HOT POST-ASYMPTOTIC GIANT BRANCH STARS AT HIGH GALACTIC LATITUDES

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ABSTRACT

Model atmosphere analyses are presented for high-resolution spectra of four stars at high Galactic latitudes. Although their derived atmospheric parameters are consistent with their previous classification as early B-type stars, their chemical compositions are significantly different from those expected for Population I objects. However both the chemical compositions and atmospheric parameters appear to be consistent with a post-asymptotic giant branch evolutionary status.

Subject headings: stars: abundances — stars: atmospheres — stars: post-asymptotic giant branch

1. INTRODUCTION

This paper reports results from a continuing program to investigate the nature of stars in the halo of the Galaxy. Previously we have used high-quality spectroscopic data coupled with model atmosphere techniques to show that a number of B-type stars in the halo have Population I chemical composition (see Conlon et al. 1992, and references therein). Although the kinematics of most of these stars are such that their present location at high Galactic latitude can be explained by cluster ejection (Conlon et al. 1990), a few stars remain whose current locations appear to be incompatible with an origin in the Galactic disk. This rather controversial result is illustrated by PG 0832 + 676 (Brown et al. 1989), an apparently normal Population I B1 V star at a distance of 18 kpc from the Galactic plane. The apparently large distances of these stars have made them ideal for studying the intervening interstellar medium (see, for example, Keenan et al. 1988; Pettini & D'Odorico 1986), and hence it is important that their evolutionary status is reliably established and accurate distances determined.

This paper illustrates the importance of having high-resolution and high signal-to-noise spectral data (coupled with a quantitative abundance analysis) in order to distinguish between early B-type hydrogen burning and evolved stars. For example, the recent work on possible cooler post-asymptotic giant branch (PAGB) stars (see Trams, van Hoof, & van de Steene 1991, and references therein) has shown that although these stars have a peculiar mix of chemical compositions, some are similar to solar, and a careful model atmosphere analysis is required to confirm their abnormality. Additionally the PAGB evolutionary tracks of Schönberner (1983) and Gingold (1976) have effective temperatures and surface gravities similar to objects evolving from the hydrogen burning main-sequence and hence these stars cannot be differentiated on the basis of their atmospheric parameters alone.

Here we present abundance analyses for four stars LB 3193, LB 3219, LS IV – 4:01 and LS IV – 12:111, previously observed by Kilkenny and coworkers (Kilkenny & Lydon 1986; Kilkenny 1987; Kilkenny & Pauls 1990). We obtained high-resolution spectra of these and other objects as part of our program to identify young early-type stars at high Galactic latitudes. The other objects appear to be normal Population I stars and are discussed elsewhere (Conlon et al. 1992). However the peculiar chemical compositions of the stars analyzed here imply that their preliminary identification as normal young stars is incorrect and that they are probably PAGB objects.

2. OBSERVATIONS AND DATA REDUCTION

In 1989 August spectroscopic observations were undertaken on the 3.9 m Anglo Australian Telescope (AAT) at Siding Springs using the University College London Echelle Spectrograph (UCLES), with the Image Photon Counting System (IPCS) as the detector. The instrumental set up used the 79 grooves mm\(^{-1}\) grating and the 70 cm camera, which provided a linear dispersion of 2 Å mm\(^{-1}\) and a resolution of 0.2 Å (FWHM). To ensure complete wavelength coverage from 3870 to 4690 Å, exposures were taken at two different grating settings with spectra being collected in orders 49–57 inclusive. In three of the four stars, typical continuum counts of 2500 were obtained resulting in a signal-to-noise ratio of approximately 50; in LS IV – 4:01 the mean count was only sufficient to give a signal-to-noise ratio of 25.

At the time that the echellograms were reduced the specially written UCLES echelle reduction package (Mills 1991) was not generally available and therefore the following procedure was adopted, using the STARLINK packages FIGARO (Shortridge 1986) and DIPSO (Howarth & Murray 1988). FIGARO was used to reduce the two-dimensional nine-order echellograms to a one-dimensional format using the methods discussed in Conlon et al. (1991). Briefly this involved flat-fielding, sky-subtraction and wavelength-calibrating the spectra using Cu Ar arc exposures which bracketed each stellar exposure. The wavelengths and positions of features in arc spectra were fitted with low-order polynomials giving wavelength scales with root mean square residuals of less than 0.02 Å.

