B-Type Stars as Tracers of Galactic Chemical Compositions

Philip Dufton

Department of Pure and Applied Physics, Queen's University Belfast, Belfast BT7 1NN, UK

Abstract. B-type stars can be used to map the current chemical composition of our own and other nearby galaxies. Recent results are presented for directions both away from and towards the Galactic centre. For the former, enhanced metal abundances may be associated with the spiral-arm structure. Additionally, while oxygen, magnesium, and silicon abundances correlate reasonably well, nitrogen appears to be uncorrelated. For stars towards the Galactic centre, both normal and enhanced metal abundances are observed with some indication of variations between elements. Combining datasets from both regions, large-scale abundance gradients are found for nitrogen, oxygen, magnesium, and silicon, with magnitudes similar to those found from H II-region studies. Very recent results indicate that a positive correlation exists between nitrogen and carbon abundances, implying a common origin (possibly in intermediate-mass stars) but appearing to be incompatible with recent processing via the CNO bicycle. Finally, abundances are presented for a low-gravity B-type star, LS 4825. If a normal young object, this would be sampling the chemical composition on the far side of the Galaxy.

1. Introduction

Early-type stars provide powerful probes of the chemical and kinematical evolution of galaxies. The research programmes at Queen's University concentrate on spectroscopy of B-type stars and fall into two main areas, viz., the nature of stars at high Galactic latitudes (often called 'halo stars') and their use as tracers of the chemical composition of our own and other galaxies. A review of the former programme has been given by Keenan (1992), while here we will concentrate on the latter. In particular, four projects, all connected with our own Galaxy, will be discussed, viz. the chemical composition both in the Galactic-anticentre direction and towards the Galactic centre, the combination of such results to search for larger-scale spatial variations, and finally some tentative results on the chemical composition on the far side of the Galaxy. In collaboration with Danny Lennon, we also have a programme on the analysis of supergiant spectra, and some preliminary results are presented by Neil McErlean at this meeting (McErlean 1998).

Such techniques can also be used in studies of external galaxies and results on the M31 and M33 spiral galaxies are reported at this meeting. At Queen's

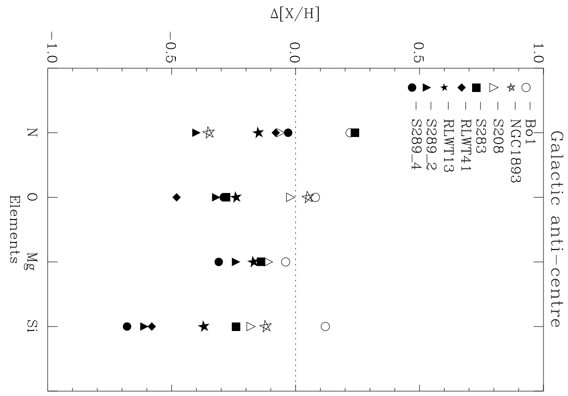

Figure 1. The chemical composition of some of the stars in the Galactic-anticentre direction. Open symbols are used for approximately normal metal abundances, while filled symbols indicate metal deficiencies.

University, we have extensively observed the Magellanic Clouds system and reported chemical compositions for the Small (Dufton et al. 1990; Rolleston et al. 1993; Lennon et al. 1996) and Large (Rolleston et al. 1996) Clouds, together with the bridge of material which joins them (Hambly et al. 1994).

2. Galactic-Anticentre Direction

Several groups have used B-type stars to investigate chemical compositions in the anticentre direction (see, for example, Gehren et al. 1985; Kaufer et al. 1994; Fitzsimmons et al. 1992). In general, flat metal-abundance gradients have been found in and beyond the solar Galactocentric radius, in contrast to those found from emission-line studies (see, for example, Shaver et al. 1983). Additionally, there is some evidence for a real scatter in metal abundances at similar Galactocentric distances. However all these studies included stars with a significant range of atmospheric parameters, which may have introduced systematic errors even when sophisticated non-LTE methods are employed.

