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Comparative abundance analysis of the hot main sequence stars and their progeny in open cluster M 25

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Abstract. Remarkable inconsistencies between elemental abundances in the main sequence stars and their progeny F-G supergiants are discussed. Comparative abundance analysis of the hot main sequence stars, the cepheid U Sgr and two cool supergiants belonging to young open cluster M 25 is performed. The detected disaccord in the abundances of carbon, oxygen and other elements between these stars having a common origin but occupying at present different evolutionary stages may be due to the fact that the chemical anomalies observed in B stars are caused by the mechanism of the radiative diffusion in the upper atmosphere layers. The chemical composition of B stars determined spectroscopically may not reflect correctly their true chemical composition, nor the chemical composition of the interstellar medium. On the other hand such abundance anomalies are not expected for F-G supergiants which have suffered the large scale mixing in the red giant phase. The observed abundances for these objects are much more reliable as a reference point in the study of galactic chemical evolution.

Three new Be stars are discovered in M 25. Our study has doubled the number of Be stars known in this cluster.

Key words: stars: abundances – stars: atmospheres – Galaxy: open clusters and associations: general – Galaxy: open clusters and associations: individual: M 25

1. Introduction

As rather young objects (with an age of several tens of Myr), the chemical composition of main sequence B stars should reflect the present day stage of the chemical evolution of the Galaxy. According to the standard evolutionary scenario developed for our Galaxy, the abundance of the heavy metal component should increase with the time due to supernovae explosions and the quieter evolution of AGB stars. In a very simple formulation, we would expect that B stars should have metallicities which are comparable to those of other young galactic objects (i.e., to either be more metal rich than is our 5 Gyr old Sun, or at the very least, to be at the same level of metallicity).

What do we have in practice? Let us consider published papers devoted to spectroscopic abundance investigations of B stars. All spectroscopic studies of B main sequence stars performed up to the present give similar results on the abundances of light elements. For example, according to Gies & Lambert (1992), Cunha & Lambert (1994), Kilian (1992, 1994), Daflon et al. (1999), Andrievsky et al. (1999) and Korotin et al. (1999) carbon and oxygen are deficient in B dwarfs by a factor of 2-7 with respective to their solar abundances. Moreover, Gies & Lambert (1992), Kilian et al. (1994), Kilian (1994), and recently Daflon et al. (1999) found that elements such as Mg, Al, Si, S and Fe are also deficient in the atmospheres of several tens of main sequence B stars (e.g. [Si/H]=-0.34 and [Fe/H]=-0.3). These stars were selected from the Ori OB1, Sco Cen, and Sgr OB1 associations as well as the field.

These results showing an overall metal deficiency have compelled some authors to come to the conclusion that our Sun possesses an anomalously high abundance of some light elements, while the young B main sequence stars represent the “normal” metallicity inherent to interstellar medium (see, e.g. Cunha & Lambert 1994, Daflon et al. 1999).

There is no doubt that any conclusion concerning anomalous abundances attributed to our solar system with respect to other field stars (especially those from different formation epochs and spatial origins) should be well grounded in reliable analyses. At present, the idea that our Sun does not represent a standard metallicity (for its time of formation), while B stars do, has gained great currency. Because of the importance of this conclusion to our understanding of galactic chemical evolution, we need to carefully consider our points of comparison. Rather than compare the determined metallicities for the main sequence B stars with solar values, it is probably more reasonable to compare the B stars with their descendants – F and G supergiants, especially if we are interested in testing the reliability of the B stars abundances.

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After hydrogen exhaustion in the stellar core, B stars evolve off the main sequence toward the red giant region. After attaining an effective temperature and luminosity appropriate to yellow/red supergiants, the star possesses a hydrogen burning shell, a core burning helium, and should have experienced the first dredge-up, which is predicted to bring incomplete CNO-cycle processed material to the stellar surface. Upon mixing with atmospheric gas, the first dredge-up changes the abundances of the CNO elements. In particular, carbon is predicted to become deficient relative to its initial abundance, nitrogen overabundant, while oxygen should remain practically unchanged. The abundances of heavier species (with possible exception for Na, Mg and Al) are not affected at this stage of the evolution.

Summarizing, one can state that, on the average, differences between the atmospheric abundances of oxygen, sulphur, calcium, iron, nickel, etc. in the main sequence B stars and F-G supergiants should not exist. For the light species (carbon and nitrogen, in particular) a difference may appear. The character of such a difference is following: the carbon abundance in F-G supergiants should be lower than in B stars, while nitrogen abundance should be higher. Let us discuss the situation as found in the literature for supergiants.

Much work on supergiant abundances has been done by Luck and co-authors. For a sample of 45 cepheids and non-variable F-G supergiants Luck & Lambert (1992) derived a mean [Fe/H] value of +0.03 ± 0.14 which indicates no significant deviation from the solar value. A later study (Luck et al. 1998) obtains [Fe/H]= -0.03 ± 0.13.

Andrievsky et al. (1996) and Kovtyukh et al. (1996) analyzed 12 cepheids and found that on average their metallicity is rather close to the solar value (the average [Fe/H] value is approximately -0.09). The same conclusion has been made for the sample of 16 non-variable F-G supergiants by Andrievsky & Kovtyukh (1996). In the latter case the mean relative iron content was -0.03 ± 0.05.

Thus, one can see that the reported metallicities for B stars (here we refer specifically to the iron abundance) generally do not agree with those determined for cepheids and non-variable supergiants, although both the stellar types are directly connected by evolution. Even larger discrepancies occur for some α-group elements. For example, silicon and sulfur in the supergiants are often solar or enhanced (see above references), while the results for B stars give underabundances relative to the Sun.

Special attention should be given to carbon abundances in both stellar types. As we already pointed out, this element is found to be remarkably underabundant in the hot B stars. It should be also underabundant in F-G supergiants (as was also noted), but the underabundance in the latter objects should be more pronounced than in former. The underabundance of carbon in F-G supergiants was first demonstrated by Luck (1978) and subsequent papers (Luck & Lambert 1981, 1985, 1992, Luck 1994, Luck & Wepfer 1995). The general trend of all of these papers is that intermediate mass stars are carbon deficient at about [C/H]=-0.3, nitrogen enhanced at about [N/H]=+0.3. These results are born out by results of the previously cited papers of Andrievsky, Kovtyukh & Usenko, Kovtyukh et al., Andrievsky & Kovtyukh, for cepheids and non-variable supergiants the relative carbon abundance [C/H] appears to be approximately $-$ 0.35 and $-$ 0.25 respectively. All these results mean that the derived carbon abundances in the evolutionary altered F-G stars is comparable (or even higher) than that of their progenitor B stars $which\ should\ not\ be$.

