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The carbon abundance in main-sequence B-type stars towards the Galactic anti-centre

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Abstract. Differential carbon abundances (based on the C II doublet at 6580Å) are presented for eight early type stars, towards the Galactic anti-centre. All the stars have similar atmospheric parameters with effective temperatures in the range 25000 − 29000 K and surface gravities between log g = 3.9 − 4.3 dex. The derived photospheric abundances vary by up to 0.6 dex, and with the exception of one star, RLWT-41, the differential abundances are found to be closely correlated with those of nitrogen. This implies that both elements may have been formed by similar mechanisms and that the lack of correlation between the nitrogen and oxygen abundances previously found in this sample is not directly due to CNO-processed core material being mixed to the stellar surface.

Key words: stars: abundances – stars: atmospheres – stars: early-type – Galaxy: abundances

1. Introduction

The photospheres of main-sequence B-type stars are often assumed to be uncontaminated by products of internal nuclear processes and to directly represent the chemical composition of their progenitor interstellar medium. This is because stellar evolutionary calculations (see, for example, Schaller et al. 1992) predict that these young objects are in a stable core hydrogen-burning phase.

However recent results have suggested that the atmospheres of some B-type stars could be contaminated by CNO-processed core material mixing to the surface. Gies & Lambert (1992) have studied 39 solar neighbourhood B-type stars with a range of surface gravities, $2.10 < \log g < 4.36$, and effective temperatures, $16450 < T_{\rm eff} < 34370$. They concluded that the nitrogen rich stars in their sample had abundances which were possibly consistent with surface enrichment by CNO-cycled material, although they could not rule out the possiblility that the nitrogen anomalies originated in the progenitor gas. Hence they were unable to confirm the strong claim by Lyubimkov (1991; and references therein) that CN-cycled material is clearly detectable in the atmospheres of many B-type core hydrogen burning stars. Some further preliminary evidence for mixing on the main sequence has come from the analysis of boron abundances in early-type objects (Venn et al. 1996, Fliegner et al. 1996).

Quantitative predictions can be made about the redistribution of photospheric abundances from evolutionary models including mixing mechanisms. For example, Maeder (1987) predicted that contamination of a stellar atmosphere by CNO-cycled material can occur as a star is in the process of evolving off the main sequence. In such a model, a nitrogen enhancement of 0.6 dex should be accompanied by a 0.2 dex increase in helium and a 0.2 dex decrease in carbon (with oxygen only slightly depleted). Dennisenkov (1994) has produced a model in which mixing from the core regions to the radiative envelope of a B-type star is achieved by rotationally induced turbulent diffusion. In either case for both models an observed anti-correlation between carbon and nitrogen abundances visible in the stellar photosphere is predicted as a tracer for contamination by core CNO-cycled material.

In two previous papers (Smartt et al. 1996a, 1996b), chemical compositions for a sample of nine main sequence stars with low projected rotational velocities and similar atmospheric parameters has been presented; using differential methods, it was possible to derive relative abundances to an accuracy of better than 0.2 dex. These results were used, for example, to correlate metal abundances with spiral structure and to search for different patterns between individual elements.

In general, a good correlation was found between the differential abundances of silicon and magnesium and those of oxygen, whereas nitrogen and oxygen did not appear to be well correlated. For example, three of the stars studied (S283-2, S289-4 and RLWT-41) had atmospheres significantly enhanced in nitrogen compared with the other α-processed elements (i.e. oxygen, magnesium, silicon), beyond that which could be explained by observational uncertainty. Additionally two stars in the cluster S289 (-4 and -2) appeared to have significantly different nitrogen abundances, whereas the abundances of oxygen, silicon and

Send offprint requests to: R.E. Hibbins magnesium were found to be consistent. Hence this stellar sample suggested either a significantly different spatial variation in the progenitor interstellar nitrogen abundance (compared with the other metals), or the products of CNO-cycle nuclear processes are being mixed to some of the stellar surfaces.

As a method of distinquishing between these possibilities we have gathered further high quality spectroscopic data to determine accurate carbon abundances in this homogeneous sample of B-type stars. We shall present carbon abundances from the C II lines at 6578.1 and 6582.9 Å for comparison with the previously published nitrogen and oxygen abundances (Smartt et al. 1996a). These lines are among the strongest carbon absorption features in the optical spectra of early B-type stars, are known to be relatively unaffected by non-LTE effects (Eber & Butler 1988) and to give reliable differential abundances (Barnett & McKeith 1988).

