CNO at the surface of low and intermediate MS stars\textsuperscript{1}

Poul E. Nissen

Department of Physics and Astronomy, University of Aarhus, Denmark

Abstract.

Recent studies of spectral lines of the CNO elements in the Sun and unevolved disk and halo stars show that most published abundance data may be affected by systematic errors due to inadequate 1D modelling of stellar atmospheres. This raises doubts about previously derived trends of CNO abundances as a function of $\text{[Fe/H]}$. In this review we concentrate on abundance ratios derived from weak spectral features with similar dependences on temperature and pressure, which ratios are then relatively insensitive to 3D model atmosphere effects and to $T_{\text{eff}}$ and surface gravity. The recent controversy about the trend of $[\text{O/Fe}]$ vs. $[\text{Fe/H}]$ is discussed, new results for C/O ratios as determined from forbidden lines and high excitation neutral lines are presented, and N/C ratios derived from NH and CH lines are commented on.

1. Introduction

In this review I will discuss CNO abundances of main-sequence (MS) stars with masses between 0.5 and 2 solar masses. Such stars have convective envelopes, which means that any pollution of the stellar atmosphere caused by accretion of interstellar gas will be diluted by mixing in the envelope. The convective envelope is, on the other hand, not deep enough to bring up products from nuclear reactions to the surface of the star, except in the case of Li and Be, which elements may be destroyed by proton reactions at the bottom of the convective zone in the less massive stars. Hence, it seems rather safe to assume, that CNO at the surface of low and intermediate MS stars can be used as a tracer of CNO abundances in the interstellar gas and dust out of which the stars were formed. By deriving abundances of MS stars with different ages and belonging to different populations we may then obtain important information about the nucleosynthesis and Galactic evolution of the CNO elements.

The assumption of undisturbed chemical composition in the atmospheres of cooler MS stars should, however, be carefully checked. As shown by Lebreton et al. (1999), a comparison of CM diagrams based on Hipparcos parallaxes of nearby, unevolved stars with stellar model computations, suggests a mild depletion of heavier elements due to microscopic diffusion at the bottom of the

\textsuperscript{1}Partly based on observations collected at the European Southern Observatory, Chile (ESO No. 67.D-0106)
convective envelope. According to the computations of Morel & Baglin (1999), the effect is of the order of 0.10 dex for metal-poor stars with ages of 10 Gyr. It is likely, however, that the corresponding effect on abundance ratios such as C/O and N/C is considerably smaller and may be neglected in comparison with other possible systematic errors arising from analysis of spectral lines.

In the following, we will first take a look at the recent controversy about the trend of [O/Fe] vs. [Fe/H]. Then follows some new results on the [C/O] - [O/H] relation compared to previous results and a discussion of the [N/C] - [Fe/H] relation stressing the need for new high resolution studies of nitrogen abundances in cooler MS stars. In particular, I will emphasize the large granulation effects on the temperature and pressure structure of metal-poor stellar atmospheres, which have to be taken into account when deriving abundances from spectral lines or molecular bands.

2. Oxygen

According to standard nucleosynthesis models, oxygen is exclusively made by supernovae of Type II, whereas iron is also produced by Type Ia SN when they start to occur after a time delay of 0.5 - 1 Gyr. Hence, the O/Fe ratio can be used as a chemical clock to date the star formation process. If [O/Fe] \( \simeq +0.4 \), the major star formation episodes must have occurred within a time interval of \( \lesssim 0.5 \) Gyr; if [O/Fe] \( \simeq 0.0 \) the time interval of star formation has been \( \gtrsim 1 \) Gyr.

Par example, standard models of the chemical evolution of the Galaxy predicts a near constant [O/Fe] \( \simeq +0.4 \) for metallicities below [Fe/H] \( \simeq -1.0 \), perhaps with an increase of [O/Fe] below [Fe/H] = -2.0 due to a higher O/Fe yield ratio in the most massive supernovae (Chiappini et al. 1999).

