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New identifications for blue objects towards the Galactic center: post-AGB stars, Be/disk stars and others*

K.A. Venn[1,2,3], **S.J. Smartt**[4,5], **D.J. Lennon**[2], **and P.L. Dufton**[4]

[1] Macalester College, Department of Physics and Astronomy, 1600 Grand Ave., St. Paul, MN, 55105, USA
[2] Universitäts Sternwarte München, Scheinerstrasse 1, D-81679 München, Germany
[3] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, Postfach 1523, D-85740 Garching, Germany
[4] Queens University Belfast, Department of Pure and Applied Physics, Belfast BT7 1NN, Northern Ireland
[5] Isaac Newton Group of Telescopes, Apartado de Correos 368, E-38700, Santa Cruz de la La Palma, Canary Islands, Spain

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Abstract. As part of a programme to investigate spatial variations in the Galactic chemical composition, we have been searching for normal B-type stars and A-type supergiants near the Galactic center. During this search we have found eleven peculiar stars, and in some cases performed detailed abundance analyses of them which suggest that they may be at a post-AGB evolutionary stage.

The A-type post-AGB candidates show [Fe/H]=−1.0 to −2.0, and [O/Fe]∼+1.4, typical of the post-AGB abundance patterns discussed in the literature. One star, LS 3591 (=SAO 243756), has also been examined recently by Oudmaijer (1996); its spectrum appears to be changing very rapidly, which may indicate erratic mass loss or the incipient formation of a planetary nebula.

A B-type post-AGB candidate, LS 4950, has a similar spectrum to a well studied post-AGB star, LSIV -12 111. However, an examination of the line strengths and elemental abundances of LS 4950 show that it is peculiar for both a Population II, post-AGB, B-type star and for a normal, Population I, B-type supergiant. Two other B-type stars, LS 4825 and LS 5112, are either post-AGB stars near the Galactic center or normal B-type supergiants lying well beyond the Galactic center. In addition, several Be-type stars have been newly (or more clearly) identified from our spectra.

Key words: stars: abundances – stars: emission-line, Be – stars: fundamental parameters – stars: AGB and post-AGB – stars: supergiants – Galaxy: centre

Send offprint requests to: K.A. Venn, Macalester College, Department of Physics and Astronomy, 1600 Grand Ave., St. Paul, MN, 55105, USA

* Tables 12, 13, 14, 15 and Appendices A,B are only available in electronic form at CDS via anonymous ftp to: cdsarc.u-strasbg.fr(130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

1. Introduction

While abundance gradients in our Galaxy have been found previously from observations of H II regions (see for example Shaver et al. 1983), early attempts to confirm these results using B-stars in clusters at galactocentric distance 6 $\leq$ R_g $\leq$ 14 kpc proved either negative (Gehren et al. 1985, Fitzsimmons et al. 1992, Kaufer et al. 1994) or highly scattered (Lennon et al. 1990, Rolleston et al. 1994). Recently, we have analysed a homogeneous group of stars in the anticenter direction and have found both metal deficient and normal stars (Smartt 1996), with some evidence for a correlation with the spiral structure. We are currently extending these studies towards the Galactic center in order to investigate both large and small spatial variations. Indeed Smartt & Rolleston (1997) have recently found an abundance gradient for oxygen compatible with H II region studies.

Only a few recent analyses have examined the abundances in stars and emission nebulae towards the Galactic center. Simpson et al. (1995) observed the far infra-red emission lines from H II regions which showed some evidence for a flat abundance gradient in the solar neighborhood, but an enhancement (of 0.3 dex) for R_g $\leq$ 5 kpc. However Afflerbach, Churchwell & Werner (1997) found that their infra-red observations for nitrogen, oxygen and sulphur were satisfactorily fitted by a simple linear relationship. Smartt et al. (1997) have found two B-supergiants between ∼3 to 5 kpc from the Galactic center that have solar-like compositions, together with two that are slightly metal enriched. A red supergiant near the Galactic center, IRS 7, has also been found to have near solar abundances by Sellgren et al. (1997), but the object is most likely a member of the Bulge population rather than the disk.

Further studies of stars near the Galactic center are needed to constrain the Galactic chemical evolution models. However, it is difficult to identify such targets primarily due to the large interstellar extinction. We have used the catalogues of Stephenson & Sanduleak (1971), Reed (1993), and Sembach et al. (1993), to search for blue objects with galactic latitudes $4 \leq l \leq 10^o$, where the interstellar extinction although significant is not prohibitive; if normal stars, they would then have distances from the galactic plane of upto 1 kpc. Solar neighborhood studies (e.g., Conlon et al. 1993 and references therein) imply that they would have been ejected from the galactic disk (possibly via close gravitational encounters with stellar clusters), and hence that their chemical compositions would reflect that of the disk.

During our search for such young objects, we have identified a number of peculiar objects including A- and B-type post-AGB candidates, Be and shell stars. Additionally two B-type stars have been found that are either very distant supergiants beyond the Galactic center or post-AGB stars. In this paper, we discuss, and in some cases analyse, the spectrum of these peculiar targets; the analysis of the corresponding normal star data set can be found in Smartt et al. (1998).

2. Observations

The observational data include spectra of various dispersions obtained at three different observing sites; the AAT, SAAO, and ESO.

2.1. Anglo-Australian Telescope

Moderate dispersion spectra were obtained of 12 B-type stars taken from the catalogue of Reed (1993). They were selected so that their magnitudes and colours were compatible with them being main sequence stars near the Galactic center. The Anglo-Australian Telescope was used in August 1994 with the RGO spectrograph, the 1200B diffraction grating, 82 cm camera and a Tektronix CCD as the detector. Each exposure gave a wavelength coverage of about 240 Å with a spectral resolution of approximately 0.7 Å (FWHM, as measured from the arc spectra). Three grating positions with central wavelengths of 4020 Å (position I), 4580 Å (position II) and 4340 Å (position III) were available. Since the primary motivation of these observations was to identify normal stars, wavelength coverage tended to be incomplete for targets where the initial exposure showed strong spectral peculiarities. Table 1 lists details of the targets and the grating positions at which observations were taken.

Image reduction was performed using the IRAF (Image Reduction and Analysis Facility) package (Massey 1989; Shames & Tody 1986). The methods were identical to those used by Kendall et al. (1996) for other data obtained during the same observing run. Briefly, frames were debiased, flat-fielded, and cosmic ray hits were removed automatically. Spectra were then extracted, sky-subtracted, and wavelength calibrated. The spectra were output to the Starlink package DIPSO (Howarth et al. 1993) and normalised by fitting a low order polynomial to the continuum.

2.2. South African Astronomical Observatory

For some B-type targets, it was not possible to unambiguously classify them as normal or peculiar from the AAO spectra. Hence additional observations of the Hα line were taken with the 1.9m telescope at the South African Astronomical Observatory between 6 – 13 September 1994. The Image Tube Spectrograph (with the RPCS detector and the 30Å/mm grating) was used giving a spectral resolution of $\sim$ 2.4Å FWHM. The observations where divided up into frames of approximately 1200 seconds and bracketed by exposures of Cu-Ar calibration arcs. Reduction was performed using the STARLINK package FIGARO with sky subtraction, removal of pixel-to-pixel variations, and wavelength calibration methods similar to those discussed in Hambly et al. (1996). The spectra have a relatively low signal-to-noise ratio, typically $\sim$20, but are adequate for identifying stars with Hα emission.