2. Observational data

Spectra for the stars RLWT-13, RLWT-41, S285-6, Bo-1a and NGC-1983a were obtained during the nights of 24–28 Dec 1996 at the 2.5 m Isaac Newton Telescope (INT) on La Palma in the Canary Islands. The Intermediate Dispersion Spectrograph (IDS) was employed with the 500 mm camera and the H1800V grating. With a pixel size of 24 μm for the TEK3 1124×1124 CCD, a resolution of 0.55 Å at the central wavelength of $\sim$ 6600 Å was achieved, as measured from the full width at half maximum of the arc lines. Bias frames and flat fields (tungsten lamp) were recorded at the beginning of each night, and wavelength calibration was undertaken using spectra of a CuAr arc lamp obtained at regular intervals throughout the night.

Spectra covering the red C II lines for the stars S208-6, S283-2 and S289-2 and S289-4, together with additional data for S285-6 were recorded at the William Herschel Telescope on La Palma over two observing runs in December 1991 and November 1993, details of which are summarised in Smartt et al. (1996a). In both cases the ISIS spectrograph was employed with the R1200R grating on the red arm giving a resolution of 0.8 Å. To ensure consistency, these data were re-reduced together with the INT data at the Northern Ireland STARLINK node at Queen's University Belfast using standard FIGARO techniques (Shortridge et al. 1996) as outlined in Smartt et al. (1996a).

Where observed, the equivalent widths of the C II features were determined by fitting Gaussian profiles after normalising to a pseudo-continuum fitted to the red wing of the H α line. The errors in the equivalent widths were estimated from the rms of the fit to the pseudo-continuum and that of the Gaussian fit to the profiles and are in the range $5-30$ %. Fig. 1 shows the spectrum of Bo-1a which is the sum of four 1200 s exposures giving a continuum signal to noise of approximately 100, typical of those obtained. The adopted continuum and the Gaussian fits to the two lines are shown.

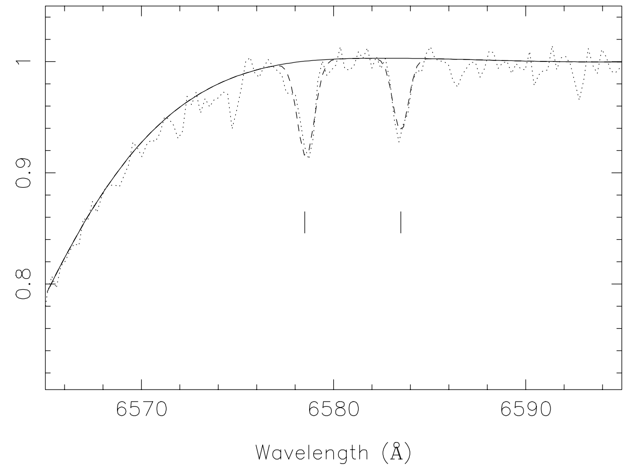

Fig. 1. IDS spectrum of the star Bo-1a showing the C II doublet (marked) on the red wing of the H α line (dotted line). The pseudo-continuum upon which the equivalent widths of the C II lines were measured is marked (solid line) together with the Gaussian fits to the C II lines (dashed line).

Table 1. Equivalent widths for the red C II lines recorded towards the nine target stars

Star	V	W_{6578}/mÅ		W_{6582}/mÅ	
S285-6	12.05	76	±11	44	±11
S208-6	12.65	82	±6	67	±8
S289-2	12.66	37	±10	-	
S289-4	13.58	76	±22	53	±19
S283-2	14.22	70	±8	-	
RLWT-13	13.00	91	±	-	
RLWT-41	11.39	129	±11	74	±9
Bo-1a	12.59	99	±13	67	±9
NGC-1893a	11.53	80	±8	33	±11

