ON THE CRIMEA-TEXAS PROJECT "SURFACE ABUNDANCES OF LIGHT ELEMENTS FOR A LARGE SAMPLE OF EARLY B-TYPE STARS"

L.S. Lyubimkov

Crimean Astrophysical Observatory, p. Nauchnyj, Crimea, Ukraine

1. Introduction

Empirical data on the chemical composition of stars provide a unique possibility for testing and correcting modern theories of stellar evolution. Light chemical elements, namely He, C, N and O, in surface layers of young massive stars are of special interest. Actually, their abundances change significantly in stellar interiors during the hydrogen-core burning which is realized in stars of interest through the CNO cycle. If some mixing exists between interiors and surface layers of the stars, appreciable changes of surface abundances of these elements should take place, too. This process can have a noticeable influence on all subsequent evolutionary stages of the stars. Moreover, when these massive stars explode as Type II supernovae at the end of their evolution and eject matter into the ambient interstellar medium (ISM), the mass of ejected elements seems to be strongly dependent on the mixing during this early evolutionary phase known as the main sequence (MS) phase. Since supernova explosions are the main source of ISM enrichment by many elements, this early mixing should be taken into consideration in models of the Galaxy's chemical evolution.

Observational manifestations of the mixing in late O- and early B-type MS stars were reviewed in detail elsewhere (see, e.g., Lyubimkov 1996, 1998; Maeder & Meynet 2000). It should be noted that the first hints of the mixing came more than 25 years ago from studies of the surface helium abundance in hot MS stars (Lyubimkov 1975, 1976; see also Lyubimkov 1988). It was shown that this value increases as the stellar age increases. Later a significant increment was found for the surface nitrogen abundance (Lyubimkov 1984). These data on the He and N enrichment of surface layers of O and B stars during the MS phase were unexpected for the theory of that time. However the present-day theory recognizes a reality of this process and suggests the stellar rotation as a source of the mixing (see, e.g., Meynet & Maeder 2000; Heger & Langer 2000).

Two important details remain incomprehensible from the viewpoint of the theory. First, an interesting dependence of the surface helium abundance He/H on age was found for hot MS stars that are components of close binaries. The dependence seems not to be monotonic; in fact, the initial abundance He/H is unchanged for the first half of the MS lifetime, but then it increases abruptly by about two times (Lyubimkov 1996). There are also some hints of similar non-monotonic increment of He/H for single B stars (Lyubimkov 1998). Second, one can expect that, according to the theory, there are correlations between the He and N abundances at the end of the MS phase, on the one hand, and rotational velocities of the stars, on the other hand. However, all attempts to find such correlations were unsuccessful.

Unfortunately, available data on the He, C, N and O abundances in O and B stars were insufficient in order to understand more in detail the process of mixing and, in particular, to solve two above-mentioned problems. It was necessary to increase strongly the number of the stars observed and to raise an accuracy of the abundances derived. Therefore the project "Surface abundances of light elements for a large sample of early B-stars" was presented as a result of collaboration between the Crimean Astrophysical Observatory (Ukraine) and the University of Texas at Austin (USA). Permanent members of the Crimean team are L.S. Lyubimkov, T.M. Rachkovskaya, S.I. Rostopchin and D.B. Poklad. The American team is presented by Prof. D.L. Lambert. Our general goal was to provide new comprehensive observations for a large sample (about 100) of early B-type MS stars and to complete a thorough analysis of CNO-cycle elements, namely He, C, N and O. A brief description of main results is given below.

2. Observatory

High-resolution spectral observations of 123 B0-B5 stars, which are likely to be in the MS phase, were implemented in 1996-1998 at two observatories, namely the Crimean Astrophysical Observatory (CrAO) and the McDonald Observatory (McDO) of the University of Texas. The 2.6-m telescope and the coude spectrograph with a 1024x256 CCD were used at the CrAO, while the 2.7-m telescope and coude 2D Echelle spectrometer with 2048x2048 CCD were employed at the McDO. All details of the observations and reductions of spectra are described in Lyubimkov et al. (2000, hereinafter Paper I).