Table 1. Details of the stellar targets

Star	V	$B-V$	$U-B$	Gratings	Hα
LS 3592	11.81	0.17	-0.67	I, III	No
LS 4039	11.94	0.42	-0.52	I, II, III	Yes
LS 4419	11.08	0.08	-0.65	I	No
LS 4530	11.90	0.21	-0.70	I, III	No
LS 4784	11.55	0.09	-0.60	I	No
LS 4825	11.99	0.05	-0.73	I, II, III	Yes
LS 4950	12.13	0.25	-0.67	I, II, III	Yes
LS 5105	11.84	0.25	-0.50	I, II, III	Yes
LS 5112	11.93	0.45	-0.44	I	No
LS 5123	13.18	0.26	-0.62	I	Yes
LS 5127	11.96	0.15	-0.55	I	No
LS 5130	12.09	0.24	-0.53	I, II, III	Yes
LS 3859	9.75	0.22	-0.42	B, R	Yes
LS 3312	9.27	0.32	-0.02	B, R	Yes
LS 3290	10.3			B, R	Yes
LS 3591	9.79	0.32	-0.26	B, R	Yes
LS 3593	9.49	0.21	-0.19	B, R	Yes
LS 4312	8.40	0.98	0.83	B, R	Yes
LS 3340	8.6	1.1		B, R	Yes
LS 5107	9.85	0.89	0.11	R	Yes

Grating positions for AAT Data: I = λ_c4020, II = λ_c4580, III = λ_c4340, with complementary data for Hα from SAAO.
Grating positions for ESO Data: B = λ_c4000, R = λ_c7000

2.3. European Southern Observatory

For the AF-type supergiant candidates, targets were again taken from the Reed (1993) catalogue, and observed at high resolution using CASPEC at the ESO 3.6m telescope between 7 – 9 July 1995. Two wavelength set-ups were available. In the blue, the central wavelength was approximately 4500 Å, with a wavelength coverage of 1300 Å and resolution $\sim$0.15 Å/pix. In the red, the central wavelength was approximately 7000 Å, with a wavelength coverage of 2400 Å and resolution $\sim$0.2 Å/pix. The data were reduced using standard IRAF packages (in a similar manner to that described by Venn 1995b, and as briefly described above for the B-type stars). Resultant signal-to-noise ratios were typically $\sim$80.

Table 2. Peculiar Blue Stars towards the Galactic center

Star	Name	l	b	Comments
B-dwarfs:				
LS 4039	CD-24 13249	0	+7.6	normal spectrum; post-AGB or distant B2 III?
LS 4825	CD-30 15464	2	−6.6	normal spectrum; post-AGB or very distant B1 Ib?
LS 4950		3	−7.3	peculiar; strong Balmer line emission, and odd abundances
LS 5105		16	−4.8	post-AGB?; spectrum has very few and weak lines
LS 5112		17	−5.4	normal spectrum; post-AGB or very distant B2.5 Ia?
LS 5123		13	−7.9	Be
A-supergiants:				
LS 3591	CD−59 6142	327	−7.5	post-AGB (Reed: A0 Ia/B8 Ia/A3 Iab/B5p)
LS 3593	CD−54 6746	330	−3.7	post-AGB (Reed: A0 Ib/B8 Iab)
LS 3312	HD 133901	324	+6.1	Be (Reed: B8 Iab/A3 Iab/A5 Ib)
LS 3859	HD 322422	345	+1.6	Be (Reed: A1 Iab/B0.5 III)
LS 5107		19	−3.7	Be (Reed: A3 Ia/B9 Ia)

Spectral types listed from the Reed (1993) catalogue for the A-type supergiant target stars.

3. Analysis and discussion

The AAT blue spectra of six stars from the B-type sample indicate that they are normal, (near) main-sequence B-type stars; these objects have been re-observed at higher spectral dispersion for abundance analyses. In addition, preliminary analysis of the CASPEC spectra of three of the A-type supergiants has shown that those stars have near solar abundances, consistent with normal, Population I stars. A detailed discussion of these apparently normal targets will be presented by Smartt et al. (1998).

The spectra of another six B-type objects are either peculiar or their status is ambiguous. Additionally, five of the candidate A-type supergiants have anomalous spectra, or a preliminary model atmospheres analysis has resulted in very non-solar abundances. These eleven stars are listed in Table 2, and provide the main focus of this paper.

On the basis of our analyses, it was possible to tentatively assign each star to a possible evolutionary status. In order to clarify the discussion, we have grouped the target stars by these assignments.

3.1. A-type post-AGB candidates

LS 3591, 3593 (CD −59 6142, CD −54 6746) both look like post-AGB stars by the weakness of their metal absorption line spectrums; see Fig. 1 for LS 3591 and the normal Galactic star HD 13476 which has similar atmospheric parameters.

A recent paper by Oudmaijer (1996; previously unknown to us) of IRAS point sources also finds that LS 3591 (=SAO 243756) is a post-AGB star from spectral and photometric analyses. Oudmaijer notes that the Balmer lines are in emission, and Hβ appears to be strengthening from a comparison with an earlier spectral description by Kilkenny & Hill (1975a,b). Our spectrum also shows strong Hβ and Hα emission, as well as significant emission components in Hγ and Hδ (but not Hϵ or H8) and several He I and Fe II lines; see Fig. 2. The emission component of Hβ now has an equivalent width $>$1.0 Å, whereas Oudmaijer reported a width of only $\sim$0.4 Å. Clearly this star's spectrum has changed.

Such spectral changes, as the presence and strengthening of the emission lines, have been interpreted in three different ways. Smith & Lambert (1994) and Parthasarathy et al. (1993) first suggested emission line variations may indicate the incipient formation of a planetary nebula (=PNe). Oudmaijer questions this interpretation because too many stars are being found with spectral variations for the predicted number of PNe and their lifetimes. Instead, Oudmaijer suggests that mass loss may behave erratically in the post-AGB stars, with an outburst responsible for the emission line spectrum. Post-AGB stars are also typically photometrically variable. Smith & Lambert's photometric monitoring of LS II+34 26 over a four month period found significant line profile, equivalent width, and radial velocity variations (at least in the absorption lines), and they note that the changes could be explained by erratic mass-loss episodes. But, the variations may also be due to orbital motions if the star is a binary. Binary orbital motions are a very real possibility since van Winckel et al. (1995) report evidence that the five known extremely iron deficient post-AGB stars are all binaries. Therefore, more monitoring is needed on these stars to distinguish PNe formation, erratic mass loss episodes, and binary motion.

Regardless of the spectral variations, and assuming that the symmetric photospheric absorption lines of these stars can be analysed with classical assumptions (i.e., hydrostatic and local thermodynamic equilibrium, and plane-parallel geometry – as though examining a snapshot of the star in time), then we have analysed these two post-AGB candidate stars using the meth-

