A&A manuscript no.
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ASTRONOMY
AND
ASTROPHYSICS
26.2.1996

Boron in main sequence B stars: a critical test for rotational mixing

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Received ; accepted

Abstract. Recently, Venn et al. (1996) showed that the strength of the UV line of B II in five Galactic main sequence B stars — i.e. in 100% of their sample — can only be understood if the boron abundance in these stars is considerably less than the meteoritic/solar boron abundance of log $\epsilon(B)$ = 2.88 (Anders & Grevesse 1989). Furthermore, a spread of the boron abundances in these otherwise similar stars appears to indicate that the boron depletion occurs during the main sequence evolution.

We analyze the results of recent stellar evolution calculations (Fliegner & Langer 1996) for stars of 10 and $15 M_{\odot}$ which include the effects of rotation on the stellar structure as well as various mixing processes triggered thereby, and an appropriate nuclear network to follow the evolution of all elements from hydrogen to silicon. Mass loss, at the observed and predicted rates for B stars, is found to have little effect on the boron depletion. The rotating models predict a distinct correlation between nitrogen enhancement and boron depletion, as the thermonuclear destruction of boron occurs in the outer stellar envelope but the synthesis of nitrogen occurs in the deep interior of the stars. Thus, the N/B ratio reflects the efficiency of the mixing processes in quite different stellar layers. The qualitative agreement of this correlation with the observed boron and nitrogen abundances of main sequence B stars provides the strongest evidence for rotational mixing acting in massive main sequence stars so far.

Key words: stars: abundances – stars: interiors stars: early-type – stars: evolution

1. Introduction

Existing stellar evolution calculations have not been entirely successful at reproducing some observational properties of early-type stars in the 10 to 20 $M_{\odot}$ range ($c.f.$, Langer 1992, Langer & Maeder 1995). This mass range is of special interest since these stars dominate the nucleosynthesis and distribution of elements in galaxies, and they are important contributors to the integrated light from galaxies used for population syntheses.

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In general, the surface abundances in models calculated without rotation remain intact until the first dredge-up of H-burned material on the red giant branch (e.g.. Schaller et al. 1992). Since H-burning is dominated by the CNO-cycle in this mass range, then the surface abundances of carbon, nitrogen, and oxygen are predicted to change in a discernible way. However, there is a growing amount of evidence to suggest that the abundances of CNO do not retain their natal values until the stars reach the red giant branch.

So called OBN stars, among them main sequence stars, have been found to be extremely enriched in CNO-cycled material (Schönberner et al. 1988, cf. also Walborn 1988). Gies & Lambert (1992) determined CNO abundances in unevolved B-stars and suggested that their spread is larger than expected from random errors in the analysis. In particular, they point out that the range in oxygen abundances is much less than in nitrogen or carbon, and that the nitrogen abundances tend to be slightly enhanced while the opposite is true of carbon, as expected from slight mixing with CNO-processed layers.

Venn (1995) showed that the abundances of CNO in 5 to 20 $M_{\odot}$ Galactic A-type supergiants are also not the pristine values, but appear to be the result of partial mixing with CNO-cycled layers. Since the A-supergiants do not have first dredge-up values of CNO, they are not evolving on blue-loops after having visited the red giant branch. Finally, Lennon (1994) also finds that B-type supergiants in the Galaxy show evidence for mixing with CNO-cycled gas. Examination of Lennon's C/N ratios suggests that the amount of mixing increases with the mass/luminosity of the star.

After the early attempt of Endal & Sofia (1978), several models including rotationally induced mixing as proposed by Zahn (1983, 1992) have been presented. According to Maeder (1987), stars with $M \gtrsim 25 M_{\odot}$ might evolve through a bifurcation, i.e. evolving as chemically homogeneous for rotation speeds above a critical value. Langer (1991) found rotational mixing able to explain the CNO anomalies of the SN 1987A progenitor. Langer (1992) showed that rotational mixing might be responsible for the helium enrichments found in main sequence O stars (Herrero et al. 1992). Finally, Denissenkov

(1994) has shown that rotational mixing in $10M_\odot$ stars may change the CNO surface abundances as they evolve off the main sequence.

Recently, Fliegner & Langer (1996) have completed a set of stellar evolution calculations for stars of various masses and initial rotation rates, including the effects of a time-varying internal angular momentum distribution on the stellar structure and on rotationally induced mixing processes (cf. Endal & Sofia 1978). Due to the incorporation of extended nuclear networks, they can predict the variation of the surface abundances with time for essentially all isotopes lighter than silicon. Therefore, these calculations allow a comparison with the recent determination of the boron abundances in main sequence B stars by Venn et al. (1996, henceforth VLL), which, as we intend to demonstrate in this *Letter*, provides an essential test of the hypothesis of rotationally induced mixing in massive stars.

