to a somewhat stronger dependence of their non-LTE corrections on [Fe/H] than those of Fabbian *et al.* (2009a).

4. Discussion

As seen from Figs. 1 and 2, the low-alpha halo stars are separated in [C/Fe] and [O/Fe] from thick-disk and high-alpha halo stars. For the latter two populations, the dispersion in [C/Fe] and [O/Fe] at a given metallicity can be explained in terms of the errors of the derived abundances, whereas there seems to be an additional cosmic dispersion in [C/Fe] and [O/Fe] for the low-alpha halo population. In support of a real cosmic scatter, Fig. 3 shows [C/Fe] versus [Na/Fe] (from NS10) for the metallicity range $-1.2 <$ [Fe/H] < -0.7, where the largest dispersion is present. As seen, there is a striking correlation between [C/Fe] and [Na/Fe] except for two strongly deviating stars.

As suggested by the ΛCDM simulations of Zolotov *et al.* (2010), a possible explanation of the abundance differences seen in these figures is that the high-alpha stars were born in the innermost part of the Galaxy in a deep gravitational potential with such a high SFR that Type Ia SNe did not contribute significantly with iron until a metallicity of [Fe/H] $\simeq -0.4$. Later these stars were dispersed to the halo by merging satellite galaxies. The low-alpha stars, on the other hand, were formed in dwarf galaxies with a relatively shallow potential, and hence low SFR, so that Type Ia SNe started contributing with iron at a metallicity around or below [Fe/H] $= -1.6$. The reason for the scatter in [C/Fe], [O/Fe], [Na/Fe], and [α/Fe] at a given metallicity could then be that the various satellite galaxies from which the low-alpha stars were accreted had different masses and therefore different star formation rates.

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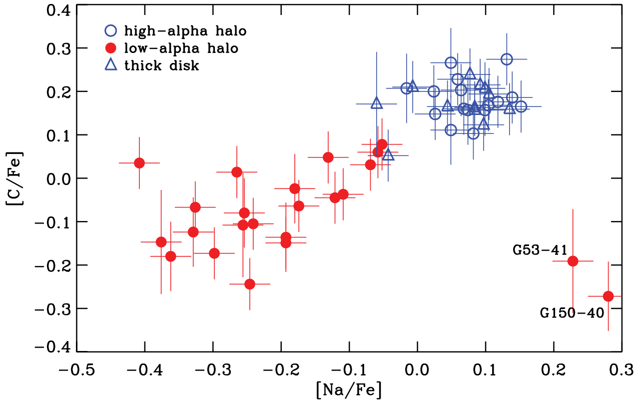

Figure 3. [C/Fe] versus [Na/Fe] for stars with $-1.2 < \mathrm{[Fe/H]} < -0.7$.

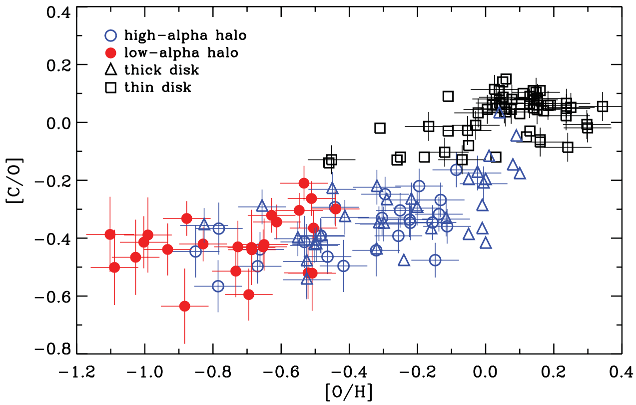

Figure 4. [C/O] versus [O/H]. Thin- and thick-disk stars from Bensby & Feltzing (2006) are included without error bars.

The two deviating low-alpha stars in Fig. 3, G 53-41 and G 150-40, require a special explanation. They have high [Na/Fe] but low [C/Fe] and also very low [O/Fe]. Hence, they share the so-called Na-O anti-correlation in second generation stars in globular clusters, which are thought to be made of gas polluted by first-generation AGB stars in which the Ne-Na cycle has occurred. This suggests that some of the halo stars originate from disrupted globular clusters, as also noted by Ramírez *et al.* (2012).

Figures 1 and 2 also give a hint for a difference in [C/Fe] and [O/Fe] between thin- and thick-disk stars in the overlapping metallicity range $-0.7 < \mathrm{[Fe/H]} < -0.2$ although we have only two thin-disk stars in this range. A systematic difference is well established in the case of [O/Fe] (e.g. Bensby & Feltzing 2006, fig. 11b) and have also been found for the alpha-capture elements, Mg, Si, Ca, and Ti (e.g. Adibekyan 2012, fig. 8), but it was not seen in the case of [C/Fe] by Bensby & Feltzing (2006, fig. 11a), Clearly, we need more thin-disk stars in the overlapping metallicity range to verify the possible difference in [C/Fe] between the thin- and thick-disk populations.

Fig. 4 shows [C/O] versus [O/H] for the four populations studied in this paper with thin- and thick-disk stars from Bensby & Feltzing (2006) included. Their C and O abundances are derived from the weak forbidden λ8727 [C I] and λ6300 [O I] lines but agree very well with our abundances derived from high-excitation C I and O I lines.