Extensive studies of the forbidden oxygen lines in K giants have resulted in a near-constant [O/Fe] \( \simeq +0.4 \) for halo stars with \(-2.5 < [\text{Fe/H}] < -1.0 \) (e.g. Barbuy 1988, Kraft et al. 1992). More recently, Sneden & Primas (2001) have confirmed this; [O/Fe] is not higher that +0.5 dex at [Fe/H] = -3.0. Israelian et al. (1998, 2001) and Boesgaard et al. (1999), on the other hand, find a linear rise of [O/Fe] with decreasing [Fe/H] when oxygen abundances are derived from the near-UV OH lines in spectra of MS stars using 1D model atmospheres. At [Fe/H] = -3.0 [O/Fe] reaches values of 1.0 to 1.2 dex. The view has been expressed that the [O i]-based results for the giants are in error on two accounts: (i) oxygen is reduced in the atmospheres of giants because the convective envelope has mixed oxygen-poor material to the surface from the ON-cycled interior, and (ii) the [O i] lines are partially filled in by chromospheric emission. These explanations seem, however, unlikely: (i) the strong nitrogen enhancement resulting from the ON cycle has not been seen, and (ii) no asymmetries of the [O i] lines have been detected.

In order to advance on this oxygen problem, Nissen et al. (2002) have recently studied the faint [O i] 6300 Å line in metal-poor MS star spectra obtained with the VLT/UVES instrument. The spectra have resolutions of 60000 to 120000 and a very high S/N of 300 - 600. Equivalent widths as small as 0.5 mÅ could be measured with an error of \( \pm 0.2 \) mÅ. Iron abundances were derived from a number of weak Fe II lines. The data were first analyzed with 1D MARCS models (Asplund et al. 1997) using \( T_{\text{eff}} \) values determined from \( b - y \) and \( V - K \),
and gravities derived via Hipparcos parallaxes and/or the Strömgren \( c_1 \) index. An important point is that the derived [O/Fe] ratio is only weakly dependent on possible errors in \( T_{\text{eff}} \) and practically independent of errors in the gravity.

In the analysis of the [O i] 6300 Å line, Nissen et al. included the effect of a blending Ni i line, which recently was shown by Allende Prieto, Lambert & Asplund (2001) to decrease the derived solar oxygen abundance by 0.13 dex. As this Ni i line has nearly disappeared when \([\text{Fe/H}] < -1.5\), the net effect is to increase the derived [O/Fe] by about 0.1 dex for metal-poor halo stars. Furthermore, a study of the influence of stellar granulation was undertaken by applying the new generation of 3D, time-dependent hydrodynamical model atmospheres (Asplund et al. 1999, 2000). Due to the expansion of rising granulation elements and the lack of radiative heating in metal-poor stellar atmospheres they have much lower temperature and electron pressure in the upper layers than classical 1D models in radiative equilibrium. The [O i] 6300 Å line is formed high up in the atmosphere and are stronger in 3D models than in 1D, whereas the Fe ii lines are formed deeper and are computed to be slightly weaker in 3D. The net 3D effect is a decrease of [O/Fe] ranging from 0.1 dex at \([\text{Fe/H}] = -1.0\) to about 0.2 dex at \([\text{Fe/H}] = -2.5\).

Fig. 1 shows the derived [O/Fe] values after having applied the 3D corrections. The figure also includes disk stars from Nissen & Edvardsson (1992) with their [O/Fe] values corrected for the presence of the Ni i blend. As seen there is a rather sharp rise of [O/Fe] around \([\text{Fe/H}] \approx -0.5\) to a constant level of \([\text{O/Fe}] \approx 0.3\) in the range \(-2.0 < [\text{Fe/H}] < -0.7\). The two subgiants, HD 140283 and BD +23 3130, give a hint of an increase of [O/Fe] below \([\text{Fe/H}] = -2.0\) but
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this has to be confirmed by more data. Hence, the new results for MS and subgiant stars essentially agree with previous results from the forbidden oxygen lines in giant star spectra.