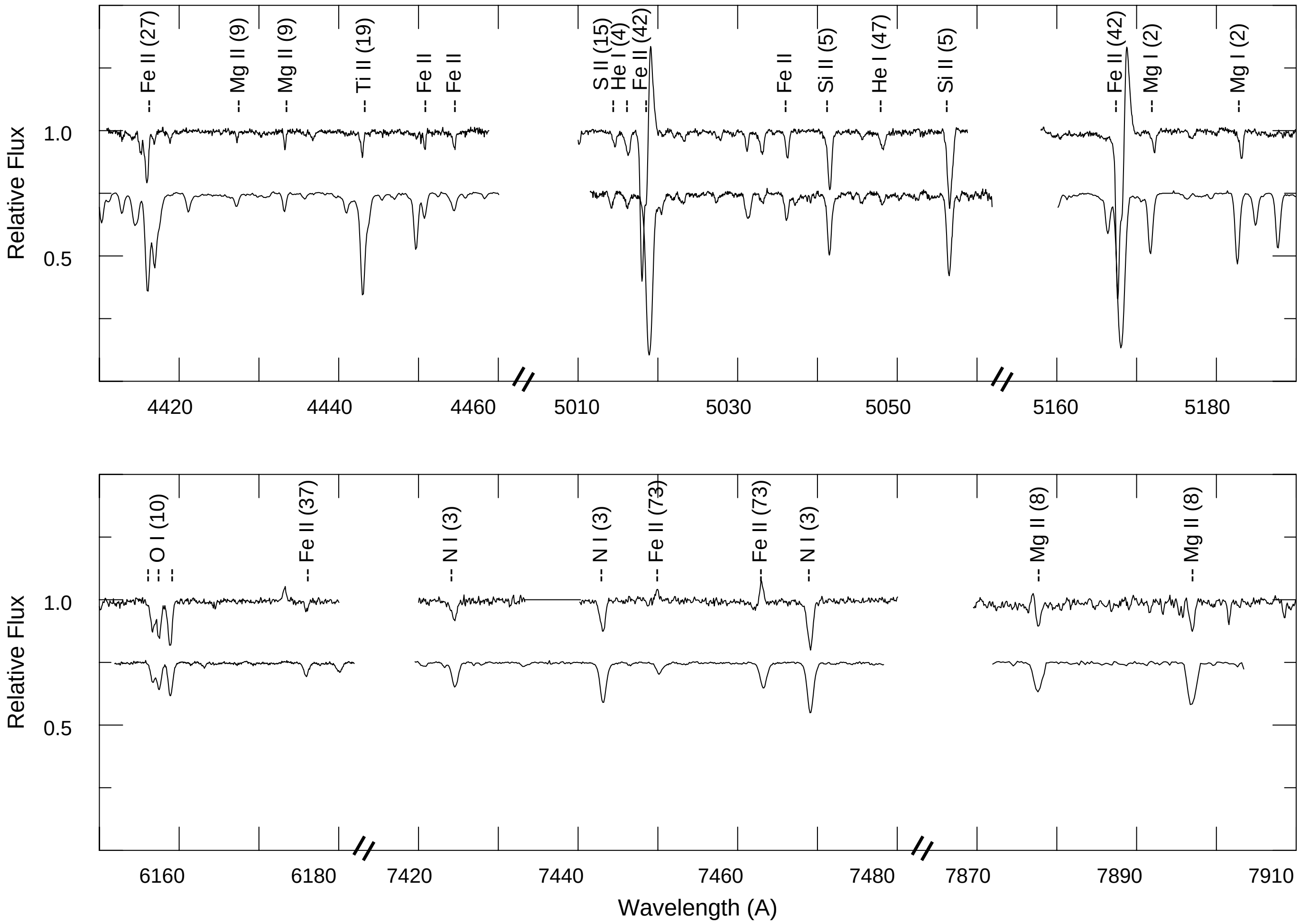

Fig. 1. Sections of the metal line spectrum of the post-AGB candidate, LS 3951, and a standard Galactic A-type supergiant, HD 13476 (from Venn 1995a,b) . Small differences in the atmospheric parameters are responsible for some spectral differences, yet the metal-poor nature of LS 3951 is clear by comparison of the Fe II and Ti II lines. In contrast, the similarity in line strengths of the N I and O I lines support that LS 3951 is N and O enriched.

Table 3. Atmospheric Parameters for the post-AGB A-type stars

Elem	LS 3591	LS 3593
$T_{\rm eff}$ (K)	8500 ± 200	9300 ± 200
$log\,$g	0.9 ± 0.2	1.7 ± 0.2
ξ (km s^{-1})	7 ± 1	5 ± 1

ods detailed by Venn (1995 a,b) for normal A-type supergiants. Kurucz ATLAS9 models have been adopted and atmospheric parameters ($T_{\rm eff}$ and $log\,$g) are found from the Hγ and Mg I/II ionization equilibrium (c.f., Venn 1995b). Two to three lines each of Mg I and Mg II were measured in both stars (see Appendix A, electronic publication only), and are the same lines as those shown by Venn (1995b) to yield reliable abundances. Atmospheric parameters for LS 3591 and LS 3593 are listed in Table 3.

Uncertainties in the atmospheric parameters were determined by examining the effects of small changes on the Hγ line profile fits and the effects on the atmospheric parameters if Mg II = Mg I $\pm$0.2 dex. Also, NLTE effects on the Mg line abundances were examined; for most lines in this analysis the NLTE corrections are $\leq$0.1 dex. Microturbulence (ξ) has been determined by forcing no relationship between the line strengths and abundances of Ti II, Cr II, and/or Fe II (up to a line strength of $\sim$175 mÅ). Galactic abundances were adopted when converging the ATLAS9 models; test calculations at SMC-like metallicities show only very small effects for some elements, where Δlog(X/H)$\leq$0.1 dex. Finally, any lines with emission components were excluded from this analysis since hydrodynamic effects, stellar wind effects, and spherical symmetry are neglected.

The parameters in Table 3 are somewhat cooler and less dense than the parameters adopted by Oudmaijer for his analysis, yet still in good agreement considering he fit optical and near-IR photometry to older Kurucz models (and with some difficulties in fitting the IR colours). The chemical abundances for the iron-group elements are $\sim$1.0 dex less than solar based

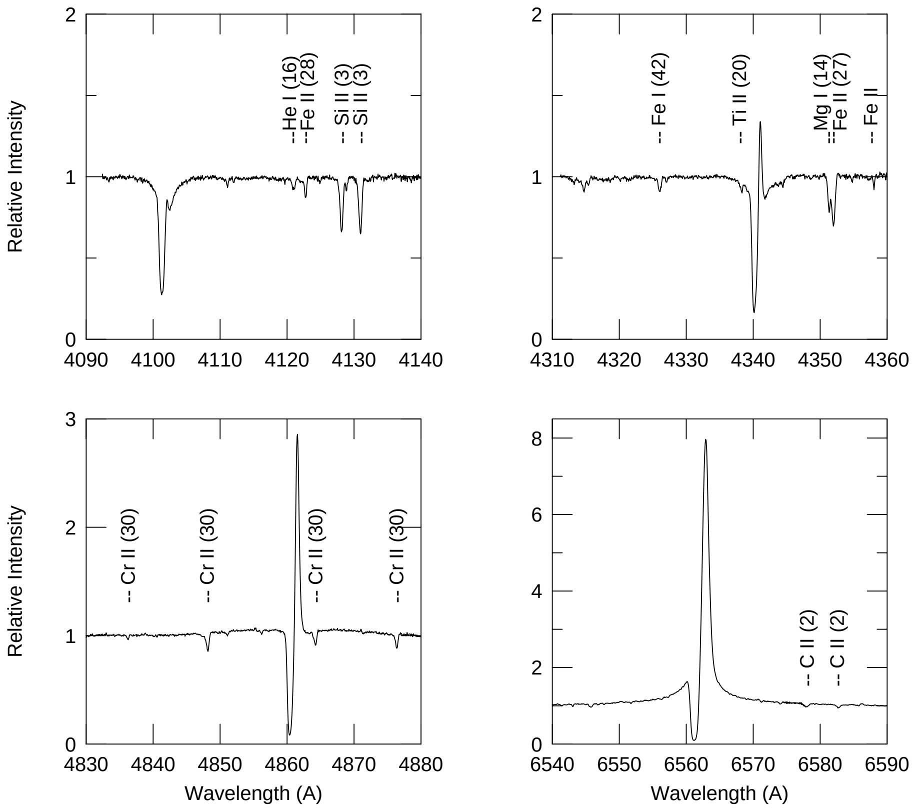

Fig. 2. Balmer line profiles for LS 3591, which show clear P Cyg-type structures.