To further exacerbate this situation, Kovtyukh & Andrievsky (1999) applying a modified spectroscopic method obtained results which bring the abundances of carbon, nitrogen and oxygen into excellent accord with the theoretically predicted atmospheric abundances for supergiants of intermediate masses after the first dredge-up phase. As an example, for δ Cep they showed that the usual standard approach produces [C/H]=-0.31, while the modified method gives [C/H] = -0.21 (the theoretically predicted value for the star having the mass of δ Cep, i.e. about 6 $M_\odot$, is [C/H]=-0.17, see Schaller et al. 1992). This result places the determined carbon abundances in the evolved F-G supergiants even higher with respect to their progenitors.

The abundance of oxygen in B stars and F-G supergiants is another potential problem. Although B star analyses all return an oxygen abundance which is deficient with respect to the solar value ([O/H] ≈ -0.2 to -0.5), and these estimates seem to be in agreement with the supergiant oxygen abundances derived by Luck and coworkers (see above), Kovtyukh & Andrievsky (1999) have shown that oxygen abundances obtained for supergiant stars using the standard method can be underestimates. For example, for δ Cep they obtained [O/H] = +0.06.

Thus, we see that despite the evolutionary connection between the main sequence B stars and their progeny F-G supergiants, the abundance analyses give surprisingly inconsistent results. This situation with abundances in B stars and their descendants has to be clarified. One has to try to show that either: 1) B stars' elemental abundances are reliable and they really represent an overall metal deficiency with respect to the solar chemical composition, while the abundance results for their progeny – F-G supergiants – are somewhat doubtful, or 2) to the contrary, F-G supergiants' elemental abundances (which are on average solar) are reliable, while B main sequence stars' elemental abundances, reflecting on the average decreased metallicity, are questionable and thus should not be considered the correct reference point for the investigation of galactic chemical evolution. As this problem is not resolved yet, any statements about anomalous abundances inherent to our Sun, which are based only on results from B stars and completely ignoring those obtained for the young supergiant stars, can be considered as premature.

The best and most direct way to investigate the above problem of the abundance inconsistencies is to perform spectroscopic analyses of B stars and F-G supergiants that were born from the same interstellar material at the same time. Open clusters afford an unique possibility for this type of investigation and we report here such a study of the young open cluster M25.

The young (log A = 7.95, Ahumada & Lapasset 1995) open cluster M 25 (IC 4725) is of great interest because it contains several hot stars situated around the turn-off point, cool supergiants, and the cepheid member U Sgr (Lynga & Lindegren 1998). The

Table 1. Program B stars.

IC 4725$^{(1)}$	HD	BD$-$19	V	Sp	Hα	$v\sin\ i^{(2)}$, (km s^{-1})	$v\sin\ i^{(3)}$, (km s^{-1})	Rem
50	170682	5036	7.96	B4III	emission	120	160	BS
51	–	5037	9.20	B9V	emission	200	260	–
91	170719	5042	8.08	B6III	–	30	0	BS
97	–	5044	8.77	B7V	emission	170	210	BS
163	170835	5055	8.84	B2Vne	emission	240	–	BS
167	170836	5052	8.97	B6III	–	20	–	BS

^{1} – Johnson (1960) number
^{2} – our measurements
^{3} – data of Schmidt (1978)
BS – blue straggler star accordingly to Ahumada & Lapasset (1995)

stellar content of this cluster affords an excellent opportunity to perform abundance analyses of stars having common origin but occupying at present different evolutionary stages. More precisely, the purpose of the present study is the spectroscopic analysis of a sample of hot main sequence stars around the turn-off point and evolved supergiant stars allowing comparison of their elemental abundances.

2. Observations

Spectra for the M 25 B stars were acquired using the CTIO 4-m telescope and echelle spectrograph. The 31.6 l mm^{-1} echelle grating was used for the observations. The detector system was the Air Schmidt coupled with a GEC 576x385 CCD with 27 micron pixels. The combination yields a resolution of order 18000, a spectral range of about 1400Å, and overlapping coverage of adjacent orders out to 8500Å. The signal-to-noise ratio for all observations was greater than 100. Two regions were observed – one centered at about 6500Å and the other at 8350Å. Note that from the infrared region 7680 Å – 8920 Å only the oxygen triplet 7774 Å was used for analysis.

Observations of U Sgr (G1 Ib) at multiple phases as well as the non-variable cool supergiants HD 170820=IC 4725(150) and HD 170886=IC 4725(251) were acquired at McDonald Observatory using the Struve 2.1m reflector and the Sandiford echelle spectrograph. The nominal resolution of this data is 60000 with a spectral range of about 1000–1200Å. Two wavelength regions were observed: one centered at about 6200Å (the bulk of the data) and second at 5400Å (one spectrum for U Sgr). For these data the signal-to-noise was well in excess of 100.

The echelle orders were extracted using standard IRAF procedures [1]. Scattered light was removed by a surface fit to points midway between order centers. For the McDonald data regions on the CCD disturbed by internal reflections in the spectrograph are replaced by a smooth pseudo-spectrum before the background subtraction. All further spectral manipulations (continuum level placement, smoothing, wavelength calibration, equivalent width and radial velocity measurement) were performed using the DECH20 package (Galazutdinov, 1992).

3. Physical parameters of the program star atmospheres

3.1. B stars

To estimate the effective temperature, gravity and other important characteristics for the program B stars (such as $E(b-y)$ and $M_{\rm v}$,) we have used the Strömgren photometry available through SIMBAD and the numerical code written by T.T. Moon (based on the grid published in Moon & Dworetsky 1985) and recently modified by Napiwotzki (1994).

Four of the six program B stars show strong $H\alpha$ emission. These stars are indicated in Table 1. Mermilliod (1999) in the WEBDA database mentions three Be stars in M 25 including one of our program stars IC 4725(163). Our present study has added another three Be stars and has thereby doubled the number of Be stars known in this cluster.

Although we did not observe the spectral region in the vicinity of the $H\beta$ line, it is not unlikely that $H\beta$ is also affected by emission. Therefore, for the emission line stars of our sample we have calculated atmospheric parameters without the β-index. In this case the β-index is estimated using cubic fit to the $c_0-\beta$ relation for luminosity class V given in Crawford (1978).

In Table 2 we present the result of the $T_{\rm eff}$ and $\log g$ determination. For comparison we also give the atmospheric parameters calculated with the β-index for the Hα emission line stars.

For IC 4725(91) low resolution IUE spectra are available through SIMBAD. They were used to check the temperature determination for this star. The spectra SWP34601 and LWP14311 (exposed on 25 October 1988) were treated as described in Andrievsky et al. (2000). Emergent fluxes were calculated from original spectra using $E(b-y)$=0.327. In Fig. 1 we show the observed and calculated UV spectra for IC 4725(91). The calculations were performed using the SYNSPEC code of Hubeny et al. (1994). Differences between observed and calculated spectra are small for an effective temperature range ± 200 K.

All the synthetic spectra calculations were performed with a microturbulence parameter of 3 km s^{-1} which is quite appropriate to main sequence B stars.

Projected rotational velocities for the B stars were estimated by fitting observed and synthesized profiles for unblended lines (Table 1). The stars with $H\alpha$ emission show strong rotation, while the two stars with pure absorption $H\alpha$ profiles possess

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Table 2. Atmospheric parameters for program B stars.