As shown by Asplund & García Pérez (2001) the 3D effects on oxygen abundances derived from near-UV OH lines are as large as $-0.6\,\text{dex}$ for turnoff stars with $[\text{Fe/H}] \simeq -3.0$ due to the fact that molecule lines are very sensitive to the temperature structure of the stellar atmosphere. This explains the high $[\text{O/Fe}]$ values derived by Israelian et al. (1998, 2001) and Boesgaard et al. (1999) on the basis of a classical 1D model atmosphere analysis. All problems are, however, not solved. As discussed by Nissen et al. (2002) oxygen abundances in MS stars derived from the $\text{O}\,\lambda\,7774$ line tend to be higher than abundances from the forbidden line even when non-LTE and 3D corrections are applied. It also remains to be seen if oxygen abundances derived from the OH IR lines (Balachandran, Carr & Carney 2001; Meléndez, Barbuy, & Spite 2001; Meléndez & Barbuy 2002) and the forbidden lines in giants will agree with the trend shown in Fig. 1 when 3D effects are taken into account.

A further problem is that the trend of $[\text{O/Fe}]$ with $[\text{Fe/H}]$ may not be universal. In Fig. 1 there are several stars in the halo-disk transition region ($-1.0 < [\text{Fe/H}] < -0.5$) that deviate $2-3$ sigma from the mean trend. Furthermore, Nissen & Schuster (1997) have clearly shown that a group of six halo stars with $-1.0 < [\text{Fe/H}] < -0.7$ have lower $\alpha$-element/Fe ratios (including O/Fe) than thick disk stars and other metal-poor halo stars in the same metallicity range. The six halo stars move in large Galactic orbits and might have been accreted from dwarf galaxies or have been formed in low-density regions in the outer halo with a chemical evolution that has proceeded more slowly than in the inner halo and the thick disk (Matteucci & François 1992).

3. Carbon

The most accurate carbon abundances of lower MS stars are obtained from the weak forbidden $\text{C}\,\lambda\,8727$ line. Recently, Allende Prieto, Lambert & Asplund (2002) determined the solar C abundance from this line and obtained $\log(\text{C}) = 8.39 \pm 0.04\,\text{dex}$ taking into account 3D model atmosphere effects and a revised $gf$ value of the line. In combination with their solar oxygen abundance $\log(\text{O}) = 8.69 \pm 0.05\,\text{dex}$ (Allende Prieto et al. 2001) the solar atmospheric C and O abundances now agree well with C and O abundances in early-type MS stars and in the local ISM.

The $[\text{C}\,\text{i}]\,8727\,\text{Å}$ line was observed in disk stars by Anderson & Edvardsson (1994) and Gustafsson et al. (1999). $[\text{C/Fe}]$ as derived from 1D models shows an increase of about $0.2\,\text{dex}$ when going from solar metallicity to $[\text{Fe/H}] \simeq -1$. In view of the differential 3D model atmosphere corrections to be expected some of this increase may, however, be spurious. It is probably more safe to compare the derived C abundance with the O abundance derived from the $[\text{O}\,\text{i}]\,6300\,\text{Å}$ line. Both lines arise from low excitation levels and are formed in the same layers of stellar atmospheres. Hence, the derived C/O ratio is insensitive to errors in $T_{\text{eff}}$ and surface gravity, and the 3D corrections for C and O are expected to be nearly the same. This is confirmed for the Sun; Allende Prieto et al. (2001, 2002) find a 3D correction of $-0.08\,\text{dex}$ for both elements. I have therefore combined
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Figure 2. The VLT/UVES spectrum of CD−35 14849 ($T_{\text{eff}} = 6120$ K, log $g = 4.1$ and [Fe/H] = −2.3). The dotted line shows the spectrum before removal of the numerous telluric H$_2$O lines. The thick, full drawn line is the spectrum after division with the spectrum of the B-type star HR 8858 using the IRAF task ‘telluric’ to obtain the best fit between the two sets of H$_2$O lines. Excessive noise in the stellar spectrum are seen where strong H$_2$O lines have been removed. The weak C I lines are marked; one of them being blended by a Fe I line.