3. Differential abundance analysis

The method of analysis followed closely the procedures discussed by Smartt et al. (1996a, 1996b), where further details can be found. Briefly line-blanketed, plane-parallel model stellar atmospheres in LTE were calculated for each object using the Atlas9 code of Kurucz (1979, 1991). Temperatures, surface gravities, microturbulent velocities and helium abundances were taken from Smartt et al. (1996a). Absolute abundance estimates derived from these model stellar atmospheres were found to be in good agreement with those calculated from a 2-dimensional linear interpolation from a grid of standard model atmospheres as used in Smartt et al. (1996a). Line-by-line differential abundances were determined relative to the same standard as used by Smartt et al. (1996b), namely S285-6. This target was chosen as it has a similar chemical composition to B-type stars observed in the solar neighbourhood (Rolleston et al. 1994). Additionally the high quality of its observational data ensured that it should be a reliable standard in that the large signal to noise ratio in the spectra resulted in accurate equivalent width measurements and hence consistent abundances calculated from the two C II lines.

4. Results

The differential carbon abundances with respect to S285-6, deduced from the two C II lines at 6578 and 6582 Å, are summarised in Table 2, together with the parameters used in the model stellar atmosphere calculations. These show significant variations covering a range of approximately 0.6 dex. The re-reduction of the data for the cluster S289 confirms the large discrepancy between the carbon abundances in the stars S289-2 and S289-4, which was also observed for nitrogen (Smartt et al. 1996b).

Carbon differential abundances are plotted against those of nitrogen in Fig. 2a. Despite typical error bars of $\pm 0.1 - 0.2$ dex they clearly show a positive correlation. An unweighted linear least squares fit to the data generates a correlation coefficient of +0.76. Indeed if the point due to RLWT-41 (a star believed to have formed between the Local and Perseus spiral arms in a region of inefficient star formation and possibly abnormal metal abundances - see Smartt et al. 1996b) is ignored then this coefficient rises to +0.94. Also plotted in Fig. 2a is the locus representing equal changes in the carbon and nitrogen abundances. Most of the stars cluster around this locus implying that abundance changes for these two elements are similar in magnitude. For comparison, the lack of correlation between carbon and oxygen and nitrogen and oxygen is shown in Figs. 2b and c respectively.

5. Discussion

The positive correlation found between the differential abundance measurements of carbon and nitrogen suggests that the two elements have a similar nucleosynthetic origin. Additionally given the relatively unevolved nature of these stars, it is unlikely that such variations could be caused by mixing of interior nuclear processed material to the stellar surface. For example, although the CNO-bicycle would lead to a nitrogen enhancement, there would also be a carbon depletion and hence an anti-correlation between these elements (Gies & Lambert 1992, Maeder & Meynet 1988). To obtain a carbon enrichment to match that of nitrogen, it would then be necessary to invoke subsequent nuclear processing by the conversion of helium into carbon. Such processes should not occur during a stellar main sequence or early post-main sequence evolutionary phase (Maeder & Meynet 1988, Schaller et al. 1992). Hence the observed carbon and nitrogen variations would appear to originate in inhomogeneities in the progenitor interstellar medium from which the stars formed. Such an abundance pattern also appears to support the hypothesis that carbon and nitrogen are generated by similar mechanisms, for example nucleosynthesis in intermediate mass stars. In contrast, oxygen evolution would appear to be decoupled from carbon and nitrogen which would suggest that it is generated by an unrelated mechanism, generally thought to