Recently Smartt et al. (1996a, 1996b) have considered a subset of the stars observed in the QUB programme, which covered a small range of atmospheric parameters ($T_{\rm eff} \simeq 26\,000$–$29\,000$K; $\log g \simeq 3.9$–4.1); additionally, all of the targets had relatively low projected rotational velocities, which allowed the measurement of reliable equivalent widths for the metal-line spectra. This subset covered a significant range of Galactocentric distance ($R_{\rm g}$), viz. $10 \leq R_{\rm g} \leq 17$ kpc, while the homogeneity of the dataset had two important advantages:

1. differential abundances from LTE and non-LTE model-atmosphere calculations should have a high accuracy.

2. although distances estimates may contain systematic errors, relative distances should be reliable.

The chemical compositions of some of our sample are shown in Fig. 1.

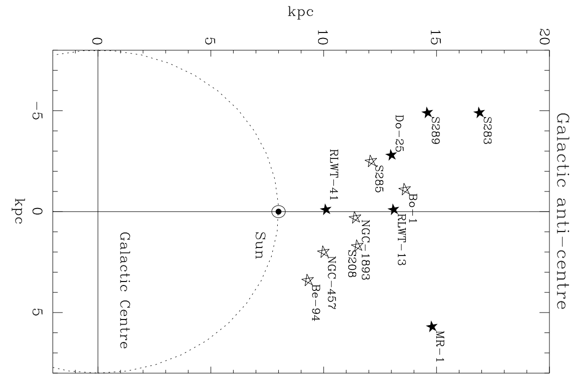

Figure 2. The position of the anticentre targets with respect to the sun. The stars with near normal metal abundances are shown as open symbols, while metal deficient stars are indicate by filled symbols.

The stars appear to fall into two broad groups with either approximately normal oxygen, magnesium, and oxygen abundances, or significant depletions. A corollary of this is that the abundances of these metals appear to be reasonably well correlated; in contrast, the nitrogen abundances do not appear to show any correlation.

The relative spatial positions of our sample are shown in Fig. 2. Some structure is apparent, with a group of stars with normal metal abundances appearing to lie in at approximately 11 kpc from the Galactic centre; it is unclear whether this represents a spiral arm. Additionally, stars which lie relatively close to one another have markedly different abundances. This confirms earlier results that indicate that a simple linear abundance gradient was too simplistic an approximation.

3. Galactic-Centre Studies

The principle difficulty in using optical spectroscopy of B-type stars to probe the inner Galactic regions is the large amount of interstellar extinction. We have circumvented this by concentrating on stars with sufficiently large Galactic latitudes ($4° \leq |\ell| \leq 10°$) that they suffer only moderate extinction. However, these targets lie at significant distances from the Galactic plane (typically 500 pc), so that there will be extra uncertainties connected with their origin and evolutionary history. Preliminary results have been presented by Smartt (1996), Smartt et al. (1997), and Venn et al. (1997), and here we briefly discuss the first two.

The relative spatial positions of our sample are shown in Fig. 3. The sample contains both supergiant and main-sequence targets and hence does not have the homogeneity of the anticentre targets discussed above. For the supergiant sample, both normal and enhanced metal abundances are found, as can be seen from Fig. 4. For the main-sequence stars, the analysis has not been completed, but again there is evidence for a range of metallicities.

It should be stressed that the Galactic-centre studies are at a relatively early stage, and hence the results should be considered preliminary. We are currently

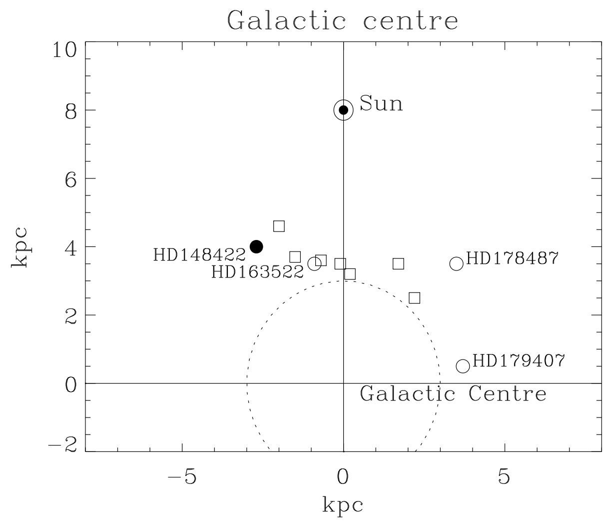

Figure 3. The position of the Galactic-centre targets with respect to the sun. Supergiants are marked by circles, with the metal-enhanced stars having open symbols, whilst the main-sequence stars are shown as squares.