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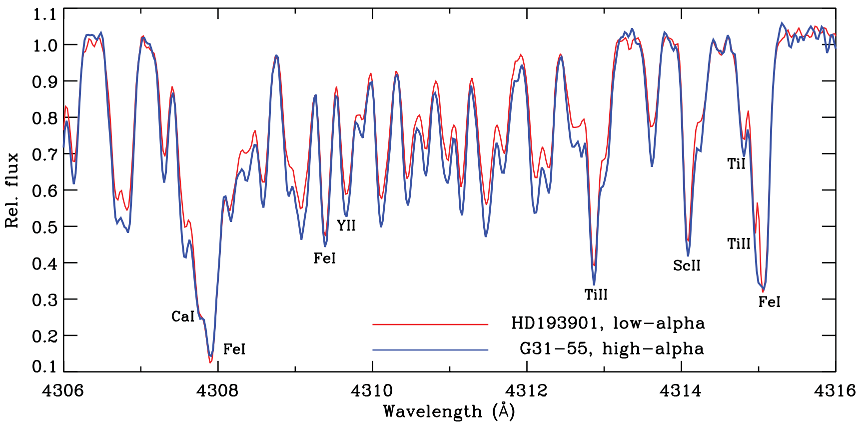

Figure 5. Part of the CH-band in a high- and a low-alpha star with similar atmospheric parameters. All unmarked lines are due to CH.

As seen from Fig. 4, there is no systematic shift in [C/O] between high- and low-alpha halo stars. This is perhaps surprising, because the time-scale for the chemical enrichment of the low-alpha population is long enough to allow Type Ia SNe to contribute with iron (our explanation for the low α/Fe ratios), and one could therefore have expected that low- and intermediate-mass AGB stars had enough time to contribute with carbon and raise [C/O] in the low-alpha stars to higher values than in high-alpha stars. The explanation may be that intermediate-mass (4–8 M_{Sun}) AGB stars contribute very little to ^{12}C (Kobayashi *et al.* 2011), and that the evolution time-scale of low-mass (1 - 3 M_{Sun}) AGB stars (which do have a high ^{12}C yield according to Kobayashi *et al.*) is longer than the chemical enrichment time-scale of the low-alpha population. We conclude that carbon in both high- and low-alpha halo stars was made primarily in high-mass stars ($> 10\,M_{\mathrm{Sun}}$), but with a metallicity-dependent yield to account for the slight increase of [C/O] with increasing [O/H].

As also seen from Fig. 4, thick-disk stars have on average the same [C/O] as high-alpha halo stars, but thin-disk stars have systematically higher [C/O] in the overlapping metallicity range $-0.5 <$ [O/H] $< +0.1$. This offset in [C/O] between thin- and thick-disk stars was already detected by Bensby & Feltzing (2006, fig. 12), but is even more clearly seen in our Fig. 4. Probably, the higher [C/O] ratios in the Galactic thin disk are due to low-mass AGB stars, i.e. the chemical enrichment time-scale of the thin disk is long enough to allow low-mass stars to contribute.

As a final remark, we note that the $\lambda\lambda 5052, 5380$ C I lines used to derive C abundances in this paper are very weak in metal-poor stars. Thus, very high S/N, high-resolution spectra are required to derive precise C abundances. The somewhat stronger C I lines in the 9000 - 9500 Å region may be used instead (Fabbian *et al.* 2009b) but they are blended by telluric lines. As an interesting alternative one may use the CH band. Fig. 5 shows part of this band in NOT/FIES spectra of a high-alpha star, G 31-55 (T_{eff}, $\log g$, [Fe/H], [α/Fe]) = (5738 K, 4.33, -1.10, 0.29) and a low-alpha star HD 193901 (5756 K, 4.39, -1.09, 0.16). As seen, the three Fe I lines have similar strengths in the two stars, whereas all CH lines are significantly weaker in the low-alpha star. Hence, it may be possible to use the CH band in large forthcoming surveys such as HERMES/GALAH and ESO/4MOST for high precision differential studies of carbon abundances in stellar populations.

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Discussion

Birgitta Nordström: Your conclusion that carbon in halo stars and thick-disk stars was made in high-mass stars - does that also apply to the most metal-poor stars, [Fe/H] < -3?

Poul Erik Nissen: At very low metallicities, [C/O] increases with decreasing [Fe/H] (see Fabbian *et al.* 2009b). This may be due to a high carbon production in zero metallicity (Pop. III) stars.

Chiaki Kobayashi: The nucleosynthesis yields of $[\alpha/\mathrm{Fe}]$ and [C/Fe] do not depend much on the progenitor metallicity (0.1 dex for $[\alpha/\mathrm{Fe}]$). Your observational results are consistent with low-mass SNe II (13 - 20 $M_{\rm Sun}$), which have lower $[\alpha/\mathrm{Fe}]$ [C/Fe] (and also lower [Cu,Zn/Fe] as you showed in your 2011 paper) than massive SNeII.

Poul Erik Nissen: I agree that this is an interesting alternative to our proposal that the low α/Fe ratios in the low-alpha population are caused by Type Ia SNe starting to contribute with iron at a low metallicity, [Fe/H] < -1.5.