Individual orders of stellar echellograms were manipulated within DIPSO. First a search was made for radial velocity variations between individual exposures using a cross-correlation technique. Finding no significant variations, exposures where added. Radial velocities were determined from the shifts of unblended metal and hydrogen lines and then corrected to our local standard of rest (see Table I for details). Spectra were normalized by selecting continuum regions free from absorption lines and by fitting either low-order polynomials or cubic splines. The large wavelength extent of hydrogen and diffuse helium lines made it difficult to define the
echelle blaze profile and hence the continuum level in some orders. In these cases, fits to continuum regions of adjacent orders were averaged and then used to remove the blaze profile from the orders in question. The hydrogen and helium lines were then normalized at ±16 Å from the line center using low-order polynomials. Equivalent widths for the narrower orders. In these cases, fits to continuum regions of adjacent spectral profiles to the observed spectra. The choice of profile did not lead to significant differences and a Gaussian profile was therefore adopted. The methods used are described in Brown et al. (1986) where further details can be found. The equivalent width data are extensive and are not published here but can be obtained from the authors on request as conventional mail or by electronic mail (SPAN 1988: RJHMC or ESC).

3. METHOD OF ANALYSIS AND RESULTS

Subluminous and Population I stars cannot be differentiated using their atmospheric parameters alone as they occupy similar regions of the effective temperature–surface gravity plane (Ebbets & Savage 1982). It is also believed that the processing of CNO and s-process elements which occurs in the latter stages of stellar evolution may produce enhancements of these elements to near solar values (see Iben & Renzini 1983 for details). However, the complex pattern of abundances that develops in the latter stages of evolution and the fact that iron should not undergo processing provides a means whereby old subluminous Population II and young Population I stars can be distinguished using a quantitative abundance analysis.

In the following analysis, observed features have been compared with those produced from Local Thermodynamic Equilibrium (LTE) model atmospheres generated by the ATLAS 6 code of Kurucz (1979). Strömgren photometry of the program stars are given in Table 1, and were obtained for LS IV —12:111 and LS IV —4:01 from Kilkenny & Pauls (1990), for LB 3219 from Kilkenny (1987) and for LB 3193 from Kilkenny & Lydon (1986). The effective temperatures were determined from the reddening-free Strömgren color indices \( [c_1] = c_1 - 0.20 (b - y) \) and \( [u - b] = u_1 + 2.0 m_t \). The calibrations of Lester, Gray, & Kurucz (1986) were used and resulted in temperature estimates consistent to within \( 1000 \) K for all program stars, while an observational error of \( \pm 0.02 \) in an index would imply an error of approximately \( \pm 500 \) K. Due to the higher effective temperatures of LS 3219 and LS IV —12:111, the ionization equilibrium of Si III/Si IV was also available as another temperature indicator. For these two stars temperatures determined from ionization equilibrium were found to agree with those determined from Strömgren color indices to within \( 1000 \) K.

Surface gravities for the program stars were determined by comparing the observed hydrogen line profiles of He, Hδ, and Hγ with those generated using the line broadening theories of Vidal, Cooper, & Smith (1973). Normally the uncertainty in the fitting procedure implied an error of less than \( \pm 0.2 \) dex in the surface gravity estimates. For one star, LS IV —12:111, there was considerable emission in the center of the Balmer lines together with other emission features due to H II and He II at 4068.70 and 4287.33 Å, respectively. For this star, satisfactory and consistent fits could be made to the wings of all the observed hydrogen lines (see Fig. 1 which shows a fit for the Hγ line), although the uncertainty in this case may be somewhat larger.

Microturbulent velocities for LB 3219 and LS IV —12:111 were estimated by minimizing the standard error in the abundances of N II and O II lines, respectively. For LB 3193 and LS IV —4:01 the lack of sufficient lines of a given species made determining the microturbulent velocity by this method impossible. A microturbulent velocity of \( 15 \) km s\(^{-1}\) was assumed for these stars consistent with that found in other low-gravity stars (Underhill & Fahey 1973). However for these stars the abundance estimates of metals are insensitive to the value chosen for the microturbulence since the corresponding line strengths are small.

Table 2 lists the derived atmospheric parameters and chemical compositions, the numbers in brackets after each abundance refers to the number of lines used to derive the abundance. The quoted errors are discussed in detail in § 4.

4. DISCUSSION

4.1. Error Analysis

As well as the results for the four stars analyzed here, we also list in Table 2 abundances for two post–AGB candidate stars analyzed by Conlon et al. (1991), and for normal early-type stars (He: Wolf & Heasley 1985; C, O: Kane, McKeeith, & Dufton 1980; N: Dufton, Kane, & McKeeith 1981; Mg: Snijders & Lamers 1975; S: Peters 1976; Ca, Ti: Adelman 1973; Fe: Kodaira & Scholz 1970). As the reliability of these chemical compositions is critical to any discussion of the evolutionary status of the six stars, we have investigated this in some detail.