There were some limitations when B stars were selected for the observations. The limitations arise from the locations of the stars on the sky, their visual magnitudes and their physical properties. The electronic version of the Bright Star Catalogue (Hoffleit & Warren 1991) has been used for the selection.

In particular, we tried to observe only normal B stars. Spectroscopic binaries, Be stars and variable stars were usually excluded. Nevertheless, 16 of 123 stars from our list were found to show hints of Ha emission, duplicity or pulsations, so they are not normal. We measured for these 16 stars the equivalent widths of HI and HeI lines, but excluded them from further analysis.

Furthermore, we selected rather bright and, therefore, rather near B stars. Two reasons can be given for our selection. First, unlike faint stars, spectra of high quality can be obtained for bright stars. Second, one may expect for distant stars that their initial helium abundance Y and metal abundance Z (by mass) differ from the Y and Z values for stars in the solar neighbourhood. Further analysis will demand the use of evolutionary tracks for determinations of masses and ages of the stars. The tracks depend on Y and Z ; therefore, generally speaking, it is impossible to use one and the same set of the tracks both for near stars and for distant ones. The B stars with the visual magnitudes I 6.7 have been included in our list.

One of our goals was to search for possible correlation between the He, C, N and O abundances and the observed rotational velocities $v \sin i$. So, we selected B stars with a wide range of $v \sin i$ values, from 0 to about 300 km/s where this value is known. For many observed stars the rotational velocities were unknown; they are determined for the first time in this project.

Other details of the star selection, as well as the full list of 123 programme stars are presented in Paper I.

3. Hydrogen and helium lines

Equivalent widths W of two Balmer lines, Hb and Hg, and ten HeI lines were measured for 123 programme stars, as well as of the HeII 4686 line for the hottest ones. The Balmer lines are used as a good indicator of the surface gravity $\log g$, whereas the HeI lines are used for determination of the helium abundance He/H, the microturbulent parameter V_t and the projected rotational velocity $v \sin i$.

All measurements of the equivalent widths have been implemented by the Crimean team. Two hydrogen lines were measured independently by two members of the team, whereas helium lines were measured independently by three members. When comparing different sets of the W values, we obtained a good agreement. The averaged W values are employed in further analysis.

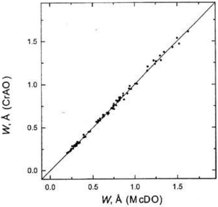

Figure 1: Comparison of the mean HeI equivalent widths measured from the CrAO and McDO spectra for 14 common stars.

It is interesting that there were 14 common stars, for which all these lines have been observed both at the CrAO and at the McDO, so we were able to compare the equivalent widths derived from two sets of spectra. Such comparison for HeI lines is presented in Fig.1. A very good agreement is seen between the CrAO and McDO data; in fact, there is no systematic difference, and the accidental scatter is within ± 5 per cent. The measured equivalent widths, as well as their detailed analysis can be found in Paper I.

4. Basic parameters

As mentioned above, 16 of 123 programme stars are not normal, so our further analysis included 107 remaining stars. We determined basic parameters of these stars, first of all their effective temperatures T_{eff} and surface gravities $\log g$. Both parameters were derived simultaneously on the basis of standard $T_{eff} - \log g$ diagrams. Two colour indices were used as good indicators of T_{eff}, namely the index Q in the UBV photometric system and the index $[c_1]$ in the $uvby$ system. As is known, both values are independent of interstellar extinction. As far as $\log g$ is concerned, equivalent widths W of the above-mentioned Balmer lines, i.e. Hb and Hg, as well as the b-index were used as good indicators of this parameter.

In Fig.2 the $T_{eff} - \log g$ diagrams are shown as examples for two B stars, namely HR 8797 (B0.5 IV) and HR 6588 (B3 IV). Various curves here are the loci from the theoretical models, which predict the observed value for each of the considered parameters, i.e. for two equivalent widths and three photometric indices. For the hotter star, HR 8797, we also display in Fig.2 the curve that corresponds to the HeII 4686 line. It should be noted that all computed values in our analysis are based on Kurucz's (1993) model atmospheres.