	Without β index		With β index		Adopted		Schmidt(1978)	
IC 4725	$T_{\rm eff}$, (K)	log g	$T_{\rm eff}$, (K)	log g	$T_{\rm eff}$, (K)	log g	$T_{\rm eff}$, (K)	log g
50	14400	3.9	14300	3.3	14400	3.9	15600	3.58
51	14400	3.9	14000	2.9	14400	3.9	15200	3.53
91			13850	3.5	13850	3.5	15000	3.70
97	14800	3.9	14000	2.4	14800	3.9	15800	3.56
163	21950	3.9	21500	3.5	21950	3.9	21200	3.98
167			15300	3.5	15300	3.5	–	–

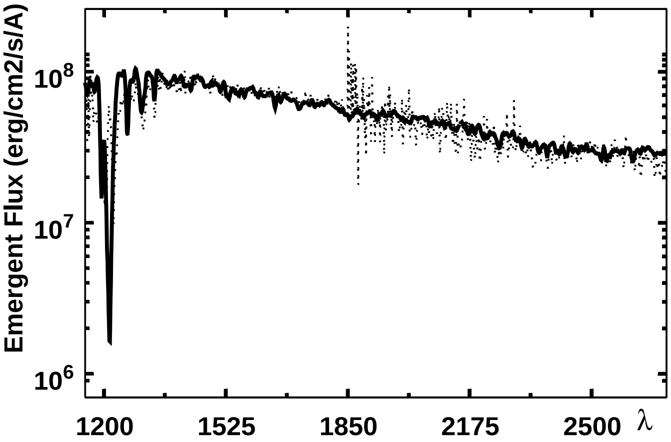

Fig. 1. Observed and calculated UV flux distribution for IC 4725(91). Assumed parameters are $T_{\rm eff}$ = 13850 K and log g=3.5. Observations – *dotted line*, calculations – *solid line*.

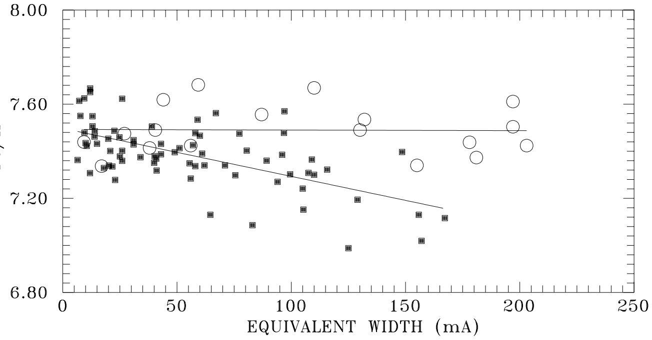

Fig. 2. The microturbulence parameter and gravity determination for U Sgr at ϕ=0.001. *Open cyrcles* – Fe II lines, *filled squares* – Fe I lines.

small projected rotational velocities. It should be noted that the $H\alpha$ lines in the spectra of these two latter stars have anomalously deep cores that could not be matched with the adopted atmospheric parameters, while the observed line wings can be reproduced by the calculations quite well.

For the sake of comparison with the data of other authors, in Table 2 we give the atmospheric parameters for our program stars as estimated by Schmidt (1978). As one can see there is a marginal agreement in fundamental parameters between our results and the data of Schmidt. Nevertheless, one can suspect that Schmidt (1978) overestimated the temperatures that resulted in apparent helium deficiency for all but one program stars from M 25. This is also supported by the result for IC 4725(163). An estimate of the stellar parameters for this star made by Schmidt gives the results which are close to what we found. Only this star from Schmidt's sample is a helium normal (similar to our result).

3.2. The Cepheid U Sgr and cool supergiants

The effective temperature of U Sgr at the different phases was calculated using the method based on the application of spectroscopic criteria (lines ratios), which was developed for yellow supergiant stars and described in Kovtyukh et al. (1998) and recently in Kovtyukh & Gorlova (2000). The effective temperature implied by the various criteria show a very small spread (typical standard deviation of 25 K for 10 indicators).

To evaluate the microturbulent velocity and the gravity value at each pulsational phase of U Sgr we applied the modified method of spectroscopic analysis described by Kovtyukh & Andrievsky (1999). Note that this method specifies that the $V_{\rm t}$ parameter determination should be based on the analysis of Fe II lines (by elimination of any dependence between iron abundance from these lines and their equivalent widths). With the $V_{\rm t}$ parameter obtained in this way, the Fe I lines show a progressively decreasing iron abundance with equivalent width increase. The iron abundance as determined from Fe I is found by extrapolating this relation to W=0mÅ, and taking the intercept as the iron abundance. The resulting abundance from Fe I lines then has to be compared with the mean abundance resulting from Fe II lines to determine the proper gravity, i.e., where the iron abundances as determined from the two ions are equal. This procedure is illustrated in Fig. 2 for phase ϕ=0.001. The $T_{\rm eff}$, log g and $V_{\rm t}$ estimates for different phases of the U Sgr pulsational cycle are given in Table 3.

Other products of the spectroscopic analysis are the microturbulence and gravity variations with a phase. "Spectroscopic" gravities (i.e., those determined from our spectroscopic analysis) can be compared (see Table 3) with the physical gravities which were calculated for $\mathsf{M} = 6.5\mathsf{M}_\odot$ (the best estimate of the U Sgr mass from $\mathsf{M} - P$ relation of Turner 1996) using the following expression:

$$\log g = \log{(\mathsf{M}/\mathsf{M}_\odot)} - \log{(L/L_\odot)} + 4\log T_{\rm eff} - 10.61 \quad (1)$$

Table 3. Atmospheric parameters of U Sgr.

Phase[1]	HJD 245...	$T_{\rm eff}$, (K)	N	σ, (K)	$\log\ g$(spec)	$\log\ g$(phys)	$V_{\rm t}$,(km s^{-1})	[Fe/H]
0.001	0677.67816	6145	26	30	1.9	1.72	4.7	0.01
0.178	0739.57384	5876	28	15	1.7	1.72	4.0	0.08
0.326	0740.57748	5710	23	13	1.7	1.67	4.0	0.09
0.326	0949.66389	5705	4	36	1.7	1.67	4.0	0.05
0.471	0741.55532	5475	28	14	1.6	1.65	4.0	0.05
0.550	0674.63784	5388	26	11	1.5	1.67	4.0	0.06
0.551	0674.64319	5416	27	12	1.7	1.69	4.0	0.07
0.581	0735.55199	5347	27	13	1.6	1.68	4.0	0.04
0.731	0736.56445	5399	23	23	1.7	1.82	5.2	0.01
0.746	1053.67960	5441	25	20	1.8	1.84	5.5	0.01
0.817	1094.62511	5746	21	21	2.0	1.93	6.0	0.02
0.896	1054.68627	6077	26	21	2.1	1.99	5.5	0.04

[1] – phases are calculated using epoch from Arellano Ferro et al. (1998) and period value from Moffett & Barnes (1984).
N – number of spectroscopic criteria (line ratios) used.