We first consider the effects of random errors in the equivalent width measurements. From the signal-to-noise ratios and profiles of the metal lines, the uncertainty of the equivalent width measurements was estimated for each spectrum. These estimates were then used to find the corresponding abundance error \( \Delta A \) for a typical line of each ionic species in each star. The uncertainty in the abundance due to random errors in the equivalent width measurements was then taken to be \( \Delta A_n = \Delta A/n^{1/2} \), where \( n \) is the number of reliable equivalent widths measured for each ionic species. This procedure was modified for those species for which only upper limits could be obtained for their abundances. Equivalent widths estimates were obtained for lines previously identified in Population I early type B-stars by fitting Gaussian profiles (with the correct width) at the appropriate wavelength. For LS IV —12:111 and LB 3219 line identifications were taken from \( \gamma \) Peg (Peters...
1976) and π Her (Peters & Aller 1970), while for LS IV —4°01 and LB 3193 line identifications were taken from π Cap (Adelman 1973). For any ionic species in a stellar spectrum a range of line strengths were found and these were used to deduce an upper limit to the equivalent widths. These upper limits were then used to constrain the corresponding metal abundances. For example, the Fe II lines in the spectrum of LB 3193 had equivalent widths estimates ranging from 8 to 13 mÅ, leading to a conservative estimate of 15 mÅ for an upper limit. This was then used to estimate the maximum iron abundance from Fe II lines that had previously provided reliable results in the analysis of the spectrum of π Cap (Adelman 1973). Four lines at 4178.87, 4233.17, 4351.76, and 4522.62 Å yielded the most useful upper limits of 6.44, 6.16, 6.24, and 6.44 dex, respectively, and implied an iron abundance of ≤6.5 dex in LB 3193. Figure 2 illustrates the discrepancy between the observed Fe spectra and the theoretical spectra generated assuming a normal Population I iron abundance for LS IV —12°111, LB 3219, LB 3193, and LS IV 4°01.

The uncertainty due to errors in the atmospheric parameters was deduced as follows. For each ionic species, the changes in the abundance due to typical errors of ±1000 K in effective temperature, ±0.2 dex in logarithmic surface gravity and ±5 km s⁻¹ in microturbulence were calculated. These estimates were then combined in quadrature to yield ΔA_m, which will be appropriate if the errors are not correlated. Note that this may not always be the case; if the effective temperature is underestimated, profile fitting of the hydrogen lines will normally lead to too low a gravity estimate. However the corresponding errors in the abundance will normally tend to cancel each other out and our procedure will probably lead to an overestimate of the error. The errors ΔA_w and ΔA_m should be independent and were therefore added in quadrature to give the errors listed in Table 2. For species where only upper limits were measured for the equivalent widths, the procedure outlined above should have allowed for any observational uncertainties, and in these cases only the error in the atmospheric parameters, ΔA_w, is listed.

The abundances of Table 2 are derived using the assumption of LTE. Due to the lack of non–LTE calculations for the range of atmospheric parameters found in the program stars, it is difficult to assess the reliability of this assumption. We have