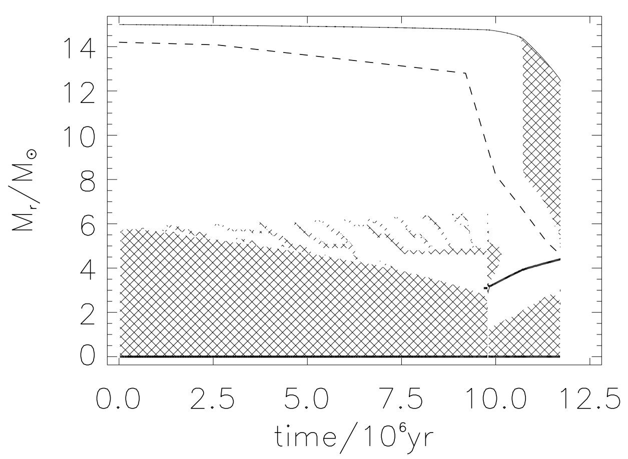

Fig. 1. Internal structure of a $15M_\odot$ star during core hydrogen and helium burning. The solid line on top indicates the total mass of the star as function of time. Hatched areas designate convectively unstable mass zones in the star. The full drawn line at $M_r \simeq 4M_\odot$ and $t \gtrsim 10^7$ yr designates the location of the H-burning shell during core helium burning. The dashed line indicates the threshold temperature for boron destruction (see text).

2. Stellar boron abundances

Interpretation of any stellar boron depletion as due to mixing requires knowing the initial boron abundance, yet this value in young stars is currently uncertain. The meteoritic abundance is given as logϵ (B)= 2.88 ±0.04 by Anders & Grevesse (1989). More recently, Zhai & Shaw (1994) determined a slightly lower meteoritic value of logϵ (B) = 2.78 ±0.05.

LTE abundances of boron in early-type stars were first determined by Boesgaard & Heacox (1978) from observations of 16 stars from 9000 to 25 000 K. They found a mean boron abundance of logϵ (B)= 2.3 ± 0.2, about 0.6 dex less than solar. The UV line list, atomic data, and model atmospheres have improved substantially in the past two decades. Nevertheless, Boesgaard & Heacox's value for the B stars is similar to Lemke, Lambert, & Edvardsson's (1993) LTE boron abundances from a B I resonance line in two F stars (cf., however, Kiselman & Carlson 1995).

Recently, boron abundances have been calculated by VLL for eight stars from 9500 to 25 000 K, including six B stars, from IUE archival spectra and a semi-empirical line list built upon Kurucz's (1988) configuration-interaction calculations. For no star could the solar/meteoritic boron abundance reproduce the UV feature; a lower boron abundance was always needed. The results of VLL for the B stars are discussed in Sect. 4 below.

3. Model predictions and the key role of boron

As outlined in Sect. 1, evolution calculations invoking rotational mixing have been successful in reproducing helium and CNO anomalies in massive stars. However, most of the observations might be explained equally well by quite different models, e.g. as the result of close binary evolution (cf. Langer 1992). The abundances of the light elements, Li, Be, and B, may play a key role in discriminating the effects of rotation and accretion. Li and Be are already used in this role in investigations of cool stars (cf. Boesgaard & Lavery 1986, Deliyannis & Pinsonneault 1993), but are unobservable in early-type stars. Boron, however, is observable through the UV resonance line of B II at 1362Å.

In contrast to helium and CNO, the light elements are destroyed relatively close to the stellar surface. For both stable boron isotopes, ^{10}B and ^{11}B, the life time against proton capture, the dominant destruction mechanism, is equal to the main sequence life time of a $10M_\odot$ star (10^7 yr) at a temperature of roughly 7 10^6 K. This temperature occurs sufficiently deep inside the stellar envelope (i.e. roughly $1M_\odot$ below the surface; cf. Fig. 1) that its surface abundance can not be altered due to mass loss alone on the main sequence in the B star regime. Thus, the boron abundance in B stars is a critical test of mixing processes in the upper stellar envelope, while CNO and helium abundances additionally trace the mixing in deeper layers.

For main sequence secondary stars in massive close binary systems, a strong boron depletion must also be expected due to the transfer of nuclear processed matter; however, a very noticeable CNO-signature is always present in this case (cf. e.g. de Loore & De Greve, 1992). Therefore, the existence of boron depleted stars with a roughly normal nitrogen abundance would be a clear indication of rotational mixing.