Table 4. Atmospheric parameters for HD 170820 and HD 170886.

Star	Sp.	$T_{\rm eff}$, (K)	$\log\ g$	$V_{\rm t}$, (km s^{-1})
HD 170820	K0 III	4540	1.8	3.5
HD 170886	G3 Ib	5150	1.4	4.0

In using the above expression for the physical gravity, we have taken into account the luminosity variation during the pulsation. The luminosity values for the phases of interest were found using the mean value of M_v for U Sgr, the individual m_v values Arellano Ferro et al. (1998) and bolometric corrections calculated for the different effective temperatures at the different phases ($B.C.$ are taken from Castelli 1999). The calculated physical gravities were also corrected for the dynamical variation (term $\frac{dV}{dt}$) using the radial velocity curve from Barnes et al. (1987), the pulsational period of U Sgr P = 6.745^d and projection factor 1.4. As one can see from Table 3 there is good agreement between the "spectroscopic" and physical gravities. We believe that the behaviour of $V_{\rm t}$ and $\log\ g$ deserve separate consideration and we plan to discuss it elsewhere.

For the hotter of the two non-variable supergiants (HD 170886) we applied the same method of effective temperature determination as for U Sgr, but for the cooler one (HD 170820) such an estimate cannot be performed (as the effective temperature for this star is outside the working region of the applied spectroscopic criteria). Therefore for HD 170820 we used the mean $T_{\rm eff}$ value based on the individual determinations from $(R-I)$, $(b-y)$ and $(B2-V1)$ indices provided by Luck (1994).

Surface gravities and microturbulent velocities for HD 170820 and HD 170886 were found using the same technique used for U Sgr, that is, the method of Kovtyukh & Andrievsky (1999). The derived atmospheric parameters for these stars are given in Table 4. The parameters adopted here are in good agreement with those of Luck (1994).

4. Elemental abundances for the program stars

4.1. LTE calculations

The SYNSPEC spectrum synthesis code (Hubeny et al. 1994) has been used to derive LTE elemental abundances for the M 25 program B stars. Atmospheric models were interpolated from Kurucz's (1992) grid. Oscillator strengths for the lines of interest were selected from the Hirata & Horaguchi(1994) data base. The line list is given in Table 5.

In the U Sgr data we found that the line profiles are asymmetric at several phases. In the cases where the U Sgr lines are asymmetric we have determined the equivalent widths using an equivalent width-depth relation. The method proceeds as follows: a) by direct integration we determined the equivalent widths and depths of unblended lines over the spectrum; b) the list of lines to be used in the analysis was divided into groups spread over about 500Å each having a number of unblended lines; c) then for each group we constructed the dependence of equivalent width on depth and approximated the relation by a second-order polynomial relation; and lastly, d) for the remainder of the lines we measure the depth and using the corresponding relation to determine the equivalent width.

All abundance calculations for U Sgr, HD 170820 and HD 170886 were performed with the WIDTH9 code and the Kurucz grid of the atmospheric models. The abundance calculations were done with models derived using a 2 km s^{-1} microturbulence. The effect of changing the model atmosphere microtubulence to 4 (or 6) km s^{-1} (test calculations for Fe I and Fe II) changes the derived abundances only on the order of 0.02 dex. The complete list of the lines used in the analysis of supergiant stars and the corresponding "solar" oscillator strengths are given in Kovtyukh & Andrievsky (1999).

4.2. NLTE calculations

For two elements (carbon and oxygen) in the hot stars of our sample NLTE abundances were found using the MULTI code

Table 5. The line list used for B star analysis.

λ	Ion	log gf
5875.599	He I	–1.51
5875.614	He I	–0.34
5875.615	He I	+0.41
5875.625	He I	–0.34
5875.640	He I	+0.14
5875.966	He I	–0.21
6678.154	He I	+0.33
7065.176	He I	–0.46
7065.214	He I	–0.68
7065.707	He I	–1.16
6578.05	C II	–0.05
6582.88	C II	–0.34
6155.97	O I	–0.68
6156.76	O I	–0.45
6158.18	O I	–0.31
7771.94	O I	+0.333
7774.16	O I	+0.186
7775.39	O I	–0.035
6096.163	Ne I	–0.27
6266.495	Ne I	–0.53
6334.428	Ne I	–0.31
6382.991	Ne I	–0.26
6506.528	Ne I	+0.03
6598.953	Ne I	–0.36
6231.718	Al II	+0.40
6243.355	Al II	+0.67
7042.048	Al II	+0.35
7056.612	Al II	+0.13
5957.559	Si II	–0.30
5978.930	Si II	–0.03
6239.614	Si II	+0.19
6347.109	Si II	+0.30
6371.371	Si II	–0.08
6829.799	Si II	–0.27
5885.015	Fe II	+0.32
5898.021	Fe II	–0.59
5948.427	Fe II	–0.18
5952.510	Fe II	–2.03
5955.698	Fe II	+0.23
5961.705	Fe II	+0.70
5965.622	Fe II	+0.07
5976.682	Fe II	–0.25
5983.831	Fe II	–0.70
5988.011	Fe II	–0.41
5991.376	Fe II	–3.56
6060.975	Fe II	–1.68
6069.675	Fe II	–0.37
6071.426	Fe II	–0.19
6082.882	Fe II	–0.54
6103.496	Fe II	–2.17
6149.258	Fe II	–2.72
6175.146	Fe II	–1.98
6179.384	Fe II	–2.60
6233.754	Fe II	–0.77
6238.392	Fe II	–2.63
6248.898	Fe II	–2.70
6331.954	Fe II	–1.98
6357.162	Fe II	+0.17
6375.792	Fe II	–0.08
6416.919	Fe II	–2.74
6456.383	Fe II	–2.08
6524.726	Fe II	+0.56
6541.356	Fe II	+0.45
6627.261	Fe II	–1.61
6664.465	Fe II	–0.13

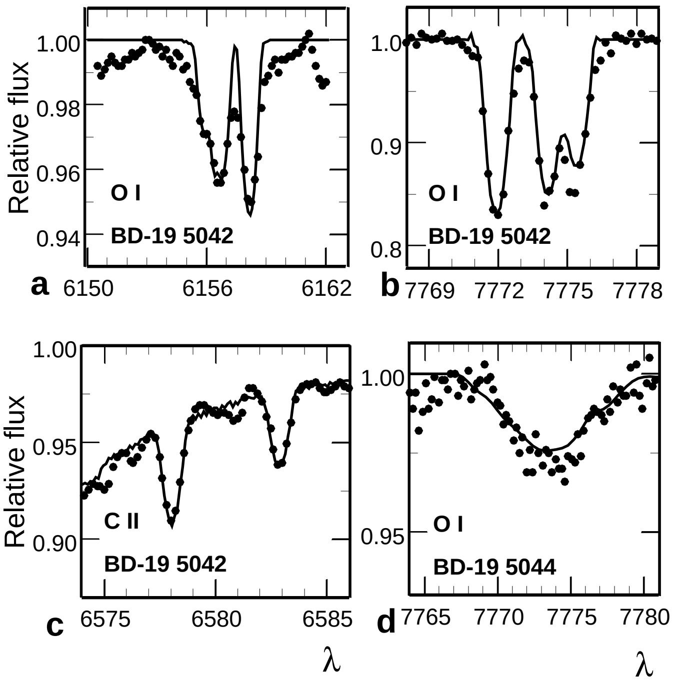

Fig. 3a–d. Calculated (NLTE) and observed spectrum profiles for a sample of lines. Synthetic spectrum – *solid line*, observed – *dots*.