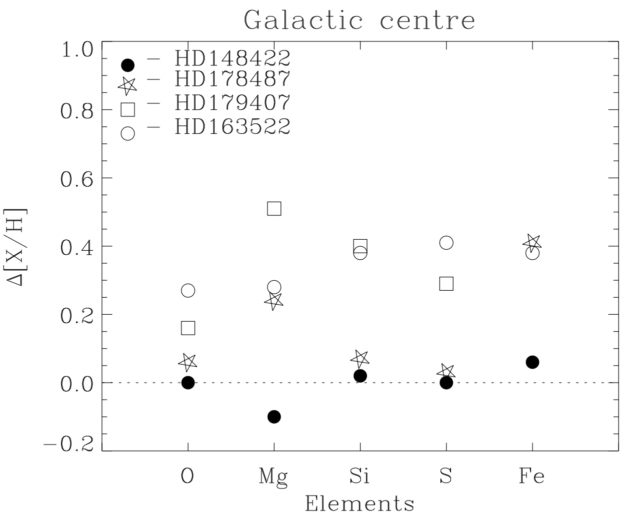

Figure 4. The chemical composition of some of the supergiants towards the Galactic centre. Filled symbols are used for those with approximately normal metal abundances, while open symbols indicate those with metal enhancements.

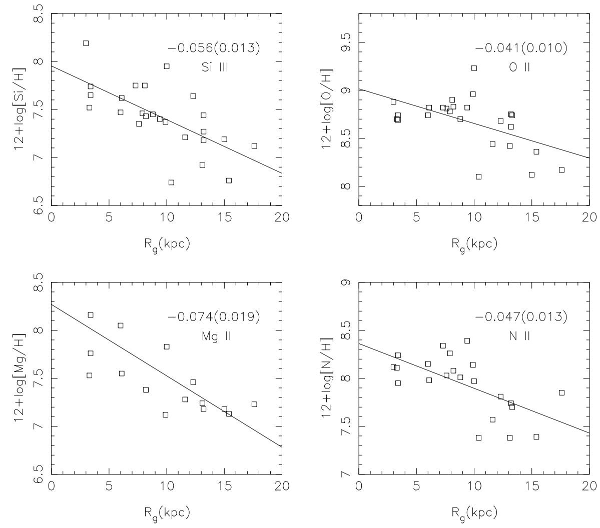

Figure 5. Variations of silicon, oxygen, magnesium, and nitrogen abundances as a function of Galactocentric distance. Also shown are the abundances gradients found from simple linear fits.

using Schmidt plate material and low-dispersion multi-object spectroscopy to increase and improve the quality of our sample for subsequent high-dispersion spectroscopy.

3.1. Abundance Gradients

One surprising result from analyses of B-type stellar spectra is that they have failed to reproduce the abundance gradients found from other methods. Recently, Smartt & Rolleston (1997) have re-analysed oxygen abundances obtained during several campaigns at Queen's University and have, for the first time, found a significant gradient of approximately -0.07 dex kpc^{-1}. Additionally, their individual abundances as a function of Galactocentric distances agree well with those from H II regions. It should be stressed that these results refer to the large-scale spatial variations in abundances and are compatible with the more complicated, smaller-scale variations discussed above. These studies have been extended to other elements, and results for carbon, oxygen, magnesium, and silicon are shown in Fig. 5. In all cases a gradient is observed, although currently it is not clear whether the range in values is significant.