TABLE 2
ATMOSPHERIC PARAMETERS AND MEAN LOGARITHMIC ABUNDANCES OF PROGRAM STARS TOGETHER WITH NORMAL B-STAR COMPOSITION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PHL 1580</th>
<th>LS IV —12°111</th>
<th>LB 3219</th>
<th>PHL 174</th>
<th>LB 3193</th>
<th>LS IV —4°01</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_eff(K)</td>
<td>24,000</td>
<td>23,750</td>
<td>21,250</td>
<td>18,000</td>
<td>13,000</td>
<td>11,000</td>
</tr>
<tr>
<td>log g</td>
<td>3.6</td>
<td>2.7</td>
<td>2.8</td>
<td>2.7</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>V_t</td>
<td>8</td>
<td>180</td>
<td>16</td>
<td>10</td>
<td>(10)</td>
<td>(15)</td>
</tr>
<tr>
<td>He</td>
<td>11.00 ± 0.02 (8)</td>
<td>11.10 ± 0.2 (9)</td>
<td>11.00 ± 0.3 (8)</td>
<td>10.80 ± 0.2 (8)</td>
<td>10.90 ± 0.3 (9)</td>
<td>10.40 ± 0.8 (5)</td>
</tr>
<tr>
<td>C</td>
<td>6.40 ± 0.2 (2)</td>
<td>6.70 ± 0.6 (1)</td>
<td>6.70 ± 0.3 (1)</td>
<td>≤6.10 ± 0.1</td>
<td>≤6.50 ± 0.1</td>
<td>≤7.20 ± 0.1</td>
</tr>
<tr>
<td>O</td>
<td>7.50 ± 0.2 (8)</td>
<td>7.80 ± 0.3 (3)</td>
<td>7.60 ± 0.1 (7)</td>
<td>6.80 ± 0.2 (7)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Ne</td>
<td>8.20 ± 0.3 (43)</td>
<td>8.80 ± 0.2 (36)</td>
<td>7.60 ± 0.2 (9)</td>
<td>7.90 ± 0.5 (5)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Mg</td>
<td>6.70 ± 0.2 (1)</td>
<td>7.30 ± 0.3 (1)</td>
<td>7.00 ± 0.2 (1)</td>
<td>6.20 ± 0.2 (1)</td>
<td>5.50 ± 0.2 (1)</td>
<td>5.60 ± 0.2 (1)</td>
</tr>
<tr>
<td>Al</td>
<td>6.00 ± 0.2 (1)</td>
<td>≤5.40 ± 0.4</td>
<td>≤5.20 ± 0.10 ≤5.70 ± 0.1</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>7.00 ± 0.6 (7)</td>
<td>7.60 ± 0.4 (5)</td>
<td>6.60 ± 0.2 (7)</td>
<td>6.50 ± 0.4 (3)</td>
<td>5.40 ± 0.4 (2)</td>
<td>5.50 ± 0.1 (2)</td>
</tr>
<tr>
<td>S</td>
<td>6.70 ± 0.2 (4)</td>
<td>6.60 ± 0.1 (4)</td>
<td>5.90 ± 0.2 (1)</td>
<td>≤5.60 ± 0.1</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Ca</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>3.70 ± 0.4 (1)</td>
<td>3.30 (1)</td>
<td>6.20</td>
</tr>
<tr>
<td>Ti</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>6.20</td>
</tr>
<tr>
<td>Fe</td>
<td>≤6.80 ± 0.2</td>
<td>≤6.70 ± 0.2</td>
<td>≤6.70 ± 0.10 ≤7.20 ± 0.1</td>
<td>≤6.50 ± 0.2</td>
<td>≤5.90 ± 0.2</td>
<td>7.50</td>
</tr>
</tbody>
</table>

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therefore undertaken a comparison of the equivalent widths of features in the spectra of program stars with those of Population I supergiants with similar atmospheric parameters. The comparison stars were selected by dividing the program stars into two groups based on their effective temperatures, with LS IV — 12:111 and LB 3219 being the hotter group and LB 3193 and LS IV — 4:01 the cooler. For each group a Population I supergiant was selected from an atlas of supergiants (Lennon, Dufon, & Fitzsimmons 1991) such that their Strömgren reddening free indices [c_j] (and hence their effective temperatures) were intermediate between those of the program stars in each group. The hydrogen profiles of the comparison stars were then compared with the stars in each group to check that their surface gravities were similar. The comparison stars HD 42087 (B2.5 Ib) and HD 35600 (B9 III) were selected for the hotter and cooler stars, respectively. Table 3 contains a list of measured equivalent widths for a number of species in both our targets and the standard stars; where no equivalent widths are given only upper limits could be measured.

The comparison of the equivalent widths for the cooler program stars with those of HD 35600 are all consistent with the extreme underabundances for the former deduced from the LTE model atmosphere calculations. Of particular interest is the large discrepancy in the Fe II equivalent widths, where only upper limits could be obtained in the program stars while strong lines are evident in the spectra of HD 35600.

For the hotter program stars relatively small changes in effective temperature, lead to large variations in the line strengths. These temperature effects are illustrated in the observational study of Didelon (1982), where equivalent width measurements of species in B-type stars were plotted against the stars MK classification. The strength of species such as O II, Si III, and Mg II are very sensitive to temperature over the range B1 to B3 which will complicate the comparison, particularly for LS IV — 12:111, which has a [c_j] significantly different to that of HD 42087 (see Table 3). However in general, the equivalent width comparison supports the results of the abundance analysis for these hotter stars. For example, while there is a large difference in the C II line strengths, the N II values are similar; and reflects the large carbon underabundances and relatively normal nitrogen abundance found for the program stars.