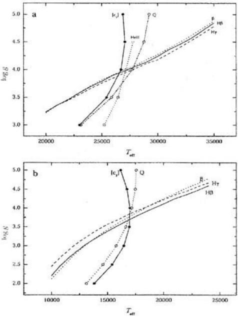

Figure 2: Diagrams for the T_{eff} and log g determination for the stars (a) HR 8797 (B0.5 IV) and (b) HR 6588 (B3 IV).

Furthermore, we found the interstellar extinction in the V band, i.e. the A_v value, basing on the *uvby* photometry. Using three derived parameters, namely T_{eff}, log g and A_v, one can evaluate the distance d of the stars (note that the masses M are necessary as well; they were determined from evolutionary tracks, see below). We found the d values and compared them with distances obtained from the *Hipparcos* parallaxes (ESA 1997). The comparison is presented in Fig.3. The upper panel shows the two sets of d values with their errors. In the lower panel the relative difference between our and the *Hipparcos* data including common errors of both sets is displayed. When taking into account uncertainties in the d values, one may see that agreement between the two sets is rather good. In particular, the scatter in the lower panel is mostly within ±50 per cent and can be explained, as a rule, by errors of the d determination.

In Fig. 4 the T_{eff} and log g values derived for programme stars are compared with the evolutionary tracks of Claret (1995). One may see that most of the stars correspond really to the MS phase. About ten stars have very likely recently completed this phase. Three stars are marginally below the Zero Age Main Sequence (ZAMS), but the uncertainty in their surface gravity would allow them to be on the ZAMS. Interpolating among the tracks we estimated the masses M of the stars. Furthermore, using the M values, we determined the radius R and luminosity L. The age t was evaluated as well from Claret's computations.

The derived values of T_{eff}, log g, d, M and other parameters for 107 stars are presented and discussed in Lyubimkov et al. (2002, Paper II). Interpolating among Kurucz's (1993) model atmospheres, we found for each star the model atmosphere according to its T_{eff} and log g values. These models were used in further analysis of the He, C, N and O abundances.

5. Helium abundances and microturbulent parameters

Non-LTE analysis of HeI lines in spectra of 102 programme stars was implemented in order to determine the helium abundance He/H, the microturbulent parameter V_t and the projected rotational velocity $v \sin i$ (five stars of 107 were omitted). A determination of He/H and V_t was based on the equivalent widths measured in Paper I; the lines 4471 and 4922 were used as indicators of He/H and the lines 4713, 5016, 5876 and 6678 were used as indicators of V_t. The velocities $v \sin i$ were found from profiles of the same lines.

The He/H-V_t diagram for the star HR 8797 is shown in Fig.5 as an example. An idea of such diagram is similar to the well-known T_{eff} − log g diagram (see Fig.2); various curves here are the loci from the theoretical models, which predict the ob-

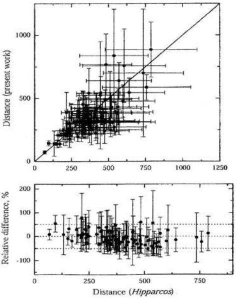

Figure 3: Comparison of our distances d (pc) with the *Hipparcos* d values.

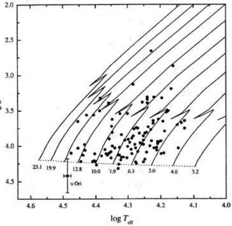

Figure: 4. Location of programme stars on the evolutionary diagram. Claret's (1995) evolutionary tracks are shown for stars with masses M from 3.2 to 25.1$M_{\odot}$. Dotted line corresponds to the ZAMS.

served equivalent widths of the used helium lines. This diagram allow to obtain simultaneously both parameters, He/H and V_t, basing on the different dependence of the lines on the microturbulent parameter V_t. The 4471 and 4922 curves, on the one hand, and the 4713, 5016, 5876 and 6678 curves, on the other hand, show a number of intersections; their averaged coordinates give He/H and V_t for the star. In particular, for HR 8797 the parameters He/H=0.131 and V_t=13.8 km/s were obtained. The He/H and V_t values for 102 stars are presented in Lyubimkov et al. (2003, Paper III).