Table 4. Abundances for the post-AGB A-type stars

Elem	LS 3591			LS 3593		
	log (X/H)	(#)	[X]	log (X/H)	(#)	[X]
N I[a]	8.0 ±0.1	(5)	+0.0	7.2 ±0.2	(4)	−0.8
O I	9.3 ±0.0	(3)	+0.4	8.3 ±0.0	(3)	−0.6
Mg I/II	7.1 ±0.1	(3/3)	−0.5	6.1 ±0.1	(2/3)	−1.1
Si II	7.6 ±0.1	(5)	+0.1	6.3 ±0.2	(7)	−1.2
Ti II	3.8 ±0.2	(11)	−1.2	...		...
Cr II	5.0 ±0.2	(17)	−0.7	...		...
Fe II	6.5 ±0.2	(12)	−1.0	5.5 ±0.2	(21)	−2.0
Fe I[b]	6.9 ±0.1	(7)	−0.6	...		...
Sr II	1.5	(1)	−1.4	...		...

The number of spectral lines averaged shown by (#).
[X] = log(X/H) − log(X/H)$_\odot$, where solar values are from Anders & Grevesse (1989).
[a] NLTE N abundances are listed in this table, where the NLTE correction log(N/H)$_{\rm NLTE}$− log(N/H)$_{\rm LTE}$ $\sim -0.8/-0.4$ for LS 3591/LS 3593.
[b] Fe I abundances are known to suffer from NLTE effects, which are not accounted for in this analysis.

on several weak and unblended optical spectral lines; see Table 4. Oxygen and nitrogen are not depleted though, based on abundances from the O I λ6158 multiplet and the N I λ7440 and 8220 multiplets. Thus, [O/Fe]=+1.4, which is typical of the post-AGB abundance pattern (e.g., van Winckel et al. 1996, Waelkens et al. 1991, Trams et al. 1991, also see the discussion by Venn & Lambert 1990). Abundance uncertainties due to the atmospheric parameters are listed in Table 5; uncertainties due to microturbulence ($\Delta\xi$=±1 km s^{-1}) result in $\Delta\log\epsilon$ $\leq$0.05 dex, throughout.

Atmospheric parameters for LS 3593 are listed in Table 3, while abundances and their uncertainties are in Tables 4 and 5. We find iron is underabundant by 1.9 dex, while O and N (same multiplets as above) show milder, but significant, underabundances. Again, [O/Fe]=+1.4, typical of the post-AGB abundance pattern. This star is also remarkable because of its near zero rotational velocity, so that even Hα is easily resolved into a Doppler core and Stark broadened wings; see Fig. 3.

Finally, we note that LS 3591's spectrum is remarkably similar to that of an LBV, with P Cyg profiles present for some H,

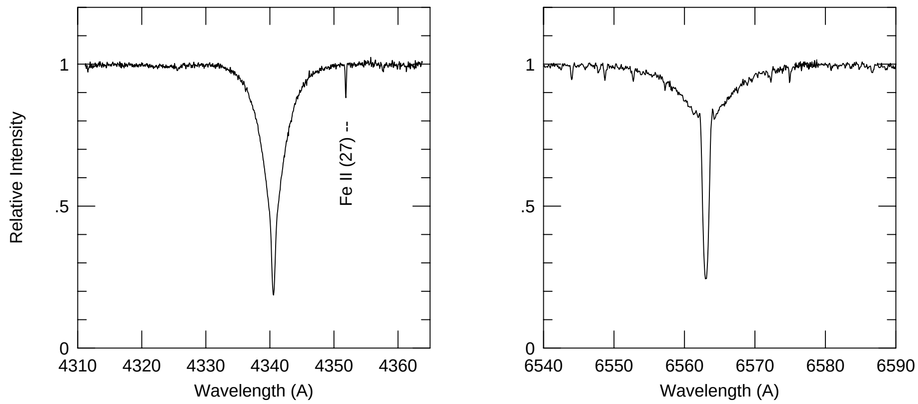

Fig. 3. Balmer line profiles for LS 3593, which resemble those of a normal A-type supergiant (i.e., no P Cyg profiles). The Doppler core of Hα supports that this star has a near zero rotational velocity typical of post-AGB stars.

Table 5. Abundance Uncertainties for post-AGB A-Supergiants

Elem	LS 3591 $\Delta T_{\rm eff}$ = ±200 K	Δlog g = ∓0.2	LS 3593 $\Delta T_{\rm eff}$ = ±200 K	Δlog g = ∓0.2
N I[a]	±0.10	±0.20	±0.06	±0.09
O I	±0.12	±0.11	±0.04	±0.06
Mg I	±0.29	±0.28	±0.19	±0.19
Mg II	±0.03	±0.05	0.00	±0.01
Si II	∓0.01	±0.03	∓0.04	∓0.03
Ti II	±0.24	±0.13	...	...
Cr II	±0.10	±0.05	...	...
Fe II	±0.07	±0.04	±0.04	±0.01
Fe I[b]	±0.28	±0.25	...	...
Sr II	±0.31	±0.25	...	...

[a] ΔN are for the NLTE analysis (although $\Delta N_{\rm LTE}$ are very similar).
[b] Fe I NLTE effects neglected here, yet expected.

He, and Fe II lines (see Figs. 1 and 2). The post-AGB stars do have similar atmospheric parameters as LBVs, and both classes of objects are undergoing rapid evolution.

It is interesting to speculate as to whether the underlying physics for the instabilities in post-AGB stellar atmospheres could be similar to those in LBV outbursts. The primary differences between these stars would appear to be only mass and metallicity, but obviously this is a fundamental parameter affecting core mass, central luminosity, nuclear burning rates, and thus the interior structure and opacities. Some theories for LBV outbursts depend on these interior quantities, such that any fundamental physical similarities between LBVs and post-AGB stars would be an interesting contrast on those theories. The other post-AGB star, LS 3593, does not have any lines in emission.

3.2. B-type Post-AGB candidates

LS 4950: This star shows relatively narrow metal absorption lines (approximately 1Å FWHM, measured from the unblended features) as illustrated in Fig. 4, although they are resolved by the spectrograph (FWHM≃0.7Å; see Sect. 2). There is clear evidence of emission in the Balmer lines – visible in the cores of Hϵ & Hδ, and much stronger in Hγ. Furthermore, the Hα emission profile shown in Fig. 5 is extremely strong. The similarity of the LS 4950 Balmer line spectrum to that of LSIV −12 111 (a confirmed post-AGB star discussed by Conlon et al. 1993 and McCausland et al. 1992) is striking and might, initially, prompt the conclusion that this star is an evolved low-mass object. However, Fig. 4 shows that there are many similarities with normal B-type supergiants also. For example, the width of the wings of the Balmer lines and the strength of the Si III/Si IV lines are consistent with a normal spectral type of B1.5 Ia, and we note that extremely luminous B-type supergiants can have filled-in Balmer lines or even the whole line in emission like the post-AGB stars.