As discussed above, although the oxygen, silicon, and magnesium abundances appear to be well correlated, nitrogen abundances exhibit a different behaviour. Recently we have observed the red C II multiplet at approximately 6580Å. This should be a more reliable abundance indicator than the blue lines that we have used previously (see, for example, Barnett & McKeith 1988). In Fig. 6, the corresponding carbon abundances are plotted against those of nitrogen and oxygen; carbon and nitrogen appear to be positively correlated, while no correlation is apparent between carbon and oxygen. This is surprising since, if the anomalous nitrogen behaviour had been caused by the mixing of CNO bicycle-processed material to the stellar surface, an anticorrelation between car-

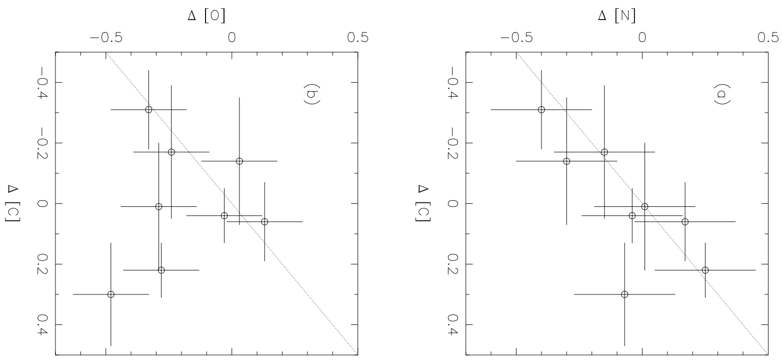

Figure 6. Nitrogen and oxygen abundances plotted against carbon abundances deduced from the C II red doublet

bon and nitrogen would have been expected. Rather, it implies a common origin for these elements (possible in intermediate-mass stars) and that both element abundances are representative of that of the progenitor ISM.

4. The Other Side of the Galaxy

During our investigations of stars towards the Galactic centre, we observed the star LS 4825 (Ryans et al. 1997). This star appeared to have a spectral type of approximately B1 II and hence, if normal, would be at a distance of approximately 20 kpc, placing it on the far side of the Galaxy. Alternatively, it could be a low-mass evolved object at a correspondingly smaller distance; its low gravity would then be consistent with a post-asymptotic-giant-branch (PAGB) evolutionary stage. A differential abundance analysis of LS 4825 relative to a standard star, HD 24398, is summarized in Table 1. In general, the metal abundances appear to be normal or slightly enhance and do not show the characteristic pattern of PAGB stars (see Hambly et al. 1996, and references therein). Hence LS 4825 may indeed be a distant, young, normal star.

Table 1. Differential-abundance analysis for LS 4825 with respect to the standard star HD 24398; 'n' is the number of lines analysed.

Spectrum	Differential abundance	n	Spectrum	Differential abundance	n
C II	$+0.20\pm0.07$	2	Si III	$+0.10\pm0.07$	2
N II	$+0.05\pm0.12$	6	Si IV	-0.05	1
O II	$+0.09\pm0.15$	28	S III	$+0.10$	1
Mg II	$+0.15$	1	Fe III	$+0.25\pm0.23$	2
Al III	$+0.11\pm0.14$	3			

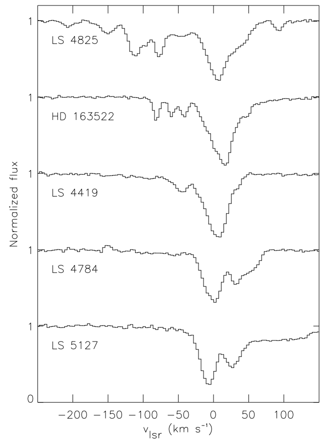

Figure 7. The interstellar Ca II K line towards LS 4825, together with those for other stars in approximately the same direction.

Additional evidence for this is furnished by its Ca II K interstellar line, which is show in Fig. 7. Also included are the same feature for other stars along similar lines of sight, but on our side of the Galactic centre. All sightlines have absorption due to low- and intermediate-velocity gas, but LS 4825 has additional components at both high negative and positive velocities. These may be due to material near the Galactic centre, which would then be incompatible with LS 4825 being a PAGB star. Hence Ryans et al. (1997) conclude that LS 4825 is probably beyond the Galactic centre and as such is giving the first estimate of chemical compositions in such a region.

