EARLY GALACTIC EVOLUTION OF CARBON, NITROGEN AND OXYGEN

G. ISRAELIAN, R. J. GARCIA LOPEZ AND R. REBOLO
1. Instituto de Astrofísica de Canarias
E-38200 La Laguna, Tenerife, Spain
2. Departamento de Astrofísica, Universidad de La Laguna
E-38071 La Laguna, Tenerife, Spain

Abstract.
We present results on carbon, nitrogen, and oxygen abundances for a sample of unevolved metal-poor stars with metallicities in the range $-0.3 < [\text{Fe/H}] < -3$. Oxygen abundances derived from different indicators are compared showing consistently that in the range $0.3 > [\text{Fe/H}] > -3.0$, the $[\text{O/Fe}]$ ratio increases from approximately 0 to 1. We find a good agreement between abundances based on the forbidden line, the OH and IR triplet lines when gravities based on $\text{Hipparcos}$ parallaxes are considered for the sample stars. Gravities derived from LTE ionization balance in metal-poor stars with $[\text{Fe/H}] < -1$ are likely too low, and could be responsible for an underestimation of the oxygen abundances derived using the $[\text{O i}]$ line. $[\text{C/Fe}]$ and $[\text{N/Fe}]$ ratios appear to be constant, independently of metallicity, in the same range. However, they show larger scatter than oxygen at a given metallicity, which could reflect the larger variety of stellar production sites for these other elements.

1. Introduction
CNO abundances in metal-poor stars can tell us about nucleosynthesis and mixing processes in stars, and about several fundamental parameters of Galactic chemical evolution (initial mass function, star formation rate, etc.). Unevolved stars play a key role in this respect because the original surface abundances of CNO in evolved giant stars can be altered by internal nucleosynthesis and mixing between the core and outer layers. Mixing is expected to occur when a star becomes a red giant following the exhaustion
of hydrogen in the core (so called “the first dredge-up”). Important results have been obtained from the analysis of CNO molecular bands and atomic lines in metal-poor stars (see Wheeler et al. 1989 and references therein). However, such analyses have been either based on high resolution spectra of small samples (less than 10) or low/intermediate resolution spectra of large samples (∼ 100) of stars. We are studying CNO abundances from high resolution spectra of more than 40 halo dwarfs. In this paper we report preliminary results based on 24 halo dwarfs discussed by Israeliian, García López and Rebolo (1998) and briefly discuss the current understanding of the galactic evolution of these elements.

2. Observations and Analysis

The observations were carried out in different runs using the UES ($R = \lambda/\Delta\lambda \sim 50000$) of the 4.2-m WHT at the Observatorio del Roque de los Muchachos (La Palma), and the UCLES ($R \sim 60000$) of the 3.9-m AAT. The final signal-to-noise ratio (S/N) varies for the different echelle orders, being in the range 30–100 for most of the stars.

A grid of LTE, plane-parallel, constant flux, and blanketed model atmospheres provided by Kurucz (1992), computed with ATLAS9 without overshooting, and interpolated for given values of $T_{\text{eff}}$, log $g$, and [Fe/H] was used. Details on the analysis of the OH lines have been presented in Israeliian et al. (1998). We have derived carbon abundances from the CH band at 3145 Å using the list of Kurucz (1992). Nitrogen abundances have been derived from the NH band at 3360 Å using the atomic and molecular data from Norris (1999, private communication). Synthetic spectra were computed with the WITA3 code by Pavlenko (1991). Effective temperatures ($T_{\text{eff}}$) for our stars were estimated using the Alonso et al. (1996) calibrations versus $V-K$ and $b-y$ colors, which were derived applying the infrared flux method, and cover a wide range of spectral types and metal content. Metallicities were adopted from literature values obtained from high resolution spectra. Gravities were derived using the accurate parallaxes measured by Hipparcos (ESA 1997). These gravity values are larger by 0.28 dex in average than the values adopted in our previous analysis of OH lines (Israeliian et al. 1998). This implies a mean small reduction of 0.09 dex in the oxygen abundances inferred in the latter paper, which does not affect the previously observed linear relationship between [O/Fe] and [Fe/H].
3. Abundances of CNO in metal poor dwarfs