(Carlsson 1986) and the method described by Korotin et al. (1999). In the NLTE spectrum synthesis for B stars we used two carbon lines CII 6578 Å and 6582 Å, and two systems of O I lines: the 6158 Å triplet and the 7774 Å triplet (for the fast rotators only the infrared oxygen triplet can be measured).

The MULTI code was also applied to the determination of carbon, oxygen and sodium abundances in the supergiant stars of our sample. The following lines were used: C I (5800 Å, 6001 Å, 6010 Å, 6014 Å, 6587 Å, 6655 Å), O I (5577 Å, 6156 Å, 6363 Å), Na I (5682 Å, 5688 Å, 6154 Å, 6160 Å).

The oscillator strengths for the C, O and Na lines involved in the NLTE analysis were taken from Biemont et al. (1993), Lambert (1978) and the Hirata & Horaguchi (1994) catalogue. The atomic models used for C II, O I and Na I are described by Korotin et al. (1999), Mishenina et al. (2000) and Korotin & Mishenina (1999) respectively. A short description of the C I atomic model is given below.

Our C I atomic model is similar to that used by Stürenburg & Holweger (1990). The main difference is that we used photoionization cross sections from TOPBASE (Cunto & Mendoza 1992) and updated oscillator strengths from the Hirata & Horaguchi (1994) catalogue with some additional data from Luo & Pradh (1989) and Biemont et al. (1993). The C I model consists of 47 C I levels and the ground level of C II in the detailed line calculations, while 63 levels of C I, 19 levels of C II, and the ground level of C III were used for particle number conservation. 113 radiative transitions were considered in detail while for 155 transitions the radiative rates were held fixed.

In Fig. 3 we show the observed and calculated profiles of C II and O I lines for two B stars: one with a low $v \sin i$ value (IC 4725(91)=BD-19 5042, Fig. 3a-c) and one rapid rotator (IC 4725(97)=BD-19 5044, Fig. 3d). It should be noted that the C II lines fall in the wing of Hα which acts as an additional source of continuum opacity (which is included in our models using the Kurucz's ATLAS9 opacity sources).

In order to ensure a correct point of comparison, we have calculated the abundances of C, O and Na in the solar atmosphere using the NLTE code, adopting the same strategy and the same spectral lines as used for our program stars. The C I, O I and Na I line profiles were taken from the solar flux spectrum of Kurucz et al. (1984). We obtained the following photospheric abundances for the Sun: (C/H) = 8.55 (exactly the same value as given by Grevesse et al. 1996, while Biemont et al.1993 give 8.57), (O/H) = 8.90 (this is only slightly higher value than the abundance adopted by Grevesse, Noels & Sauval), (Na/H) = 6.25 (Grevesse, Noels & Sauval adopt 6.33 for solar

Table 6. Relative elemental abundances for program B stars.

	IC 4725					
Elem	50	51	91	97	163	167
He	+0.00(1)	+0.00(1)	+0.58(0.16,3)	+0.00(2)	+0.00(1)	–0.45(0.10,3)
C			–0.30(2)			–0.30(2)
O	–0.55(1)		+0.00(2,0.06)	–0.90(1)	–0.30(1)	–0.10(2,0.04)
Ne			+0.40(0.12,6)			+0.60(0.15,4)
Al			+0.20(0.17,4)			–0.60(2)
Si	+0.00(0.10,3)	+0.00(3)	–0.30(0.03,5)	+0.00(1)		+0.00(0.25,6)
Fe			+0.00(2)			+1.25(0.05,30)

1) Given in the brackets are σ (except for n=1,2) and number of lines used respectively.

2) For C and O the NLTE abundances are given. Note also that the number 1 or 2 indicated in the brackets for oxygen data means that one triplet (i.e. 3 lines) or two triplets (6 lines) were used.

atmosphere, but the NLTE calculations made by Mashonkina et al. 2000 and Takeda & Takada-Hidai 1994 produce somewhat smaller values: 6.21 and 6.23 respectively). Our program star relative abundances of carbon, oxygen and sodium are referred to the above values.

4.3. Results for program stars

The elemental abundances results for B stars are presented in Table 6. Rapidly rotating stars allow a determination of the abundances for only a restricted number of elements (He, O and Si, as a rule) which are reprsented in the observed spectral region by several strong lines only, while for the stars with small $v \sin i$ values the number of investigated lines and hence, elements is greater.

Average elemental abundances for U Sgr are represented in Table 7. Note that individual [Fe/H] values for each phase are given in the last column of Table 3 whereas the abundances presented in Table 7 are averaged over all 12 observed phases. Table 8 presents the results on the chemical abundances for two non-variable cool stars.

4.3.1. Error estimate

It is important to estimate how uncertainties in the adopted effective temperatures and gravities affect the abundance results for B stars. The relevant consideration was performed for the star IC 4725(167). Several sets of the atmosphere parameters ($T_{\rm eff}$/log g) were used. Among them: two sets (14950/3.8) and (15400/3.1) correspond to possible uncertainties in the photometrical indices (in this case the parameters were calculated using the formal errors in the photometric data of ± 0.03). One set corresponds to spectral class B6III (14100/3.4), and the last one (12000/2.5) corresponds to an extreme case (spectral class B8II, which is also reported for this star, see Mermilliod 1999). In the latter two cases the temperatures and gravities were roughly estimated from Lang (1992). In Table 9 we summarize the results for some of representative elements: He, C, O and Fe.

As one can see from Table 9 in the temperature range from 14000 K to 15500 K the differences in iron content are always small. Even for extreme case of the lower temperature and gravity an obvious overabundance of this element still exists (the same behaviour demonstrates also the silicon, for which the test calculation for some lines were carried out).

Table 7. Average elemental abundances for U Sgr.