The high-quality and wavelength range of the spectra of LS 4950 permit an LTE model atmospheres – LTE line formation analysis. Line data for LS 4950 is listed in Appendix B (electronic publication only). Kurucz ATLAS9 models have been adopted and atmospheric parameters (log g and $T_{\rm eff}$) were determined by fitting the wings of Hδ and Hϵ while simultaneously satisfying the Si III/Si IV ionization balance (additional details in Smartt et al. 1996, 1997). The wings of both Hδ and Hϵ are relatively unaffected by the core emission, in contrast to the Hγ line where the strong emission precludes its use. The helium abundance was determined by fitting the lines of He I 4009, 4026 and 4387Å with a microturbulence deduced from ensuring that the abundances from the O II lines were independent of line strength. McErlean et al. (1997) have suggested that helium fractions determined from the 4387Å line should be the most reliable, but we find consistent results for all three (only the He I 4471Å line gives a lower abundance, which we suspect is due to a neglected emission component). We have also analysed a normal Galactic B-type supergiant, HD 14956, in order that we may improve the abundance estimates of LS 4950 from a differential analysis. Exactly the same analysis method was employed to determine the atmospheric parameters of HD 14956, in particular the same diagnostic lines were employed. Line strengths were taken from Lennon et al. (1992), and the final atmospheric parameters determined here for LS 4950 and HD 14956 are listed in Table 6. The very high values of microturbulence reported here are characteristic of LTE analyses of B-type supergiant atmospheres (e.g Gies & Lambert 1992, Van Helden 1972, Smartt et al. 1997). These supersonic values are difficult to interpret in

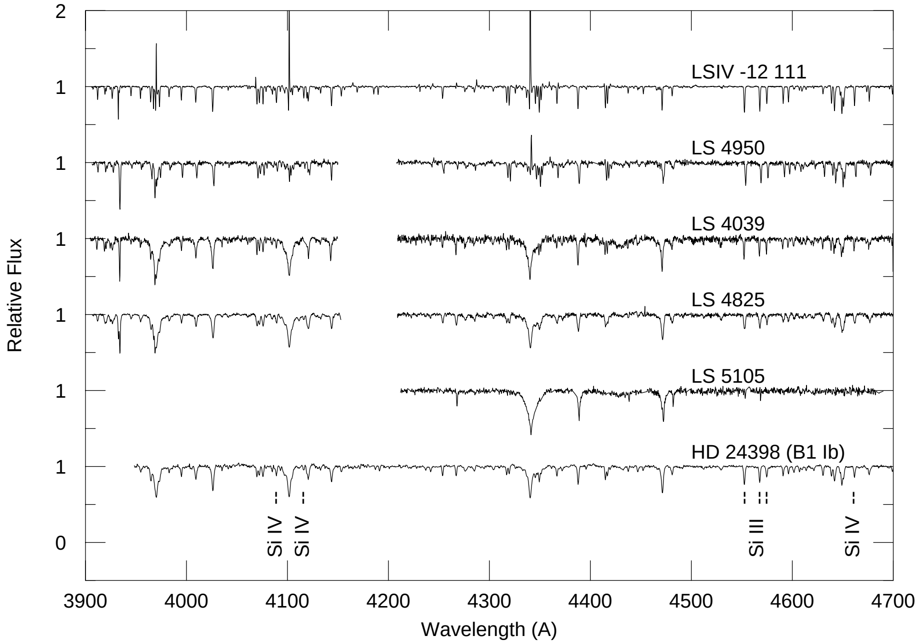

Fig. 4. Spectra of B-stars that are post-AGB candidates or possibly very distant, normal B-type supergiants. Spectra of a normal Galactic B-type supergiant (HD 24398) is included for comparison, as well as spectra of a confirmed post-AGB B-type star (LSIV −12 111). Si III/IV lines have been identified; additional line identifications available from Lennon et al. (1992).

Table 6. Atmospheric Parameters for the Peculiar B-type star, LS 4950

	LS 4950	HD 14956
$T_{\rm eff}$ (K)	18500 ±1000	19000 ±1000
log g (dex)	2.2 ±0.2	2.2 ±0.2
log(He/H) (dex)	11.20 ±0.17	11.08 ±0.15
ξ (km s^{-1})	20	30

Table 7. Differential Abundances for the Peculiar B-type star, LS 4950

Elem	log(X/H)− log(X/H)$_{\rm B\,I}$	log(X/H)− log(X/H)$_\odot$	log(X/H)− log(X/H)$_{\rm pAGB}$	#
C II	−0.2	−0.6	+0.4	(1)
N II	−0.5 ±0.1	−0.8	−0.7	(4)
O II	+0.6 ±0.1	+0.3	+0.5	(11)
Mg II	−0.1	−0.1	+0.1	(1)
Si III	+0.2 ±0.1	+0.2	+0.3	(3)
Si IV	+0.1	+0.1	+0.2	(1)
Fe III	−0.1	−0.1	+0.5	(1)

Differential abundances have been determined relative to the Galactic standard B2 Ia star, HD 14956 (column 1), the standard solar composition (column 2), and the confirmed post-AGB star, LSIV −12 111 (column 3); see text.

a precise physical manner and are probably due to our LTE analyses compensating for the neglect of velocity fields on all scales as well as real non-LTE effects. However as large, similar, values are found in both the standard and target star analyses, conditions in each atmosphere will be comparable and the differential abundances will not be in serious error.

Table 8. Abundance Uncertainties for the Peculiar B-type star, LS 4950, and Comparison

Elem	LS 4950 $\Delta T_{\rm eff}$ = ±1000 K	Δ*log* g = ∓0.2	HD 14956 $\Delta T_{\rm eff}$ = ±1000 K	Δ*log* g = ∓0.2
C II	±0.24	±0.30	±0.24	±0.31
N II	∓0.09	±0.25	±0.07	±0.24
O II	∓0.11	±0.10	∓0.20	±0.11
Mg II	±0.25	±0.45	±0.25	±0.44
Si III	∓0.09	±0.07	∓0.19	±0.08
Si IV	∓0.38	∓0.13	∓0.49	∓0.17
Fe III	±0.08	±0.09	±0.07	±0.08

Elemental abundances derived for LS 4950 are listed in Table 7, in particular, differential abundances relative to a normal B-supergiant (HD 14956), differential abundances relative to solar, and differential abundances relative to the confirmed post-AGB star, LSIV −12 111. Uncertainties due to the atmospheric parameters for LS 4950 are listed in Table 8. Firstly, the chemical composition of LS 4950 is incompatible with that of a normal Population I object. The differential abundances suggest that the metals (Mg, Si, Fe) are similar between LS 4950 and the normal Galactic star, but that CNO are significantly different. There are several ways to examine these CNO abundances:

(1) If we assume that HD 14956 has normal B-star (i.e., B-dwarf) abundances (e.g., [C, N, O] = −0.4, −0.3, −0.3 relative to the Sun, c.f., Gies & Lambert 1992, Kilian 1992, Cunha & Lambert 1994), then the atmosphere of LS 4950 appears enriched in oxygen, while carbon and nitrogen are depleted; see Table 7. This CNO pattern does not fit any standard stellar evolution theory.