Figure 3. A sequence of VLT/UVES spectra of metal-poor turnoff stars around the $\lambda$9094.9 C I line (left) and the O I triplet (right). The arrows indicate positions where telluric H$_2$O lines have been removed.
the carbon abundances from Anderson & Edvardsson (1994) and Gustafsson et al. (1999) with oxygen abundances determined from the [O i] λ6300 line as measured by Nissen & Edvardsson (1992) including corrections for the Ni i blend discussed in Sect. 2. The derived [C/O] values are shown in Fig. 4.

The [C i] 8727 Å line is too weak to be measured in halo MS stars with [Fe/H] < −1. Instead one may use four high excitation C i lines around 9100 Å and the O i triplet at 7774 Å to derive C/O. This technique was first applied by Tomkin et al. (1992), who correctly emphasized that the derived abundance ratio is insensitive to errors in stellar atmospheric parameters and the $T, P$ structure of the model atmosphere, i.e. 3D hydrodynamical effects. Furthermore, non-LTE corrections are relatively small and go in the same direction for the C i and O i lines. As seen from their Fig. 10, [C/O] is nearly constant at the level of −0.5 dex in the range −2.5 < [Fe/H] < −1.0.

In order to test and expand the C/O results of Tomkin et al. (1992), I have derived C and O abundances from near-IR VLT/UVES spectra originally obtained together with M. Asplund and M. Pettini to determine sulphur abundances from the S i 9212 - 9237 Å triplet. The spectra have $R = 60000$ and $S/N \sim 200$ to 300. The equivalent widths of the O i triplet can be very accurately determined (see Fig. 3), whereas the C i lines around 9100 Å fall in a spectral region with many strong telluric H$_2$O lines. As seen from Fig. 2, these lines may, however, be removed by dividing with a spectrum of a hot star, and Fig. 3 shows that the C i line at 9094 Å can be clearly observed down to metallicities of about −3 in halo turnoff stars.
The [C/O] ratios derived from a 1D, LTE model atmosphere analysis of the UVES spectra are shown in Fig. 4 together with data from Tomkin et al. (1992) and the disk star results discussed above. The disk star analysis of the forbidden C and O lines was made differentially with respect to the Sun; hence the adopted solar abundances do not matter. In the analysis of the UVES spectra of the high excitation permitted C\textsc{i} and O\textsc{i} lines the new solar C and O abundances of Allende Prieto et al. (2001, 2002), log\(\epsilon\)(C) = 8.39 and log\(\epsilon\)(O) = 8.69, were adopted. Tomkin et al. (1992), on the other hand, used the older values of Grevesse et al. (1991), log\(\epsilon\)(C) = 8.60 and log\(\epsilon\)(O) = 8.92. The solar C/O ratio is, however, practically the same, so no offset in [C/O] is present. None of the data have been corrected for non-LTE or 3D effects, because these effects are expected to cancel in the C/O ratio as explained above. As seen from Fig. 4 [C/O] is nearly constant at the level of $-0.5$ dex among the halo stars perhaps with a slight decrease when going from $[O/H] = -2.0$ to $[O/H] = -0.5$. Around $[O/H] = -0.3$, [C/O] is rising steeply to the solar abundance ratio. It will be interesting to see how well Galactic chemical evolution models can explain this upturn of [C/O] in terms of metal-enhanced production of carbon in massive stars (Maeder 1992) and/or delayed production of carbon in intermediate mass stars. In this connection, one should note the peculiar position of HD 7424 in Fig. 4, an oxygen rich but carbon poor star with halo kinematics, which gives a first hint of a dichotomy in the evolution of [C/O] between the Galactic halo and the disk.

4. Nitrogen

Nitrogen abundances of intermediate and low main-sequence stars are more difficult to determine than C and O abundances. The forbidden N lines are very weak and have not been detected even in the solar spectrum. Weak high excitation N\textsc{i} lines can be measured in spectra of disk stars. The studies of Clegg, Lambert & Tomkin (1981) and Shi, Zhao & Chen (2002) suggest that N follows Fe, i.e. $[N/Fe] \sim 0.0$ in the metallicity range $-0.8 < [Fe/H] < +0.1$, but the dispersion is quite large, which may be caused by errors in the observations of the weak lines.