Fig. 2 shows the stellar evolution tracks of non-rotating models of 10 and $15M_\odot$, and of a moderately ($v_{\rm eq} \simeq 280$ km/s at the ZAMS) and a rapidly rotating ($v_{\rm eq} \simeq 400$ km/s) $10M_\odot$ star in the HR diagram. The models have been computed for a composition of (X,Y,Z)=(0.70,0.28,0.02), with up-to-date microphysics input, and including the effects of rotation on the stellar structure and on angular momentum and chemical element transport (see Fliegner & Langer, 1996, for details). The dependence of the stellar tracks on the rotation rate, mostly pro-

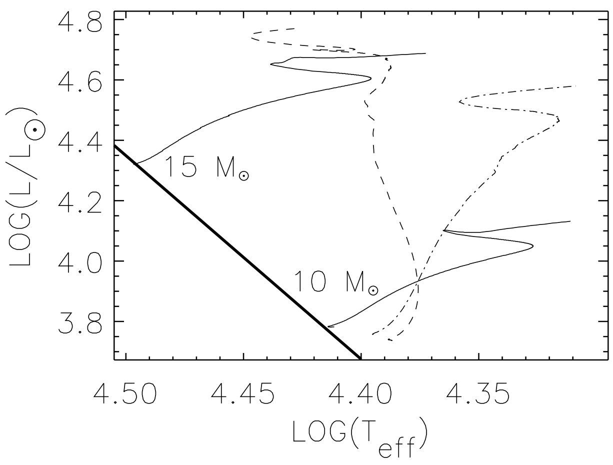

Fig. 2. Evolutionary tracks in the HR diagram for non-rotating 10 and $15 M_\odot$ stars (solid line), and a moderately (dashed-dotted) and rapidly rotating (dashed) $10 M_\odot$ star, during the main sequence evolution. The thick solid line marks the ZAMS position for non rotating models.

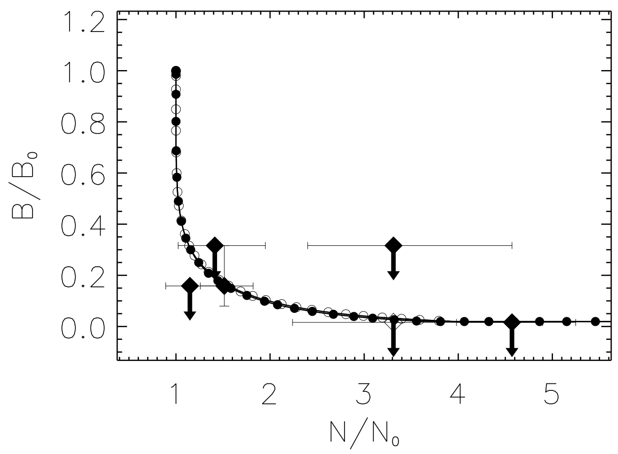

Fig. 3. Boron depletion versus nitrogen enrichment for rotating stars of $10 M_\odot$ during the main sequence evolution. Open circles correspond to the moderately, filled circles to the fast rotating model. Two neighboring symbols on each line indicate a constant distance in time of 10^6 yr. Diamonds indicate the location of the five B main sequence stars (filled symbols) and one B giant (open symbol) of Venn et al.'s (1996) sample. Arrows designate upper limits.

duced by the fact that faster rotating stars obtain larger helium cores due to more efficient mixing of hydrogen into the core (cf. Langer 1992), has the following consequence. Assuming that stars are born with a distribution of initial rotation rates, there is no clear trend of changes in surface composition due to rotational mixing as a function of the proximity to the zero age main sequence. For example, a non- or slowly rotating star of $15 M_\odot$, which keeps its initial surface abundances during the main sequence evolution, leads to the same point in the HR diagram as a rapidly rotating $10 M_\odot$ star which has changed surface abundances. This may explain the lack of a correlation of the N-overabundance with stellar age found by Gies & Lambert (1992).

However, due to the different sampling depths of boron and (e.g.) nitrogen, the models of Fliegner & Langer (1996) predict a distinct evolution in the boron-depletion vs. nitrogen-enhancement. The boron vs. nitrogen predictions are remarkably similar for models of different masses and rotation rates (see Fig. 3). This is because the evolution proceeds through three different stages of surface abundances: i) An initial phase of unaltered abundances, which lasts roughly $1.5\ 10^6$ yr. ii) Boron depletion occurs at the stellar surface without a change in nitrogen, since boron survives in only the outermost $1 M_\odot$ and nitrogen is synthesized at much deeper layers. iii) After another time span of about $7\ 10^6$ yr, nitrogen starts to be enriched with only a small additional boron depletion.

4. Comparison with observed boron and nitrogen abundances

Due to the degeneracy of the HRD positions during the main sequence evolution (see Sect. 3 and Fig. 2), a comparison of the observed stellar boron abundances and effective temperatures with theoretical results may be spurious. However, a distinct correlation of the boron depletion with the nitrogen enhancement can be expected. VLL have already looked into the observational boron versus nitrogen dependence, considering eight stars, among them two A supergiants. They found only a weak trend. To reinvestigate this problem here, and to arrive at a comparison with theoretical results, we consider only the B stars in the VLL sample, and reconsider the effect of the adopted initial boron and nitrogen abundances.