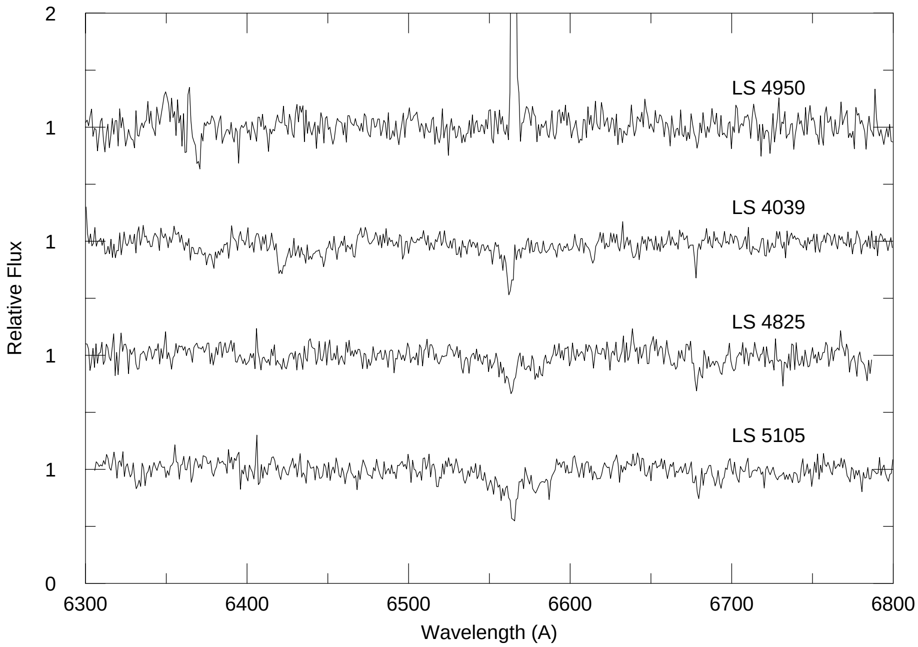

Fig. 5. Hα profiles of the B-type stars in Fig. 4 to further examine whether they are post-AGB stars.

(2) If we adjust these abundances to compare to the standard solar composition (i.e., consider the fact that normal B-stars in the solar neighbourhood differ in CNO from the Sun as stated above, and assume that the B-supergiant HD 14956 has a standard B-star composition as above), then CNO in LS 4950 still differs significantly from the solar comparison. The oxygen enrichment is reduced, but the carbon and nitrogen depletions are even larger; see Table 7. Again, this CNO pattern does not reflect any theoretical models for stellar evolution.

(3) If we attempt to account for the fact that normal B-supergiants might have undergone the first dredge-up (FDU) of CNO-cycled gas, then the comparison star HD 14956 could have an enrichment in N (+0.5 dex), and depletions in C and O (-0.2 and -0.1 dex, respectively) as predicted from standard stellar evolution scenarios (e.g., Schaller et al. 1989). Attempting to correct for possible CNO-cycled gas in the atmosphere of our comparison star continues to make the CNO abundances in LS 4950 peculiar: log(C, N, O) $-$ log(C, N, O)$_{\rm FDU}$ = -0.4, 0.0, +0.5). This abundance pattern continues to be difficult to understand. If LS 4950 has undergone more mixing, such as the third dredge-up (which converts C to O, Mg, Si, etc through α-captures), then depleting C and enriching O is possible as seen in this example, but how a star reaches the third dredge-up without enriching N via the first and second dredge-up is a mystery.

The CNO abundances for LS 4950 are also incompatible with those of the metal-poor Galactic anti-center B-type stars (Smartt et al. 1996), and with the metal-rich Galactic center stars (Smartt et al. 1998, Feltzing & Gustafsson 1997). Metal-rich stars towards the Galactic center show an enrichment in oxygen (as seen here), but also enrichments in nitrogen (by $\sim$0.2 to 0.3 dex, also observed in nebular emission line studies); while the metal-poor Galactic anti-center stars show depletions in each of CNO (corroborated by the nebular studies also).

The abundance pattern in LS 4950 is also significantly different from the confirmed post-AGB star, LSIV -12 111, which is reported as having a relatively metal-rich atmosphere, apart from its iron abundance (by Conlon et al. 1993); see Table 7. The iron abundance determined here for LS 4950 is from only one line of Fe III which is blended with a diffuse interstellar band, making our iron abundance determination rather uncertain (even differentially since DIBs can vary in strength depending on the site line). If LS 4950 is an old low mass, post-AGB star, we might expect it to have a less than solar iron abundance, however as this star lies in the direction of the Galactic center then it's abundances at formation may reflect those of old stars in a metal rich region. For example, McWilliam & Rich (1994) tend to find an *average* iron abundance of -0.25 dex for a sample of Bulge K-giants, they also find a large range of metallicities from [Fe/H]=-1 to [Fe/H]=+0.45. However, if this star began as a metal-rich star, the CNO abundances still do not reflect any normal evolutionary pattern. Thus, the CNO abundances do not concur with the scenario of it being a post-AGB star which has evolved from a old object in the inner Galaxy, even if it did not have initial Population II-like abundances. In any evolved low-mass star explanation, we would expect the nitrogen abundance to be enhanced from its natal value, whereas LS 4950 shows considerable depletion.

Our overall impression is that the abundance pattern in LS 4950 is puzzling, and difficult to attribute to any evolutionary state of the star. We may be seeing a post-AGB star which has evolved from a low mass, initially metal-rich, star. Or perhaps the analysis and interpretation of differential B-type supergiant abundances remains too complex due to large star-to-star variations.

LS 5105: The spectrum of LS 5105 (shown in Fig. 4) has a very sparse metal line spectrum. The only lines clearly present are C II 4267 Å, Mg II 4481 Å, and Si III 4552, 4567Å and thus we surmise that this star does not have a Population I composition. Additionally, the metal lines are very narrow and indeed are not resolved at our spectral resolution. Similar spectral characteristics were found by McCausland et al. (1992) in their sample of B-type post-AGB stars. Difficulties in the atmospheric parameter determinations, original chemical composition, and evolutionary history make a direct comparison of line strengths difficult, and this has not been attempted here. However we tentatively identify LS 5105 as a post-AGB star.

3.3. Young, very distant stars or post-AGB stars?

LS 4039: The spectrum of this star at first sight appears to be that of a sharp-lined early B-type giant. Fig. 4 shows it's Balmer lines (Hϵ, Hδ, and Hγ) symmetric in absorption, which is further confirmed at Hα in Fig. 5 . The strength of these features, and in particular the extent of the line wings, tend to indicate that this star does not have a supergiant type spectrum, but is somewhat less luminous. The star has relatively sharp unblended metal line features, that are resolved at the spectrographs resolution (i.e. they have a FWHM of greater than 1Å).

We again have carried out a detailed model atmospheres analysis of the spectra of LS 4039, with techniques similar to those used for LS 4950. Line data for LS 4039 is listed in Appendix B. The atmospheric parameters derived are listed in Table 9 and are compatible with a B2 III spectral type. The star HD 14053 (a member of h & χ Persei) was adopted as a standard in the differential analysis. This nearby cluster in the Perseus spiral arm has been analysed by Lennon et al. (1988) and found to have a relatively normal chemical composition. The observational data for HD 14053 was obtained at the McDonald Observatory and forms part of a larger data set, which will be discussed in detail by Vrancken et al. (1998). Most of the derived metal abundances for LS 4039 are similar to those of the chosen standard implying that it is a normal massive B-type object; see Table 10 (abundance uncertainties for the target and the comparison stars are listed in Table 11). Exceptions are the nitrogen and aluminium abundances. For the former, estimates from individual lines suffer from a large scatter, and indeed the derived differential result is only 1σ from that of our chosen standard comparison. The abundance determination of aluminium was based on only two weak lines, and must be treated with some caution. Hence, we conclude that this object shows normal abundance ratios in its photosphere.

An estimation of the stellar distance can be made by putting it on the evolutionary tracks of Schaller et al. (1992) to obtain a mass and luminosity, and then using the bolometric corrections of Kurucz (1979) to get an absolute visual magnitude. The photometry listed in Table 1 then indicates a distance of 6 ± 1.5 kpc (the errors reflecting those of the atmospheric parameters, in particular that of *log* g). Therefore, this appears to be a B2.5 giant star located only 2.5 kpc from the Galactic center, but with a normal solar neighbourhood-like composition.

LS 4825: This star was initially identified as a normal B-type supergiant based on its rich metal line spectra, and that the Balmer line profiles are in absorption and symmetric. In Fig. 4, the spectra of LS 4825 is strikingly similar to that of the standard B1 Ib star.