3.1. OXYGEN

Type II SNe are expected to produce significant amounts of oxygen. Iron is produced in both, Type II and in Type I SNe. Since the latter come from longer lifetime progenitors, it has been argued for a long time that oxygen must be overabundant in very old stars. Evidence for high [O/Fe] ratios in many metal-poor stars has been reported during the last decades. A so-called “traditional” view is based on the study of [O i] lines at 6300 and 6363 Å in giants (though the second line at 6363 Å is not visible in very metal-poor stars and the analysis is based only on one line) by Barbuy (1988), Gratton & Ortolani (1992), Sneden et al. (1991) and Kraft et al. (1992). These authors found that [O/Fe] = 0.3 – 0.4 dex at [Fe/H] < −1 and is constant with decreasing metallicity. In contrast, oxygen abundances derived in dwarfs using the O i IR triplet at 7774 Å by Abia & Rebolo (1989), Tomkin et al. (1992), King & Boesgaard (1995), and Cavallo, Pilachowski, & Rebolo (1997) point towards increasing [O/Fe] values with decreasing [Fe/H], reaching a ratio ~ 1 for stars with [Fe/H] ~ −3, suggesting a higher production of oxygen during the early Galaxy.

New oxygen abundances derived from near-UV OH lines (which form in the same layers of the atmosphere as [O i]) for 24 metal-poor stars have been presented by Israelian, García López, & Rebolo (1998). It is shown how the [O/Fe] ratio of metal-poor stars increases from 0.6 to 1 between [Fe/H] = −1.5 and −3 with a slope of −0.31 ± 0.11 (Fig 1). Contrary to the previously accepted picture (Bessell, Sutherland, & Ruan 1991, who used older model atmospheres with a coarser treatment of the opacities in the UV), these new oxygen abundances derived from low-excitation OH lines, agreed well with those derived from high-excitation lines of the O i IR triplet at 7774 Å. The comparison with oxygen abundances derived using O i data from Tomkin et al. (1992) showed a mean difference of 0.00±0.11 dex for the stars in common. On the other hand, Boesgaard et al. (1999) have obtained high quality Keck spectra of many metal-poor stars in the near UV, and recently concluded their analysis of a different set of OH lines. They find a very good agreement with the results obtained by Israelian et al. (1998), and basically the same dependence of [O/Fe] versus metallicity. The mean difference in oxygen abundance for ten stars in common is 0.00 ± 0.06 dex when the differences in stellar parameters are taken into account. In Fig. 1, upper panel, we plot these oxygen abundances based on OH lines as a function of metallicity.

Balachandran & Bell (1998) have pointed out that the continuous opacity of the Sun is not fully accounted for in the spectral syntheses performed in the near UV region. Although this is still a matter of debate, it would
Figure 1. [O/Fe] vs. [Fe/H] for unevolved stars. Abundances from OH lines were derived by Israelian et al. (1998; filled circles) and Boesgaard et al. (1999; open squares, corrected to the scale of stellar parameters adopted by Israelian et al.). Abundances from the IR triplet were derived in NLTE by Mishenina et al. (2000; filled circles), Cavallo et al. (1997; filled squares, corrected for NLTE effects by Mishenina et al.), and in LTE by Boesgaard et al. (1999; open circles). Finally, abundances from the [O I] line come from Spiesman & Wallerstein (1991; open diamonds), Spite & Spite (1991; open squares), Israeli et al. (1998; filled circles), Mishenina et al. (2000; filled squares), and Fulbright & Kraft (1999; open circles). Filled triangles indicate the change in abundances associated with the change in gravity according to the Hipparcos parallaxes for the two stars studied by Fulbright & Kraft. The abundances derived by Edvardsson et al. (1993; crosses) are shown in the three plots to indicate the trend in metal-rich stars.
have a minor effect on the recent OH results since most of the stars in the samples of Israeliian et al. and Boesgaard et al. are hotter than the Sun (and very metal-poor), and the corrections to oxygen abundances for individual stars due to this effect would be lower than 0.15 dex. This would not affect significantly the [O/Fe] vs. [Fe/H] trend.