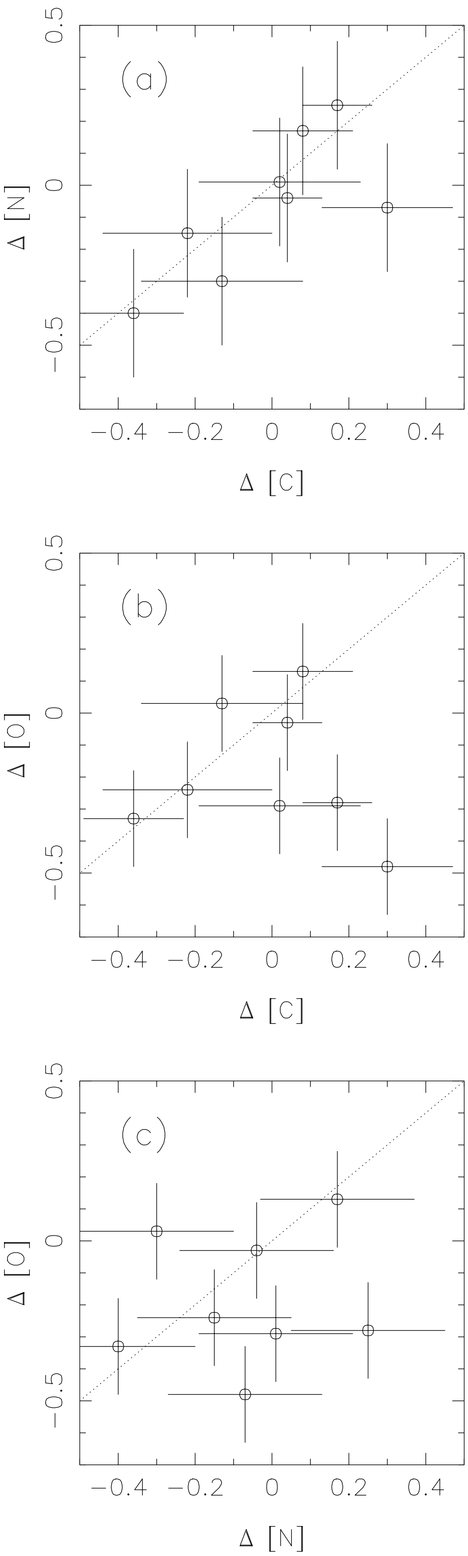

Fig. 2a–c. Plot of differential carbon abundances against: **a** nitrogen abundances and **b** oxygen abundances for the eight stars studied. 1 σ error bars are shown and the dotted lines represent the loci of equal differential abundance ratios. For reference the plot of differential abundance of nitrogen versus oxygen, taken from Smartt et al. (1996b) is shown **c**.

Table 2. Atmospheric parameters together with absolute and differential C II abundances with respect to S285-6 for the programme and previously observed stars. The abundance in the stars marked * was determined from the equivalent width of the 6578 Å line only. For reference the differential abundances of oxygen and nitrogen, taken from Smartt et al. (1996a), are shown

Star	R_g/kpc	T_{eff}/K	log g	V_t/kms^{-1}	12 + log $\left[\frac{C}{H}\right]$	Δ[C II]	Δ[O II]	Δ[N II]
S285-6	12.3 (±0.3)	27500	4.0	6.0	7.59 (±0.12)	–	–	–
S208-6	11.6 (±0.8)	26000	4.0	5.0	7.63 (±0.08)	+0.04 (±0.09)	−0.03	−0.04
S289-2*	15.4 (±0.7)	28500	4.0	5.0	7.28 (±0.17)	−0.36 (±0.13)	−0.33	−0.40
S289-4	15.4 (±0.7)	27000	4.1	5.0	7.61 (±0.24)	+0.02 (±0.21)	−0.29	+0.01
S283-2*	17.6 (±1.0)	29000	3.9	5.0	7.81 (±0.10)	+0.17 (±0.09)	−0.28	+0.25
RLWT-13*	13.1 (±1.0)	25000	4.0	8.0	7.42 (±0.21)	−0.22 (±0.22)	−0.24	−0.15
RLWT-41	10.4 (±1.0)	26000	4.3	5.0	7.89 (±0.10)	+0.30 (±0.17)	−0.48	−0.07
Bo-1a	13.2 (±0.2)	25500	4.0	5.0	7.67 (±0.12)	+0.08 (±0.13)	+0.13	+0.17
NGC-1893a	13.3 (±0.2)	27000	4.3	5.0	7.46 (±0.15)	−0.13 (±0.21)	+0.03	−0.30

be type II SNe in massive ($M/M_\odot > 8$) stars (see for example Matteucci & François 1989).

The two stars which appear to be in the cluster S289 (2 and 4) are found to have similar chemical compositions in oxygen, magnesium, aluminium and silicon. However, their carbon and nitrogen abundances differ by $0.3-0.4$ dex. Although the abundance estimates for S289-2 are based on the observation of a single line for each element, the failure to detect other features in our high signal to noise spectral data, allows upper limits to be set on the equivalent widths of other lines. These confirm an underabundance of at least 0.3 dex in S289-2 compared to S289-4 for both elements. A similar result has been found for the cluster S285 (Rolleston et al. 1994) in which the star S285-1 has a nitrogen abundance approximately 0.4 dex higher than S285-6, and a carbon abundance approximately 0.2 dex higher. Again good agreement between the two cluster members is found for the abundances of other elements.