Ion	[El/H]	σ	N	(El/H)
C I	−0.14	0.11	1-5	8.41
O I	0.12	0.05	1-2	9.02
Na I	0.20	0.06	1-2	6.45
Mg I	−0.17		0-1	7.41
Al I	0.22	0.06	0-2	6.69
Si I	0.07	0.10	6-14	7.62
Si II	0.34		0-1	7.89
S I	0.15	0.21	1-6	7.36
Ca I	0.03	0.11	1-5	6.39
Sc II	−0.16	0.12	1-2	3.01
Ti I	0.06	0.20	3-18	5.08
Ti II	0.01		0-1	5.03
V I	0.04	0.17	1-12	4.04
V II	−0.04	0.04	1-2	3.96
Cr I	0.09	0.17	2-9	5.76
Cr II	0.13	0.20	1-6	5.80
Mn I	−0.09	0.12	1-4	5.30
Fe I	0.04	0.11	49-102	7.54
Fe II	0.06	0.08	5-13	7.56
Co I	−0.12	0.16	2-8	4.80
Ni I	0.01	0.12	11-27	6.26
Cu I	0.02	0.12	1-2	4.23
Zn I	0.24		0-1	4.84
Y I	0.27	0.26	1-2	2.51
Y II	0.22	0.08	1-4	2.46
Zr II	−0.11		0-1	2.49
La II	0.14		0-1	1.36
Ce II	−0.12	0.11	1-4	1.43
Pr II	−0.24	0.07	0-2	0.47
Nd II	0.05	0.16	2-8	1.55
Eu II	0.01	0.13	1-2	0.52
Gd II	−0.03		0-1	1.09

N – minimal and maximal number of lines used per phase.
(El/H) in the final column denotes as usual log(El/H)+12.00

Table 8. Elemental abundances for HD 170820 and HD 170886.

	HD 170820				HD 170886			
Ion	[El/H]	σ	N	(El/H)	[El/H]	σ	N	(El/H)
C I					−0.02		1	8.53
O I	+0.13	0.01	3	9.03	+0.05	0.02	2	8.95
Na I	−0.06	0.12	3	6.19	+0.14	0.04	4	6.39
Mg I					−0.24		1	7.34
Al I	−0.01	0.02	2	6.46	+0.16	0.02	2	6.63
Si I	+0.14	0.15	19	7.69	+0.05	0.09	20	7.60
S I					+0.15	0.18	3	7.36
Ca I	−0.10	0.34	4	6.26	−0.10	0.07	4	6.26
Sc II	−0.12	0.03	5	3.05	−0.09	0.15	3	3.08
Ti I	+0.03	0.12	33	5.05	−0.04	0.14	17	4.98
Ti II					+0.00		1	5.02
V I	+0.01	0.16	28	4.01	−0.01	0.07	13	3.92
Cr I	−0.10	0.23	11	5.57	−0.03	0.12	6	5.64
Mn I	+0.04	0.14	2	5.43	−0.07	0.38	3	5.32
Fe I	+0.02	0.19	179	7.52	+0.00	0.14	149	7.50
Fe II	−0.01	0.12	7	7.49	+0.03	0.11	8	7.53
Co I	−0.03	0.14	9	4.89	+0.12	0.25	6	5.04
Ni I	−0.02	0.15	38	6.23	+0.04	0.13	33	6.29
Cu I	−0.03		1	4.18	−0.05		1	4.16
Y I	+0.04		1	2.28				
Y II	+0.23	0.04	2	2.47				
La II	+0.36		1	1.58	+0.08		1	1.30
Ce II	+0.08	0.18	2	1.63	−0.20	0.11	2	1.35
Nd II	+0.19	0.05	2	1.69	−0.12	0.01	2	1.38
Eu II	+0.35		1	0.86	+0.01		1	0.52

Table 9. Error estimate for elemental abundances in IC 4725(167)

Element	(15300/3.5)	(14950/3.8)	(15400/3.1)	(14100/3.4)	(12000/2.5)
He	–0.45	–0.14	–0.75	–0.12	+0.54
C	–0.30	–0.05	–0.50	–0.03	+0.05
O	–0.10	–0.05	–0.20	–0.20	–0.60
Fe	+1.25	+1.21	+1.25	+1.17	+0.91

Variations of the C and O abundances are stronger, and for the helium they reach more than order of magnitude. Let us note that for all the cases where the temperature is higher than 14000 K, the helium appears to be underabundant. Only adopting the stellar parameters from the spectral type B8II one can get a helium overabundance. Nevertheless, we would like to stress that in the particular case of IC 4712(167) we do not see any firm reasons to rely on spectral classification in the parameter determination, rather than on the photometrical data.

5. Discussion

5.1. Membership in the cluster

Before discussing the elemental abundances in the program stars it is worthwhile to discuss their membership in M 25. For all B stars listed in Table 1 we calculated the true distance modulii using the Strömgren photometry and Napiwotzki (1994) code. As four of the six program B stars are Be stars (i.e., they have Hα emission) with Hβ being not observed, it is not ($a\ priori$) known whether the β index is affected by emission or not. Therefore, similar to the determination of the effective temperature and gravity values, we also determined the distance modulii of the Be stars for two different cases, i.e with the β index and without it (see Table 10). Let us recall that in the latter case the β index was estimated from the main sequence $c_0 - \beta$ relation of Crawford (1978), and then the absolute magnitudes were calculated by applying the calibration of Balona & Shobbrock (1984). Some additional notes to Table 10: a) $E(b{-}y)$ for U Sgr was calculated using the usual expression $E(b{-}y)$=0.73$E(B{-}V)$=0.294 with $E(B-V)$=0.403 (Fernie 1990). Since Fernie et al. (1995) give also $E(B-V)$ values ranging from 0.38 to 0.48, the calculated $E(b-y)$ value falls within the interval from 0.277 to 0.350.

It should be noted that Schmidt (1977) derived from his sample of B stars a mean true distance modulus of M 25 ($V_0{-}M_v) \approx 8.7$. He did not consider the possibility of emission in the Hβ line, therefore in the case of IC 4725(97) he probably obtained an overestimated distance modulus, and came to the conclusion that this star is possibly not a member of M 25.

Table 10. Photometric distance modulii and proper motion for the program stars.

IC 4725	$E(b-y)$	$(V_0-M_\mathrm{v})_\beta$	$(V_0-M_\mathrm{v})_{no\beta}$	M(Feast)	M(Schmidt)	$\mu_\alpha\cos\delta$	μ_δ
50	0.343	9.0	7.3	yes	yes	-2.2	-5.6
51	0.346	10.7	8.5	yes	yes	–	–
91	0.327	8.0	–	yes	yes	-7.0	-1.7
97	0.381	11.5	8.1	yes	?	–	–
163	0.321	10.8	10.1	–	–	-4.6	-6.0
167	0.322	9.6	–	–	–	$+1.0$	-4.9
U Sgr	0.294^*					-4.15	-6.05
HD 170820	0.215^{**}					-2.18	-3.03
HD 170886	0.200^{**}					-1.23	-6.95

M(Feast) – membership from Feast (1957)
M(Schmidt) – membership from Schmidt (1977)
μ_α and μ_δ in mas y^{-1}.
* – calculated on the basis of Fernie (1990) data.
** – calculated using the relation from Arellano Ferro & Parrao (1990).

Table 11. Radial velocities V_r (km s^{-1}) for program stars.