If this star is a normal, massive supergiant, then it would have to be very distant and lie significantly beyond the Galactic center. Alternatively, it could be subluminous (possibly at a post-AGB evolutionary stage) and be located close to the Galactic center. As an initial step, we have undertaken a preliminary model atmospheres and abundance analysis of LS 4825, along with the spectroscopic standard star HD 24398 (line strengths taken from Lennon et al. 1992).

Using the same methods as described above for LS 4950, a model atmosphere analysis was performed for LS 4825 and HD 24398. Atmospheric parameters for these two stars are listed in Table 9. Line data for LS 4825 is listed in Appendix B. The element abundances derived for LS 4825 suggest that it has a metallicity similar to that of the normal B-type supergiant in the solar neighbourhood; see Table 10. All the differential results are zero to within the 1σ error level (where quoted) or to within the expected errors intrinsic to any such analysis (i.e. of the order of 0.1 – 0.2 dex). There is no clear evidence of consistent metal underabundances generally associated with older post-AGB objects, or any of the peculiarities discussed above for LS 4950. Hence from the data available, we suggest that LS 4825 is probably a normal B1 Ib supergiant, which places it approximately

Table 9. Atmospheric parameters for Distant B-star Candidates and Comparison Stars

	LS 4039	HD 14053
$T_{\rm eff}$ (K)	22000 ±1000	24000 ±1000
log g (dex)	3.4 ±0.2	3.5 ±0.2
log(He/H)	11.00 ±0.15	11.0 ±0.1
ξ (km s^{-1})	20	20
	LS 4825	HD 24398
$T_{\rm eff}$ (K)	22000 ±1000	22000 ±1000
log g (dex)	2.9 ±0.2	2.9 ±0.2
log(He/H)	10.82 ±0.1	10.7 ±0.1
ξ (km s^{-1})	30	30

Table 10. Preliminary Differential Abundances for Distant B-supergiant Candidates

Elem	$\log(X/H)_{\rm LS4039}$ $-\log(X/H)_{\rm HD14053}$	(#)	$\log(X/H)_{\rm LS4825}$ $-\log(X/H)_{\rm HD24398}$	(#)
C II	...	(0)	+0.1	(1)
N II	+0.3 ±0.3	(7)	0.0 ±0.1	(7)
O II	+0.1 ±0.3	(21)	+0.2 ±0.1	(11)
Mg II	0.0	(1)	−0.2	(1)
Al III	+0.3 ±0.2	(2)	+0.1 ±0.1	(2)
Si III	+0.1 ±0.1	(3)	+0.1 ±0.1	(3)
Si IV	+0.1	(1)	−0.1	(1)

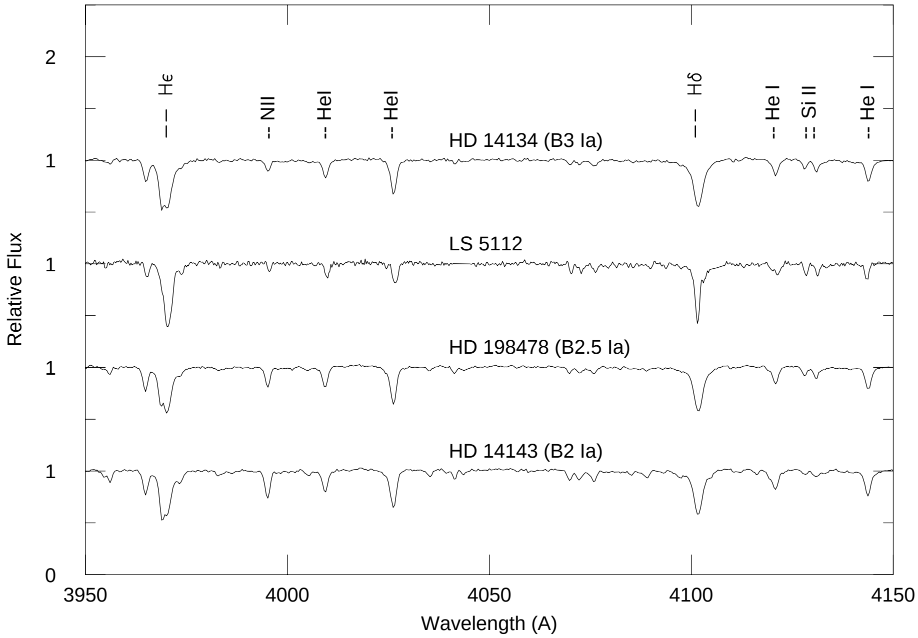

Fig. 6. Spectra of LS 5112 and three Galactic standard stars.

Table 11. Abundance Uncertainties for Distant B-star Candidates and Comparisons

Elem	LS 4039		HD 14053		LS 4825		HD 24398	
	$\Delta T_{\rm eff}$ =±1000	Δlog g =∓0.2	$\Delta T_{\rm eff}$ =±1000	Δlog g =∓0.2	$\Delta T_{\rm eff}$ =±1000	Δlog g =∓0.2	$\Delta T_{\rm eff}$ =±1000	Δlog g =∓0.2
C II	...	...	...	...	±0.05	±0.10	±0.05	±0.09
N II	∓0.07	∓0.05	±0.06	±0.02	±0.07	±0.08	±0.07	±0.07
O II	∓0.19	∓0.11	∓0.12	∓0.08	∓0.12	∓0.05	∓0.11	∓0.05
Mg II	±0.12	±0.05	±0.10	±0.05	±0.13	±0.12	±0.14	±0.12
Al III	±0.04	∓0.04	±0.08	±0.03	±0.10	±0.08	±0.12	±0.09
Si III	∓0.16	∓0.11	∓0.07	∓0.06	∓0.08	∓0.05	∓0.07	±0.04
Si IV	±0.39	∓0.26	∓0.33	∓0.25	∓0.33	∓0.20	∓0.35	∓0.21

20 kpc from the Sun, and hence some ∼8 kpc on the other side of the Galactic center (by assuming an absolute visual magnitude appropriate for a B1 Ib supergiants of $M_v = -6.0^m$ from Walborn 1972, and the photometry values listed in Table 1). This makes LS 4825 the most distant Galactic star studied in a detailed spectroscopic manner, and an extremely interesting probe for the far side of the Galaxy.

However, we cannot definitely rule against this star being a B-type post-AGB candidate. Some post-AGB stars do not show the severe Population II metal underabundances (c.f. LSIV -12 111 in McCausland et al. 1992, Conlon et al. 1993). We have obtained higher resolution, higher signal-to-noise echelle spectra of this star for follow-up spectral studies (including the interstellar absorption lines). A more detailed analysis of this new spectra is reported in Ryans et al. (1997), and supports our preliminary conclusions that it is a normal, Population I, but very distant B-type supergiant.

LS 5112: This star is similar to LS 4825 in that it appears to be a normal B-type supergiant, and if so, then it must be located on the other side of the Galaxy. A detailed model atmospheres analysis will be necessary to ascertain its status. Unfortunately, LS 5112 has been observed at only one wavelength setting so far (see Sect. 2), and hence sufficient optical data are not currently available for a detailed analysis (see Appendix B for the available line data information). Its spectra will be discussed here qualitatively, along with some preliminary spectral synthesis results.