In the case of halo stars the high excitation N\textsc{i} lines cannot be detected and molecular lines of NH or CN have to be applied for the determination of N abundances. In order to be independent of the carbon abundance determination the best choice is the NH band at 3360 Å. Bessell & Norris (1982) were the first to make a high-resolution survey and spectrum synthesis analysis of this feature. Among 25 halo dwarfs they discovered two stars (HD 74000 and HD 160617) with very high N abundances, i.e. $[N/Fe] \sim 1.7 - 2.0$. Tomkin & Lambert (1984) made a careful high resolution study of the $\lambda$3360 NH band relative to the $\lambda$4300 CH band in spectra of 14 halo and disk stars with $-2.3 < [Fe/H] < -0.3$. They noted that the CH and NH hydrides have almost identical dissociation energies; hence the circumstances of CH and NH line formation are similar and the derived N/C abundance ratio is insensitive to atmospheric parameters and structure. As an important result they found $[N/C] \sim 0.0$ and concluded that nitrogen behaves like a primary element with respect to carbon down to a metallicity of $[Fe/H] \sim -2$. This conclusion is, however, based on only five halo stars.
More extensive studies of N abundances in lower MS stars have been carried out by Laird (1985) and Carbon et al. (1987), in both cases based on intermediate resolution spectra of the NH $\lambda 3360$ band and a 1D model atmosphere synthesis. The conclusion is that N tend to follow Fe, i.e. $[\text{N}/\text{Fe}] \sim \text{constant}$ except for a small decline of $[\text{N}/\text{Fe}]$ for $[\text{Fe/H}]$ below $-1.5$ in the work of Carbon et al. The two studies are, however, puzzling in some respects. Laird’s data have an unexplained offset $\Delta [\text{N}/\text{Fe}] \sim -0.6$ with respect to Carbon et al., and in both studies there is a clear dependence of the derived $[\text{N}/\text{Fe}]$ on $T_{\text{eff}}$. Furthermore, one can expect large downward 3D corrections of the N abundances derived from the NH band like in the case of oxygen abundances derived from the OH lines.

5. Conclusions

Progress has been made in understanding recent discrepancies on the $[\text{O}/\text{Fe}] - [\text{Fe/H}]$ relation. It looks like $[\text{O}/\text{Fe}]$ values derived from a 1D model atmosphere analysis of the near-UV OH lines are much too high (Asplund & García Pérez 2001). From a 3D analysis of the $[\text{O}1] \lambda 6300$ line in MS stars $[\text{O}/\text{Fe}]$ seems to be near constant at a level of $[\text{O}/\text{Fe}] \simeq 0.3$ for halo stars with $-2 < [\text{Fe/H}] < -1$ (Nissen et al. 2002). It remains, however, to be seen if oxygen abundances derived for subgiant and giant stars from the O1 triplet and the IR OH lines will be in agreement, and the trend of $[\text{O}/\text{Fe}]$ below $[\text{Fe/H}] \sim -2$ has to be studied in detail.

New results for the C/O ratio show an interesting trend of $[\text{C}/\text{O}]$ vs. $[\text{O}/\text{H}]$ with a strong upturn of $[\text{C}/\text{O}]$ at $[\text{O}/\text{H}] \simeq -0.3$. More data should be obtained especially for stars in the halo-disk transition region to look for a possible dichotomy in the evolution of C/O in the Galactic halo and the disk.

Nitrogen appears to have the least reliable abundances of the CNO elements. Existing data for $[\text{N}/\text{Fe}]$ are affected by unexplained systematic errors, and large downward 3D corrections of N abundances from the NH $\lambda 3360$ band are to be expected for stars at low metallicities. Hence, we very much need a new high resolution study of the NH $\lambda 3360$ lines in Galactic halo stars coupled with a careful 3D model atmosphere study. The recent discovery of large variations of N/O ratios among oxygen poor damped Lyman $\alpha$ systems (e.g. Pettini et al. 2002) accentuates the need for more reliable data and hence a better understanding of the nucleosynthesis of nitrogen.

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