Acknowledgments. The work discussed above has been undertaken with colleagues both at Queen's University and elsewhere, including Nigel Hambly, Rob Hibbins, Francis Keenan, Danny Lennon, Neil McErlean, Robert Rolleston, Robert Ryans, Ken Sembach, Stephen Smartt, and Kim Venn. I am grateful to them for letting me 'lift' their results!

References

Barnett, E. W., McKeith, C. D., 1988, MNRAS, 234, 325

Dufton, P. L., Fitzsimmons, A., Howarth, I. D., 1990, ApJ, 362, L59

Fitzsimmons, A., Dufton, P. L., Rolleston, W. R. J., 1992, MNRAS, 259, 489

Gehren, T., Nissen, P. E., Kudritzki, R. P., Butler, K., 1985, in ESO Workshop on the Distribution of CNO elements (ESO, Garching), p. 171

Hambly, N. C., Dufton, P. L., Keenan, F. P., Rolleston, W. R. J., Howarth, I. D., Irwin, M. J., 1994, A&A, 285, 716

Hambly, N. C., Dufton, P. L., Keenan, F. P., Lumsden, S. L., 1996, MNRAS, 278, 811

Kaufer, A., Szeifert, T., Krenzin, R., Baschek, B., Wolf, B., 1994, A&A, 289, 740

Keenan, F. P., 1992, QJRAS, 33, 325

Lennon, D. J., Dufton, P. L., Mazzali, P. A., Pasian, F., Marconi, G., 1996, A&A, 314, 243

McErlean, N. D., 1998, in Boulder-Munich II: Properties of Hot, Luminous Stars (ASP Conf. Series, Vol. 131), ed. I.D. Howarth (ASP, San Francisco), p. 148

Rolleston, W. R. J., Dufton, P. L., Fitzsimmons, A., Howarth, I. D., Irwin, M.J., 1993, A&A, 277, 10

Rolleston, W.R.J., Brown, P.J.F., Dufton, P.L., Howarth, I.D., 1996, A&A, 315, 95

Ryans, R.S.I., Dufton, P.L., Keenan, F.P., Smartt, S.J., Sembach, K.R., Lennon, D.J., Venn, K.A., 1997, ApJ, 490, 267

Shaver, P.A., McGee, R.X., Newton, M.P., Danks, A.C., Pottasch, S.R., 1983, MNRAS, 204,53

Smartt, S.J., 1996, PhD Thesis, Queen's University of Belfast

Smartt, S.J., Rolleston, W.R.J., 1997, ApJ, 481, 47

Smartt, S.J., Dufton, P.L., Rolleston, W.R.J., 1996a, A&AS, 116, 483

Smartt, S.J., Dufton, P.L., Rolleston, W.R.J., 1996b, A&A, 310, 123

Smartt, S.J., Dufton, P.L., Lennon, D.J., 1997, A&A, 326, 763

Venn, K.A., Smartt, S.J., Lennon, D.J., Dufton, P.L., Keenan, F.P., 1997, ApJ, in preparation

Discussion

Jeffery: Before I invite questions, I have an announcement: this is a special occasion for Philip, being his 50th birthday. [Applause, shamefully mingled with whoops of derision.]

Kaper: LS 4825 is well below the Galactic plane – about 12 kpc? How does it get there?

Dufton: That's not actually a problem, and LS 4825 isn't unique in this respect. The most likely mechanism is ejection from the Galactic disk, either from a cluster (following momentum transfer through a collision) or by evolving a massive close binary to a supernova stage (when the companion gets a 'kick'). There are a number of normal, young B-type stars in the solar neighbourhood which are 2, 3, even up to $\sim$10 kpc from the sun.

Gies: Is there any velocity information on 4825 that would help, and is there a UV spectrum from which the wind terminal velocity could be measured? Ebbets and others have shown that the escape velocity can be estimated from v_∞.

Dufton: The radial-velocity information is consistent with the star corotating with the plane, if it's at 20 kpc. Of course, it would then be in the halo, with the implication of a significant ejection velocity, but we have no information on the transverse velocity. We've tried to use the $v_\infty/v_{\rm esc}$ method for several stars, and always end up with ambiguous results.