These results are surprising if the stars assigned to a given cluster are indeed members formed from the same interstellar material. To test this hypothesis, we have considered the stars assigned to S289 and tried to estimate an upper limit on their separation. Smartt et al. (1996b) have estimated masses from their positions on the $T_{eff} - \log g$ diagrams of Maeder & Meynet (1988) and then, applying the bolometric corrections of Kurucz (1979), calculated the absolute visual magnitudes. Heliocentric distances of 7.0 and 8.6 kpc respectively were determined assuming a standard Galactic extinction law. The average of these two values is in good agreement with a distance of 7.9 kpc to the cluster determined by Moffat et al. (1979) by zero-age main-sequence fitting in the colour-magnitude diagram. However limits on the reliability of the measurement of surface gravity (calculated from the profiles of the hydrogen lines using the line broadening theory of Vidal et al. 1973) suggests that the logarithmic gravity may be as low as 4.0 dex in S289-4 giving a heliocentric distance of ∼9.6 kpc. Hence a realistic upper limit on the distance between the two stars is 2.6 kpc, which would be consistent with the observed abundance differences. However we note that for both clusters, S285 and S289, the proposed members are closely associated with an H II region, and have radial velocities and reddenings that are consistent with membership. Hence their different nitrogen and carbon abundances remain puzzling.

We have presented above *differential* carbon abundances which trace accurately the variations amongst the programme stars. Also we have included our estimated absolute abundances in Table 2, (on the usual scale of $\epsilon(X) = n(X)/n(H)$, with $\log \epsilon(H) = 12.0$). These are the first determinations of Population I carbon abundances in areas of low metallicity in the outer Galaxy. Indeed accurate abundances of carbon in Galactic nebular studies have not been available from optical data (see Shaver et al. 1983, Vilchez & Esteban 1996); Garnett et al. (1995, 1997) have shown the necessity of using high quality HST UV spectroscopy to tie down carbon compositions in H II regions in star-forming Galaxies. Hence there is little current information in the disk with which to compare our results. We must however be careful when comparing the absolute values in Table 2 to other studies of stellar or nebular origin. Smartt & Rolleston (1997) have highlighted the difficulties in comparing inhomogeneous data sets to trace large scale abundance variations in the Galaxy, and suggest that it is essential that any study (e.g. to determine a meaningful Galactic abundance gradient of a particular element) is based upon rigorous, self-consistent analyses. Comparing the abundances listed in Table 2 of the roughly metal-normal stars (e.g. S285-6) to those found by Gies & Lambert's (1992) study of bright nearby objects, we find our absolute values significantly lower (by 0.3 – 0.6 dex). Indeed using our line formation codes, and atomic data to estimate the abundances in the stellar data presented by Gies & Lambert, we still produce systematically lower values for carbon from the two red lines (by approximately 0.3 on average). This again reinforces the arguments in Smartt & Rolleston (1997) that studies of radial and spatial abundance variations must be done in a consistent manner.

6. Conclusions

From high resolution spectra of the C II lines at 6578 and 6582 Å recorded in a homogeneous sample of B-type stars, we have applied standard LTE model atmosphere techniques to determine accurate carbon abundances. Using differential methods we have been able to show that the abundances of carbon and nitrogen are closely correlated and unrelated to those of oxygen.

This result provides strong evidence for a common nucleosynthetic origin for carbon and nitrogen in the interstellar medium, distinct from that of oxygen and the other α-processed elements, and offers little support to the theory that the enhanced nitrogen abundance measured in the stars S283-2, S289-4 and RLWT-41 is the result of CNO-cycled material mixing to the surface. This abundance pattern is consistent with carbon and nitrogen being mainly generated by nucleosynthesis in intermediate mass stars, while oxygen appears to have been created by an unrelated environment such as the interiors of massive stars.

On the basis that the CN abundances in this stellar sample appear not to have been contaminated by core CNO processed material, and that they hence reflect variations in the progenitor gas, we shall present a future consistent, systematic study of the large-scale Galactic variations of carbon, nitrogen, oxygen, silicon and magnesium (Hibbins et al, in preparation). These variations will play a crucial role in constraining future models of Galactic chemical evolution.

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