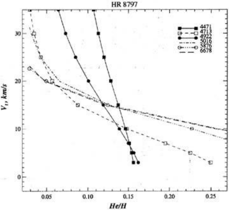

Figure 5: Diagram for the *He/H* and V_t determination for the star HR 8797.

Two of 102 stars were found to be the helium-weak stars. Since one of our objectives was a search of possible correlations of He/H and V_t with stellar masses M, we divided the remaining 100 stars into three groups as follows. Group A includes the stars with relatively low masses between 4.1 and 6.9$M_{\odot}$, 42 objects in all ($M_{\odot}$ is the solar mass). Group B contains the stars of intermediate masses between 7.0 and 11.2$M_{\odot}$, 46 objects in all. Group C includes the most massive stars with M between 12.4 and 18.8$M_{\odot}$, 12 objects in all.

We analyzed a relation between the microturbulent parameter V_t and the relative age t/t_{ms} for each group separately (here t_{ms} is the MS lifetime). In group A the parameter V_t seems to be small for all stars independently of t/t_{ms}. The V_t values vary within the 0-5 km/s region, as a rule. Similar low velocities V_t were found for stars of group B with the relative ages $0.0<t/t_{ms}<0.8$, however the evolved stars with $0.8<t/t_{ms}<1.02$ showed a large scatter of V_t from 0.3 to 11.0 km/s. For most massive stars of group C, in contrast with group A and B, a strong correlation between V_t and t/t_{ms} was obtained. Actually, for the non-evolved stars with $t/t_{ms}<0.3$ the V_t values varied from 4 to 7 km/s, whereas for the most evolved stars with $t/t_{ms}>0.8$ the high velocities V_t in the 16 to 23 km/s range were found.

It is interesting that, when V_t>7 km/s, the V_t(HeI) values determined from HeI lines are systematically overestimated as compared with the V_t(OII,NII) values derived from OII and NII lines. Moreover, this discrepancy tends to increase as V_t increases, so the most marked difference takes place for hottest evolved B giants. One may suppose that the velocity gradient due to mass loss is very likely to exist in atmospheres of such giants, like O and B supergiants. This effect can be a principal cause of overbroadening of HeI lines as compared with weaker OII and NII lines (see Paper III for details).

We analyzed as well a relation between the helium abundance He/H and the relative age t/t_{ms}. A correlation was found for each of the groups A, B and C, so the helium abundance tends to increase with the age. For instance, Fig.6 displays this relation for stars of group A. The straight line drawn by the least squares method shows that the He/H value increases from 0.105 to 0.134 during the MS phase when t/t_{ms} varies from 0 to 1. Therefore, the mean helium enrichment of atmospheres of the 4.1-6.9 $M_{\odot}$ stars is 28 per cent.

The most pronounced helium increment was found for most massive stars, i.e. for group C. When using the V_t(HeI) values derived from HeI lines, we obtained for this group the mean He enrichment of 43 per cent, while when the V_t(OII,NII) values based on OII and NII lines are employed, the He abundance increases on the average by 2.2 times. It should be noted that the He/H values based on the V_t(OII,NII) scale are in better agreement with the

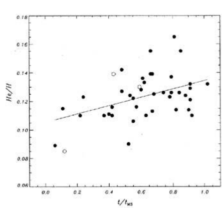

Figure 6: The helium abundance as a function of the relative age for stars of group A. The straight line is drawn by the least-squares method.

theory (see Paper III). There is a possibility that such massive single stars, like massive components of binaries, keep their initial He abundance unchanged during the first half of the MS lifetime.