Recently, Mishenina et al. (2000) performed a non-LTE analysis of the O i IR triplet to re-derive oxygen abundances for a sample of 38 metal-poor stars from the literature. They confirmed earlier results (Abia & Rebolo 1989; Tomkin et al. 1992; Kiselman 1993) indicating that the mean value of the non-LTE correction in unevolved metal-poor stars is typically 0.1 dex and never exceeds 0.2 dex. Mishenina et al. found the same linear trend as Israeliian et al. (1998) and Boesgaard et al. (1999) from the OH lines, and confirmed that oxygen abundances do not show any trend with \( T_{\text{eff}} \) or \( \log g \) (Boesgaard et al. 1999). Furthermore, Asplund et al. (1999) showed that the O i IR triplet is not affected by 3D effects, convection and small-scale inhomogeneities in the stellar atmosphere. In addition, oxygen abundances derived form this triplet are not significantly affected by chromospheric activity either, and we can conclude that the O i IR triplet provides reliable oxygen abundances in metal-poor dwarfs. This conclusion should also apply to the oxygen abundances derived from the UV OH lines given the good agreement shown between both indicators. In Fig. 1, mid-panel, we plot oxygen abundances based on the oxygen triplet. The larger scatter observed, as compared with the measurements based on OH lines, can be associated with the different scales of stellar parameters (\( T_{\text{eff}} \), gravities, and metallicities) adopted by the authors of each set of stars, and to the fact that some measurements have not been corrected for NLTE effects.

Israeliian et al. (1998) found four dwarfs (HD 22879, HD 76932, HD 103095 and HD 134169) in their sample for which oxygen abundances had been previously derived using [O i]. They synthesized the forbidden oxygen line for these stars adopting the same set of stellar parameters than for the OH analysis, the \( gf \) value given by Lambert (1978), and the equivalent widths provided in the literature for the \( \lambda \) 6300 Å line. The estimated abundances were in reasonable agreement with those derived from OH but still slightly lower. The abundances found in that work using Hipparcos gravities when analyzing both indicators are in better agreement, which strongly suggests that a reliable gravity scale may indeed be key to explain the discrepancies on oxygen abundances from forbidden and permitted lines in unevolved metal-poor stars.

In the lower panel of Fig.1 we compile oxygen measurements for un-evolved stars based on the [O i] \( \lambda \) 6300 Å line. The presence of a linear trend of [O/Fe] versus metallicity strongly depends on the only two measurements available at [Fe/H] \( \leq -2 \). These two measurements have been
recently reported by Fulbright & Kraft (1999) for the stars BD +37 1458 and BD +23 3130, which were also considered by Israeli et al. (1998) and Boesgaard et al. (1999; only BD +37 1458 in this case). There is an apparent discrepancy between the results obtained from the forbidden and the OH lines. However, we argue here that this discrepancy cannot be sustained when a critical analysis of the uncertainties involved in the determination from the forbidden line is performed. The analysis carried out by Fulbright & Kraft is based on gravities derived from LTE iron ionization balance of these subgiants where it is well known that NLTE effects are strong. In a recent paper, Allende Prieto et al. (1999) have shown that gravities derived using this technique in metal-poor stars do not agree with the gravities inferred from accurate Hipparcos parallaxes, which casts a shadow upon oxygen abundance analyses of very metal-poor stars based on gravities derived from the ionization balance. They find that gravities are systematically underestimated when derived from ionization balances and that upward corrections of 0.5 dex or even higher can be required at metallicities similar to those of our stars. We remark here that any underestimation of gravities will also strongly underestimate the abundances inferred from the forbidden line. For the two stars under discussion our Hipparcos based gravities are 0.45 and 1.05 dex (for BD +37 1458 and BD +23 3130, respectively) higher than derived by Fulbright & Kraft, and would imply the corrections in the oxygen abundances indicated in Fig. 1 (the details of the analysis are out of the scope of these proceedings and will be presented in a forthcoming paper). Our conclusion is that the uncertainties in the gravities of these subgiants allow the abundances inferred from the forbidden line to be consistent with those estimated from the OH lines or the triplet. Actually, consistency with the other oxygen indicators is achieved for the high gravities inferred from Hipparcos, and this could be taken as an indication that the high gravities are indeed the correct ones.