For the observed stars, we have adopted the following natal abundances: the mean nitrogen abundance in ~ 10 M$_\odot$ B stars (mean of 70 non-supergiant B stars from Gies & Lambert 1992, Kilian 1992, and Cunha & Lambert 1992, 1994) is $\sim$0.2 dex less than solar. However, the stellar evolution models with rotation predict mixing on the main-sequence and therefore some nitrogen enriched B-stars . Thus, we choose $\log \epsilon$(N)=7.6 as the natal nitrogen abundance, which is about the median abundance of the B-stars in these samples. A larger initial nitrogen abundance would shift the stellar data points in Fig. 3 to the left.

The B star boron abundances derived by VLL (and in the Boesgaard & Heacox sample) are a factor of $\sim$ 4 (0.6 dex) smaller than the solar system value. Thus, one might argue for a less than solar interstellar boron abundance as appears to be the case for nitrogen. However, there are two arguments against this proposition. Firstly, the difference of a factor of 4 is difficult to understand in terms of Galactic chemical evolution models, which do not predict large differences between the solar and the present day ISM composition (cf. e.g. Timmes et al. 1995). Secondly, the data from VLL indicate that the boron abundances of main sequence B stars show a large spread, which suggests a boron depletion during main sequence evolution. Therefore, for the evaluation of boron in Fig. 3, we adopted the solar system boron abundance as given in Zhai & Shaw (1994), although a slightly smaller natal boron abundance in B stars could be possible.

Fig. 3 shows that the prediction from the rotating stellar models and the observed boron versus nitrogen abundances agree well. As noted in Sect. 3, this is not trivial since the thermonuclear processes which affect the boron and the nitrogen abundances occur in completely different stellar layers. In particular, the existence of boron depleted stars with a normal nitrogen abundance (i.e. the stars HD 886, HD 29248, and HD 216919; cf. VLL) appears to specifically support the idea of rotational mixing, since such abundance ratios are not considered a possible result of close binary evolution (cf. Sect. 3).

5. Discussion

The theory of rotating stars and corresponding internal mixing processes exists, yet only in a rudimentary form, and it still involves considerable uncertainties. Therefore, properties of rotating stellar models which depend on this theory are not quantitatively very reliable yet. This holds also for the theoretically derived surface boron abundances in the sense that one might not expect a good agreement between the absolute value of the boron abundance of an individual star with a certain age and rotation velocity and a corresponding model. However, Fig. 3 shows that the correlation of boron versus nitrogen is almost independent of the stellar rotation rate, and thus is also not expected to be sensitive to uncertain parameters in the theory of rotational mixing. It is the mere fact that boron is destroyed in the outer envelope while nitrogen is produced in the deep stellar interior that determines the qualitative shape of the boron versus nitrogen relation — i.e. an early surface boron depletion and only later a nitrogen enhancement — and which makes a meaningful comparison between theory and observations possible.

Despite the fact that the average initial abundances of boron and nitrogen for Galactic B stars are not very well known, the agreement of the theoretical B vs. N correlation with the observed values derived by VLL and Gies & Lambert (1992) is remarkable. The observed abundance pattern has the following properties (Fig. 3):

(1) Main sequence B stars appear to be boron deficient compared to the solar system.

(2) A considerable spread in the boron abundances of very similar main sequence B stars indicates that boron depletion occurs during the main sequence evolution.

(3) A large fraction of main sequence B stars are not strongly enriched in nitrogen.

(4) Another fraction of main sequence B stars are N-enriched.

All four properties are consistent with models of rotating massive main sequence stars, and thus add to the growing list of evidence in favour of rotational mixing. Moreover, the first listed property appears inconsistent with competing massive close binary models in a statistical sense, and the first and the third points together are directly inconsistent with those models, but specifically support the idea of rotational mixing.

In summary, boron abundances appear to be an extremely important diagnostic for the evolution of B stars and cooler luminous stars since rotational mixing on the main sequence deeply affects the post-main sequence evolution. Therefore, a comprehensive study of this element with highest quality data (HST GHRS) for hot stars is highly desirable. This, as well as the analysis of boron in supergiants (cf. VLL) may allow us to considerably reduce persisting uncertainties in the theory of rotational mixing, which is not only fundamental for studying stars within the mass range considered here, but which is also required for a thorough understanding of more massive stars (Maeder 1987, Fliegner & Langer 1996).

Acknowledgements. This work has been supported by the Deutsche Forschungsgemeinschaft through grant No. La 587/8-2

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