6. Rotational velocities

A determination of the projected rotational velocities $v \sin i$ for 102 programme stars was based on analysis of profiles of the same HeI lines; the individual parameters He/H and V_t were taken into consideration for each star. The non-LTE profiles computed for the various $v \sin i$ values were fitted to the observed ones to derive $v \sin i$. It is important that a difference in $v \sin i$ for various HeI lines was found to be small. The averaged rotational velocities are presented in Paper III; they vary from 5 to 280 km/s. It should be noted that for many stars the $v \sin i$ values have been not determined earlier.

The theoretical models of rotationally mixed stars predict a strong dependence of the helium enrichment during the MS phase on the rotational velocity. Unfortunately, spectral observations of stars allow to obtain only the projected rotational velocity $v \sin i$, but not directly the equatorial velocity v. Nevertheless, a comparison of the derived He/H values with $v \sin i$ would be useful for a check of the theory.

We compared He/H with $v \sin i$ for stars with relative ages $t/t_{ms} > 0.7$, i.e. close to the MS termination. When the abundances He/H are based on the V_t(OII,NII) scale, there is an obvious trend: the stars with the greater velocities $v \sin i$ tend to have the higher final abundances He/H.

Therefore, a qualitative agreement with the theory takes place.

7. Concluding remarks

A significant part of the project is already implemented. Actually, high-resolution spectra of more than 100 early B stars were obtained. A number of basic parameters was determined including the effective temperatures T_{eff}, surface gravities log g, masses M, ages t etc. A detailed non-LTE analysis of HeI lines was effected to find the helium abundance He/H, microturbulent parameter V_t and rotational velocity $v \sin i$. Relations between He/H and V_t, from the one hand, and M, t/t_{ms} and $v \sin i$ from the other hand, were constructed. It was confirmed that there is the helium enrichment during the MS phase, which correlates with the masses M and rotational velocities $v \sin i$. It is necessary to note that from the outset we tried to get a highest accuracy on each stage of this work.

At present we are implementing a last stage of the project, i.e. an analysis of CII, NII and OII lines on the basis of non-LTE computations. Our goal is an accurate determination of the C, N and O abundances and a search for correlations with M, t/t_{ms} and $v \sin i$.

References

ESA, 1997, *The Hipparcos and Tycho Catalogues, ESA SP-1200. ESA, Noordwijk.*

Heger A., Langer N., 2000, *Ap.J.*, **544**, 1016.

Hoffleit D., Warren W.H., Jr, 1991, *The Bright Star Catalogue, 5th revised edn. ADS, Srasbourg* (electronic version).

Kurucz R.L., 1993, CD-ROM 13.

Lyubimkov L.S., 1975, *Pis'ma Astron. Zh.*, 1, #11, 29.

Lyubimkov L.S., 1976, *Izv. Krym. Astrofiz. Obs.*, **55**, 112.

Lyubimkov L.S., 1984, *Astrofizika*, **20**, 475.

Lyubimkov L.S., 1988, *Astrofizika*, **29**, 479.

Lyubimkov L.S., 1996, *Astrophys. Space Sci.*, **243**, 329.

Lyubimkov L.S., 1998, *Astron. Zh.*, **75**, 61 (*also Astron. Rep.*, **42**, 52).

Lyubimkov L.S., Lambert D.L., Rachkovskaya T.M., Rostopchin S.I., Tarasov A.E., Poklad D.B., Larionov V.M., Larionova L.V., 2000, *Mon. Not. Roy. Astron. Soc.*, **316**, 19 (Paper I).

Lyubimkov L.S., Rachkovskaya T.M., Rostopchin S.I., Lambert D.L., 2002, *Mon. Not. Roy. Astron. Soc.*, **333**, 9 (Paper II).

Lyubimkov L.S., Rostopchin S.I., Lambert D.L., 2003, *Mon. Not. Roy. Astron. Soc.* (in press, Paper III).

Maeder A., Meynet G., 2000, *Ann. Rev. Astron. Astrophys.*, **38**, 143.

Meynet G., Maeder A., 2000, *Astron. Astrophys.*, **361**, 101.