Chemical evolution models of the early Galaxy where stellar lifetimes are taken into account and assuming that Type Ia SN appear at a Galactic age of 30 million years can also explain the evolution of oxygen delineated in Fig. 1. (Chiappini et al. 1999.). The evolution of oxygen proposed in this paper also helps to understand the evolution of $^6$Li versus [Fe/H] and the $^6$Li/Be ratio at low metallicities in the framework of standard Galactic Cosmic Ray Nucleosynthesis (Fields & Olive 1999). In addition, Ramaty et al. (1999) have proposed that a delay between the effective deposition times into the ISM of Fe and O (only a fraction of which condensed in oxide grains) can explain a linear trend of [O/Fe].
3.2. CARBON

Until very recently, it has been commonly accepted that intermediate mass stars ($M_\odot < M < 10M_\odot$) are the main source of Galactic C (Wheeler et al. 1989). It has been shown (Laird 1985, Carbon et al. 1987, Tomkin et al. 1992) that $[\text{C/Fe}]$ is approximately zero independently of $[\text{Fe/H}]$. Note that all these studies were based on the 4300 Å feature of CH. Tomkin et al. (1992) have demonstrated that C\textsc{i} at $\sim 9100$ Å provides an average $[\text{C/Fe}]=+0.3\pm0.2$, whereas the CH band provides $[\text{C/Fe}]=-0.1\pm0.2$. Recently, Gustafsson et al. (1999) performed an abundance analysis of carbon in a sample of 80 unevolved disk stars. They found that $[\text{C/Fe}]$ increases with decreasing $[\text{Fe/H}]$ with a slope of $-0.17\pm0.03$. This result was explained by carbon enrichment from superwinds of metal-rich massive stars. Our preliminary analysis for more metal-poor stars confirms earlier results that $[\text{C/Fe}]$~0 in a wide range of $[\text{Fe/H}]$ (Fig. 2). Studies of very low metallicity halo stars ($[\text{Fe/H}]<-3$) have revealed a significant number of stars with very high overabundance of carbon, up to 1-2 dex (Beers et al. 1992). Given these new results, it appears necessary to review our knowledge about carbon production sites in the Galaxy.
3.3. NITROGEN

The isotope $^{14}\text{N}$ is synthesized from $^{12}\text{C}$ and $^{16}\text{O}$ through the CNO cycles in the H-burning layer. Observations of the NH band at 3360 Å have allowed to delineate the Galactic evolution of N down to $[\text{Fe/H}]\sim -2.8$. Tomkin & Lambert (1984) used high resolution spectra of 8 disk and 6 halo stars ($-0.3 < [\text{Fe/H}] < -2.3$) and found $[\text{N/Fe}] \approx -0.25$. Laird (1985) and Carbon et al. (1987) obtained $[\text{N/Fe}] = -0.67 \pm 0.14$ (intermediate resolution spectra of 116 stars) and $[\text{N/Fe}] = -0.11 \pm 0.06$ (low resolution spectra of 76 stars), respectively. However, we should stress that this band is blended with Ti and Sc lines and it is preferable to use high resolution spectra in order to avoid any systematics due to the overabundance of Ti ($\alpha$-element) and Sc in metal-poor stars. Our preliminary analysis confirms previous results that $[\text{N/Fe}]$ is constant in a wide range of $[\text{Fe/H}]$. It would be extremely interesting to check how $[\text{N/O}]$ behaves in ultra metal-poor stars with $[\text{Fe/H}] < -3$. The trend of $[\text{N/Fe}]$ at very low metallicities is not yet investigated but the existence of N rich halo subdwarfs has been already demonstrated. It is very important to check the $[\text{N/O}]$ trend at $[\text{Fe/H}] < -3$ as this may help to understand the possible sites for a production of nitrogen as primary element. Recently, Maeder & Meynet (2000) have shown that the average rotation of massive stars can possibly be faster at lower metallicities. They have also found a primary N production in rapidly rotating stars in the mass range 10-15 $M_\odot$. To our knowledge these are the only models showing a primary nitrogen production in normal stars (see also Maeder, A., this conference).