Hence we conclude that the abundance anomalies found in the cooler stars are certainly real. For the hotter stars, the position is less clear and non-LTE effects could be significant. However although they might affect the magnitude of the

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abundance peculiarities, they do not appear sufficient to eliminate them. For the other two stars in Table 2, PHL 1580 and PHL 174, a detailed discussion of non-LTE effects can be found in Conlon et al. (1991), who again conclude that they were not large enough to explain the abundance peculiarities found in these stars.

Having demonstrated that the effects of non-LTE are probably not a significant source of error, further discussion of abundances will be confined to the results as they appear in Table 2. In Figure 3, the abundances are plotted against atomic species. Usually when considering the evolutionary state of a star, abundances are quoted with respect to iron and normalised to the solar values. In the case of stars considered here, only upper limits to the iron abundance could be obtained, so abundances are measured with respect to hydrogen and normalised using the B-type stellar values listed in Table 2. Figure 3 clearly shows that the stars do not have a normal Population I composition. Deficiencies of different degrees are observed in all six objects for all elements heavier than helium, with the exception of LS IV −12°111 where, N, O, Mg, and Si are all approximately normal. In all the stars, except PHL 174, iron depletions determined from upper limits are greater than 1.3 dex. The effective temperature of PHL 174 is such that both the Fe II and Fe III spectra are weak so it is more difficult to set a meaningful upper limit; however even for this star iron appears depleted. A common feature among all the stars is a severe underabundance of carbon ranging from 1.0 to 2.0 dex below the normal B-star value. In addition it appears that the cooler stars may exhibit larger depletions of the heavier species.

### 4.2. Evolutionary Status

We now consider the evolutionary status of our targets and, as they were originally selected as candidate young hydrogen burning B-type stars, this possibility is considered first. The evolutionary tracks of Maeder & Maynet (1988) would then imply masses ranging from 12 $M_\odot$ to 40 $M_\odot$, while their derived effective temperature and gravities are consistent with a location on the blue supergiant branch (Meader 1987). For

![Figure 3](image-url)
the four stars in which CNO abundances can be measured, the C/N and O/N ratios suggest that the products of CNO equilibration reactions are visible at the photosphere. However the calculations of Maeder suggest that for stars of 60 $M_\odot$ or less, such processed material should only be mixed to the surface on the red supergiant branch. Thus our targets appear to be at too early an evolutionary stage for this mixing to occur and moreover, the heavy element deficiencies (and in particular that of iron) provide strong evidence against a Population I nature.

One remaining possibility for their interpretation as young hydrogen-burning stars is that they formed far out in the halo and their anomalous atmospheric abundances reflect the initial composition of a metal deficient progenitor medium. However, previous studies of early type B-stars in the halo (see Conlon et al. 1991, all our targets show severe carbon depletions. This is would be enhanced with respect to solar values, in agreement with the four-supergiants that should have been produced by the third dredge-up. Two possibilities exist which may explain these results. One is that the program stars have undergone the third dredge-up. However unlike the cooler objects discussed by Trams et al. (1991) have undertaken simple calculations of the effects of mixing on the surface composition in PAGB stars and find that there are no significant changes in the carbon and nitrogen abundances over a PAGB lifetime. Hence, irrespective of how these stars originally came to be carbon-poor, there should exist both precursors and successors for our objects on the PAGB. Although many of the cooler supergiants so far analyzed show carbon to hydrogen abundances that are approximately solar, two stars HR 4912 (Lambert et al. 1988) and HR 7671 (Lambert & Saffer 1984) show carbon depletions of more than 1.0 dex. It thus seems likely that these two stars could be the natural precursors to those discussed here. As pointed out previously SMC-SMP 28 might be a possible successor to our program stars, although if our stars have undergone HBB, it has not been as efficient as in this planetary nebula. Another candidate is the halo planetary nebula DDDM-1 for which (Clegg, Peimbert, & Torres-Peimbert 1987) found a carbon depletion of 1.5 dex. It would, therefore, appear that our stars may complete the carbon-poor link between cool supergiants such as HR 4912 and HR 7671 and carbon-poor planetary nebulae such as DDDM-1.

As mentioned previously, one of the program stars, LS IV −12:111, has an infrared excess from its association with an IRAS point source. In addition, Balmer emission and forbidden lines of [N II], [O III], and [S III] are observed in the optical spectra. Hence the central star appears to have started to photoionize the surrounding nebula, confirming the post-

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AGB nature of this object. Further observations of this interesting object are being obtained to investigate the nature of its circumstellar material.

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