Star	our results				literature			
IC 4725	JD=244660+	V_r,(km s^{-1})	σ	N	1	2	3	4
50	6.8139	–10.0	0.97	4	+1.3	–	–	–
51	6.8227	–	–		+17.3	–	–	–
91	6.8438	–12.0	0.84	8	+21.8	+25.8	–	–
97	6.8507	–	–		+14.5	–	–	–
163	6.8830	+9.7	–	1	–	–	–	–
167	6.8752	+3.3	0.70	11	–	–	–	–
U Sgr								+2.6*
	JD=245073+							
HD 170820	7.5757	–0.15	0.10	56	–	–	–5	+2.2
HD 170886	7.5660	+2.0	0.12	23	–	–	–4	+1.7

1 – Wallerstein (1957)
2 – Wallerstein (1960)
3 – Duflot et al. (1995)
4 – Mermilliod et al. (1987)
* – γ-velocity accordingly to Mermilliod et al. (1987). Fernie et al.(1995) also give close value 2.8 km s^{-1}.

Gieren et al. (1997) find a true distance modulus of 8.9 from a detailed study of U Sgr.

If we assume that the more reliable distance modulii for Be stars listed in Table 10 are those calculated without β index, then we see that for most program objects the (V$_0$−M$_\mathrm{v}$) values are within the $8-10$ interval with the one exception of IC 4725(50). In Table 10 we also give the proper motion for program stars selected from Hipparcos and Tycho catalogue (available at SIMBAD). Lynga & Lindegren (1998) consider IC 4725(50) as a member of M 25 from its proper motion, but from the estimated photometric distance modulii for the program B stars one can see that its distance modulus determined without the β index slightly deviates from the (V_0-M_v) for the rest of stars. The modulus is underestimated because of the assumed dwarf luminosity class (of course, this star may not possess Hβ emission and if this is the case then the value of 9.0 would be preferred).

To have more reliable data allowing a qualitative estimate of the membership, we have determined the radial velocities for stars with narrow spectral lines. The results are presented in Table 11. For the B stars only a few lines are available for use (e.g., He I 6678 Å and 7065 Å, Si II 6347 Å and 6371 Å). Our radial velocity results indicate that the stars of our sample can be the cluster members. (Note that Feast 1957 gives the mean radial velocity value for M 25 $V_\mathrm{r} = -4 \pm 4\,\mathrm{km\ s}^{-1}$). Rather large differences between the independent V_r estimates for some stars (see Table 11) could indicate that they may be, for example, physical variables or binary systems. For example, IC 4725(91) with large range in radial velocities is known as a star in double system (SIMBAD). In this case it is not completely excepted that such binary may suffer line dilution because of the extra secondary flux, and the derived abundances may be somewhat affected by this effect.

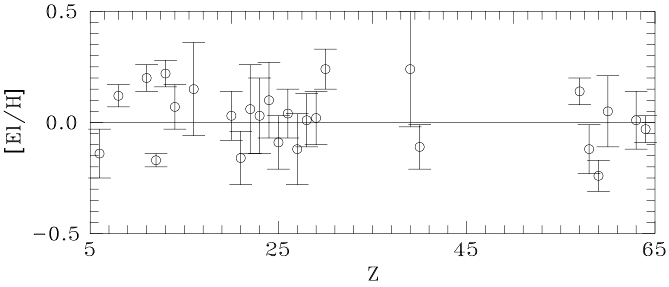

Fig. 4. Averaged elemental abundances for U Sgr. Two-σ interval is indicated for each element abundance.

It should be noted that even for supergiant stars HD 170820 and HD 170886 the measured radial velocities appear to be rather different. For example, accordingly to Mermilliod et al. (1987), Wallerstein (1960) and Hayford (1932) the individual measurements of radial velocities range from –15 km s^{-1} to +26 km s^{-1} for HD 170820, and from –14 km s^{-1} to +13 km s^{-1} for HD 170886. Wallerstein (1960) detected a variability of HD 170820 with mean velocity close to the cluster mean value. Mermilliod et al. (1987) confirmed its variability. Our second program cool supergiant HD 170886 is a star with constant velocity (Mermilliod et al. 1987). Both these stars are considered by Lynga & Lindegren (1998) as cluster members.

Completing this section we have to state that with our present day fragmentary knowledge about the target stars (mainly on radial velocities), all of them, in principle, can be considered as members of M 25. Thus, they are coeval and formed from the same interstellar cloud.

5.2. Elemental abundances of B stars

Inspecting Table 6, which summarizes the chemical abundances of B stars, one notes several interesting features. First is the helium abundance. The two stars with small projected rotational velocities, IC 4725(91) and IC 4725(167), show a marked over- and underabundances of helium, respectively. Both helium-rich as well as helium-weak stars are known among the B stars. Recently Andrievsky et al. (2000) described several blue stragglers in open clusters which display a low helium content (let us rememeber that IC 4725(91) and IC 4725(167) are also classified as blue stragglers). The authors also detected an anti-correlation between the helium content and the silicon abundance: the lower the helium content, the higher the silicon abundance. This also appears to be the case for IC 4725(91), but for IC 4725(167) the silicon abundance is solar.

Both stars with small $v \sin i$ values show low carbon abundances, but normal oxygen content. The carbon abundance was not determined for the rapid rotators as the C II lines could not be measured in their spectra. The infrared oxygen triplet in the spectra of rapid rotators has a well expressed profile allowing one to measure the oxygen abundance in these stars. The stars with high rotation appear to be oxygen deficient.

Finally, one has to note that the neon abundance, where it was measured, is significantly increased, as well as iron abundance in the IC 4725(167) atmosphere. The sharp core of Hα and the small $v \sin\ i$ value measured for this star suggest the possibility that IC 4725(167) is a “shell star”. Such “shell” features are ususally formed in gas that is cooler than the photosphere. Note that Maitzen (1985) considers this star to be chemically peculiar based on photometric measurements.

5.3. Elemental abundances of U Sgr

Fig. 4 shows the average elemental abundances in the U Sgr atmosphere. As easily seen, the essential point concerning its chemical composition is the following: within the 2σ confidence level the cepheid demonstrates solar-like abundances for the great majority of the elements.

As expected for a star which has experienced the dredge-up, its atmospheric carbon abundance is decreased and sodium is slightly enhanced. The carbon abundance in U Sgr [C/H] = -0.14 appears to be in excellent agreement with the theoretically expected value for a star of $6M_{\odot}$: [C/H] = -0.17 according to Schaller et al. (1992).

The oxygen abundance in U Sgr is 0.15 dex higher than predicted by Schaller et al. for the stars after the dredge-up. But if we normalize the carbon and oxygen abundances to the iron content ([Fe/H] = +0.04), then we get [C/Fe] = -0.18 and [O/Fe] = +0.08. These latter values are in somewhat better agreement with the theoretical predictions (Schaller et al. used [Fe/H]=0 as their standard metallicity). The essential point is that the comparison allows one to conclude that the U Sgr abundances of the carbon and oxygen are completely consistent with the theoretical predictions for the stars of $6M_{\odot}$ to within the limitations of the respective analyses.