4. Concluding remarks

We have derived carbon, nitrogen and oxygen abundances for a sample of metal-poor unevolved stars. $[\text{C/Fe}]$ and $[\text{N/Fe}]$ ratios appear to be constant, independently of metallicity, in the range $0.3 > [\text{Fe/H}] > -3.0$, while the $[\text{O/Fe}]$ ratio increases from approximately 0 to 1, with consistent oxygen abundances derived from different indicators. Carbon and nitrogen abundances show larger scatter than oxygen at a given metallicity, which could reflect the larger variety of stellar production sites for these elements. Work is in progress to derive CNO abundances for a larger sample of unevolved metal-poor stars using other features in the optical and IR spectral regions, which should allow a fully reliable estimate of the Galactic evolution of these elements. Consistent abundances from different spectral features of C, N and O will be used in order to delineate $[\text{N/O}]$, $[\text{C/O}]$ and $[(\text{C+N+O})/\text{Fe}]$ behaviour as a function of $[\text{O/H}]$ and $[\text{Fe/H}]$. 
**Figure 3.** Nitrogen abundances in halo dwarfs. Typical error bar is 0.2 dex.

**References**

1. Abia, C., & Rebolo, R. 1989, *ApJ*, **347**, 186
2. Allende Prieto, C., García López, R. J., Lambert, D. L., & Gustafsson, B. 1999, *ApJ*, **527**, 879
3. Alonso, A., Arribas, S., & Martínez-Roger, C. 1996, *A&A*, **313**, 873
4. Asplund, M., Nordlund, Å, Trampedach, R., & Stein, R. 1999, *A&A*, **346**, L17
5. Balachandran, S., & Bell, R. 1998, *Nature*, **392**, 791
6. Barbuy, B. 1988, *A&A*, **191**, 121
7. Beers, T., Preston, G. & Shectman, S. 1992, *Astron. J*, **103**, 1987
8. Bessell, M. S., Sutherland, R. S., & Ruan, K. 1991, *ApJ*, **383**, L71
9. Boesgaard, A.M., King, J.R., Deliyannis, C. P., & Vogt, S.S. 1999, *Astron. J*, **117**, 492
10. Carbon, D., Barbuy, B., Kraft, R., Friel, E., & Suntzeff, N. 1987, *PASP*, **99**, 335
11. Cavallaro, R., Pilachowski, C., & Rebolo, R. 1997, *PASP*, **109**, 226
12. Chiappini, C., Matteucci, F., Beers, T.C., & Nomoto, K. 1999, *ApJ*, **515**, 226
13. Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, *A&A*, **275**, 101
14. ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
15. Fields, B.D., & Olive, K.A. 1999, *ApJ*, **516**, 797
16. Fulbright, J., & Kraft, R. 1999, *Astron. J*, **118**, 527
17. Gratton, R., & Ortolani, S. 1999, *A&A*, **169**, 201
18. Gustafsson, B., Karlsson, T., Olsson, E., Edvardsson, B. & Ryde, N. 1999, *A&A*, **342**, 426
19. Israeliian, G., García López, R. J., & Rebolo, R. 1998, *ApJ*, **507**, 805
20. King, J.R. & Boesgaard, A.M. 1995, Astron. J, 109, 383
21. Kiselman, D. 1993, A&A, 275, 269
22. Kraft, R., Sneden, C., Langer, G., & Prosser, C. 1992, Astron. J, 104, 645
23. Kurucz, R. 1992, CD ROMs, Atlas9 Stellar Atmospheres Programs, SAO, Cambridge
24. Laird, J. 1985, ApJ, 289, 556
25. Maeder, A. & Meynet, G. 2000, Ann. Rev. Astron.& Astrophys., in press
26. Mishenina, T., Korotin, S., Klochkova, V., & Panchuk, V. 2000, A&A, in press
27. Pavlenko, Ya. V. 1991, Soviet Ast., 35, 212
28. Ramaty, R., Vangioni-Flam, E., Casse, M., & Olive, K. 1999, PASP, 111, 651
29. Sneden, C., Kraft, R., Prosser, C., & Langer, G. 1991, Astron. J, 102, 2001
30. Spiesman, W. & Wallerstein, G. 1991, Astron. J, 102, 1790
31. Tomkin, J., Lemke, M., Lambert, D. L., & Sneden, C. 1992, Astron. J, 104, 1568
32. Tomkin, J., & Lambert, D. 1984, ApJ, 279, 220
33. Wheeler, J., Sneden, C., & Lambert, D. 1989, Ann. Rev. Astron.& Astrophys., 27, 279