For illustrative purposes only, we have assumed that LS 5112 has an approximately normal chemical composition, and compared the strength of the Si II $\lambda\lambda$ 4130 multiplet to those in a standard grid of B-type supergiants (by Lennon et al. 1992); see Fig. 6. The star appears to have a spectral type near B2.5. Examination of the Hδ and Hϵ profiles tends to indicate that the star is close to a B2.5 Ia, however the He I lines are perhaps somewhat weak. A B2.5 star would have $T_{\rm eff} \sim$ 15,000 to 17,000 K (c.f., Lennon et al. 1992, and references therein) and the Hδ and Hϵ profile fits would imply *log* g ∼ 2.1 dex. These parameters, although tentative, are consistent with LS 5112 being a young, massive supergiant with an absolute visual magnitude

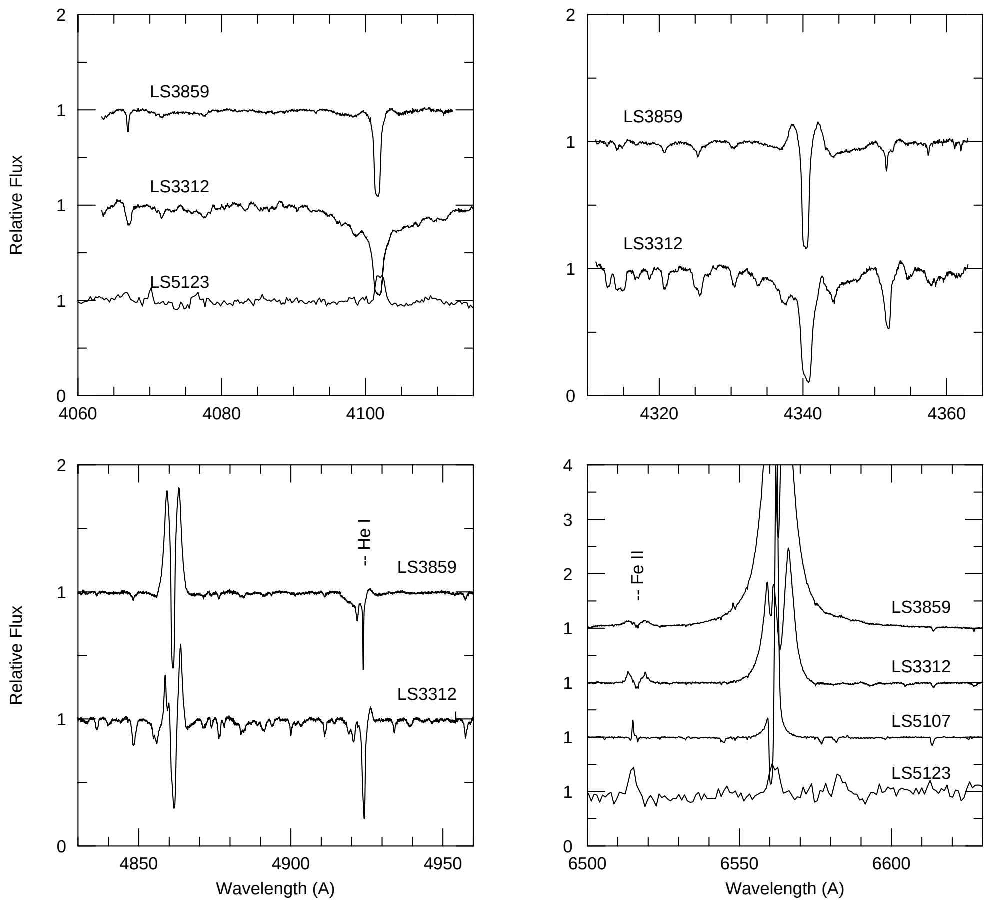

Fig. 7. Available Balmer line spectra of the Be stars.

of $M_v \simeq -7.0$ (Walborn 1972), placing it at a similar distance to LS 4825 ($d_\odot \simeq$20 kpc).

From our limited spectral range, we cannot rule out the possibility that LS 5112 is a nearby, sub-luminous post-AGB star though. Indeed there are some possible anomalies in its spectrum. For example at spectral type B2, the N II line at 3995Å should be relatively strong in supergiants (approximately 200−250 mÅ, from Lennon et al. 1992) but this absorption feature is quite weak in LS 5112 with an equivalent width of ∼70 mÅ. This is more in line with a BC2 Ib classification (see Lennon et al. 1992, 1993) which has generally weak N II lines. Also there is some evidence for filling-in of the Hδ profile (from comparisons with model profiles, and the standard MK types) on its red-ward wing which could conceivably be a weak P-Cygni signature. In P-Cygni type stars, this effect becomes progressively stronger in the lower lines of the Balmer series, and hence further observations of Hγ, Hβ and Hα are desirable. While such emission is evident in normal, massive supergiants due to their strong winds, it is also a frequent feature in post-AGB stars due to their circumstellar material (see previous section). Finally the FWHM of the unblended metal lines in this spectra give a mean of 0.87 ± 0.12Å, which is only slightly greater than the intrinsic width of the arclines. As very sharp metal lines are generally a feature of post-AGB stars (in supergiants macroscopic velocity fields, and non-zero rotational velocities tend to broaden the absorption features slightly more), then higher resolution observations would be necessary to ascertain the evolutionary status of this star.

3.4. Be/disk stars

LS 3859, LS 5107 (HD 322422, BD−13 5061, respectively) are known Be stars (Kozok 1985), see Fig. 7. These stars were included in our candidate list because the Reed (1993) catalogue indicated that they are A-type supergiants (although for LS 3859, there is a second spectral type listed, B0.5 IIIe). These stars were likely misclassified as A-type supergiants because of their disk-like spectra which show very sharp metal lines; at low resolution, these might resemble a typical supergiant. At high resolution, broad emission features can clearly be seen around the sharp metal lines, such as Fe II line near 6515 Å in LS 3859 seen in Fig. 7.

LS 3312, LS 5123 (LS 3312 = HD 133901) are newly identified Be-stars, see Fig. 7. Clearly they too have Balmer emission line spectra, but also LS 3312 has a disk-like spectrum (like the Be-stars above) with emission in the wings of (sharp) metal absorption lines. In Fig. 7, shell structures can clearly be seen in the helium (He I) and iron (Fe II) lines in LS 3312. Hα is triply peaked in LS 3312, which is most likely a projection effect of the disk (as discussed for the Be-star, HD 50138, by Dachs, Hummel, & Hanuschik, 1992).

4. Summary

We have presented new identifications for several blue stars towards the Galactic center. Previously, low resolution spectra suggested that these stars might be normal B-stars or A-type supergiants located very near the Galactic center. However, the roughly half of our target stars for high resolution spectral analyses (11 out of 20) are peculiar. These peculiar stars do not help in our primary goal of searching for normal stars with which to extend the studies of abundance gradients in the Galaxy, since their locations are uncertain and their evolutionary status is inconsistent with the normal, young stars.

In some cases, the chemical peculiarities are obvious only after a detailed model atmospheres analysis. Two stars, LS 3591 and LS 3593, are clearly post-AGB stars as evidenced by their typical post-AGB abundance pattern; they have Population II metal abundances, but [O/Fe] much greater than solar. Thus, these two stars have lower luminosities than expected if they were massive supergiants, placing them between us and the Galactic center. Two other stars, LS 4825 and LS 5112, are either post-AGB stars near the Galactic center or normal B-type supergiants lying on the other side of the Galaxy. Preliminary analysis suggests they are normal stars, which would make them unique and useful probes of metallicity on the far side of the Galaxy. One star, LS 4950, remains very puzzling since our analysis suggests that it is peculiar as either a Population II, post-AGB star or as a normal, Population I supergiant. And finally, several Be-type stars have been newly (or more clearly) identified from our spectra.

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Appendix A: Tables 12-15, only available at CDS

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