5.4. Elemental abundances of HD 170820 and HD 170886

These two stars are situated in the upper right corner of the M 25 HR diagram. Two possibilities for their position can be considered: 1) it is due to their first visit to the massive red giant region, or 2) the stars may have already passed the cepheid evolutionary phase and now enjoy their position in the red giant region for the second time.

In principle, the carbon abundance (and probably also sodium) can be considered as a tracer of the operation of the dredge-up process. In this sense, no definite conclusion can be made for HD 170820, because of the lack of carbon lines in our observed spectral region for this star. However, Luck (1994) derived a carbon abundance for HD 170820 that is very much like that that found here for HD 170886. The rather high carbon abundances found could indicate that these stars are in the red giant region for the first time. The abundance of iron group elements in both stars are close to solar. This is demonstrated in Figs. 5 and 6.

5.5. Potential causes of inconsistencies in stellar abundances: atomic diffusion

Only two B stars from the whole sample possess small projected rotational velocities, and further comparison will be based on the

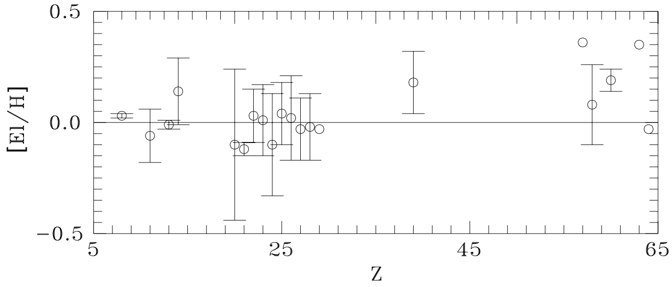

Fig. 5. Elemental abundances for HD 170820.

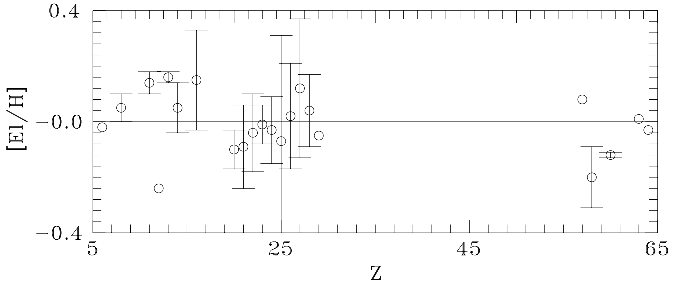

Fig. 6. Elemental abundances for HD 170886.

results obtained for them, and U Sgr, HD 170820, HD 170886. Comparing the abundances of C,O and Fe for above mentioned stars, we see that there is a large degree of discord (in all senses), especially in the carbon abundances. It is especially difficult to understand the lower value of the carbon abundance in the B stars than in their progeny – the supergiants.

With the present state of our knowledge of stellar spectroscopy we can conclude that the relative elemental abundances derived for F/G supergiant stars 1) are likely more reliable than those determined for the hot main sequence stars, and 2) they correspond to the elemental abundances inherent to interstellar medium much more than B star abundances do. The main reasons to believe this are the following: 1) similar spectral lines seen in the supergiant spectra and in the spectra of the Sun and solar-type stars allow one to perform a more direct and correct comparison of the elemental abundances in these stellar groups, while for B stars such a comparison is not possible; 2) any local abundance anomalies that can appear in the stable hot progenitor atmosphere unavoidably will be obliterated after the star becomes a cool supergiant and experiences a large-scale mixing event. The question itself about the stability of the atmosphere of B star (even if the star rotates slowly and no large-scale motions are expected) deserves a special investigation, but anyway we can conclude that we do see the signs of the mixing in the supergiants (the altered superficial carbon and nitrogen abundances, as discussed in the Introduction), and we do not see such signs in the most of the hot main sequence stars (although Lyubimkov 1996, 1998 argues that evidence exists in favour of mixing in main sequence B stars). It is possible that the chemical anomalies detected in B stars could be purely superficial. The most probable mechanism leading to the visible abundances anomalies in B stars is a radiative upward diffusion or gravitational settling of the different species in the stellar atmosphere (Michaud 1970; Michaud et al. 1976).

Such a mechanism has been widely discussed in connection with the problem of the Am stars. As was shown by Roby & Lambert (1990) the underabundances of carbon, nitrogen and oxygen observed in Am stars are consistent with the hypothesis that the abundance anomalies in CP stars are primarily created by atomic diffusion. For CNO elements Gonzalez et al. (1995) calculated radiative accelerations acting on ions in A-F star envelopes. They found that the radiative accelerations appeared to be smaller than the local gravities which can lead to a settling of these elements below the convective zone. Such a settling can explain the general deficiency of CNO elements observed in CP stars. The study of Gonzalez et al. (1995) was performed over the temperature range 6000 K–10000 K. The $T_{\rm eff}$ values of our program B stars are outside this region and this excludes the comparison of the determined CNO abundance with those predicted by the diffusion hypothesis. Nevertheless, inspecting Fig. 8 from Gonzalez, Artu & Michaud and roughly extrapolating [CNO/H]–$T_{\rm eff}$ dependencies one can conjecture, for example, that a carbon deficiency of the order of several tenths of a dex is quite reasonable for the late B stars. However, see below for caveats concerning the reliability of these predictions.

LeBlanc & Michaud (1995) investigated the radiative acceleration of iron. Their theoretical results give a hint that the iron abundance has a tendency to be increased locally in stars with higher temperatures. This could explain the anomalously high iron abundance in IC 4725(167).

In radiative diffusion /gravitational settling theory it is assumed that the atmosphere of the star is stable enough for the effective operation of the diffusion processes. In the real case, any dynamical events in the atmosphere (e.g. meridional circulation caused by rotation, turbulence, etc) can inhibit or alter the diffusion effects. Purely formal consideration of the radiative diffusion/gravitational settling model which ignores the above mentioned dynamical processes in stellar atmospheres can lead to unrealistic results concerning elemental abundance anomalies in stars. For example, Michaud et al. (1976) found that diffusion in Am stars leads to overabundances of three to five orders of magnitudes for heavy elements, whereas overabundances of 1-2 orders of magnitude are observed. At the same time, underabundances of the light elements are predicted by diffusion, but predicted values are much larger than observed. In more recent work, Gonzalez et al. (1995) obtained underabundances of CNO elements that are only marginally consistent with observations (see Fig. 8 from that work).

As far as we know the complete numerical scheme for the solution of the atomic diffusion problem including the dynamical effects in the stellar atmosphere is not yet elaborated. This means that formal calculations of atomic diffusion aimed at reaching quantitative agreement with observations have not yet reached maturity. Therefore, though there are some indications that B star abundances can be linked to the theoretical predictions of the atomic diffusion hypothesis, we have to leave this discussion concerning detected anomalies in B stars at the following point: the anomalies may be only superficial, they may not reflect the general chemical composition of the star, and they also may not correctly reflect the chemical composition of the interstellar medium.

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