Deep mixing in slowly-rotating B dwarfs: the possible role played by magnetic fields

Thierry Morel

Katholieke Universiteit Leuven, Departement Natuurkunde en Sterrenkunde, Instituut voor Sterrenkunde, Celestijnenlaan 200D, B-3001 Leuven, Belgium

Abstract. Evolutionary models for massive stars which take into account rotational mixing effects do not predict any core-processed material at the surface of B dwarfs with low rotational velocities. We present a detailed and fully homogeneous non-LTE abundance analysis of a sample of largely unevolved B stars which points to the existence of a population of intrinsically slowly-rotating, yet nitrogen-rich objects contrary to theoretical expectations. These observations are discussed in relation to the boron content and the (weak) magnetic field detected in some targets.

Keywords: early-type stars, stellar interiors, magnetic fields, stellar abundances
PACS: 97.10.Tk, 97.10.Cv, 97.10.Ld, 97.20.Ec

BACKGROUND AND MOTIVATION FOR THIS STUDY

Fast rotation is one of the most distinctive features of massive stars and may lead to the dredge up of CNO-processed material from the convective core to the surface. On the other hand, the boron surviving close to the stellar surface after the star has evolved off the zero age main sequence (ZAMS) will quickly be transported downwards to deeper layers where it will easily be destroyed, even in the case of shallow mixing. Therefore, the B and CNO surface abundances of OB stars are powerful probes of rotation-related mixing phenomena throughout the entire stellar interior and at different evolutionary phases, and can thus be used to constrain theoretical models.

Evolutionary models do not predict any detectable N excess in main-sequence B stars with rotation rates below 100 km s^{-1} (Heger & Langer 2000; Meynet & Maeder 2003). However, evidence has already been presented for a substantial amount of N-enriched material at the surface of such slowly-rotating objects (e.g. Gies & Lambert 1992). We have recently revealed the same peculiarity in a number of β Cephei variables, which have been inferred from asteroseismic or line-profile variation studies to be intrinsically very slow rotators (Morel et al. 2006). As an illustration, the B1.5–B2 subgiant δ Cet has a true rotation rate of at most 28 km s^{-1}, yet exhibits an unexpected N excess reaching a factor about four. Such an extra amount of deep mixing in OB dwarfs would clearly have consequences on their post main-sequence evolution and other related, important issues. Here we extend this study by presenting a non-LTE abundance analysis of a sample of 20 dwarfs/(sub)giants comprising stars not established as pulsating variables and *all* boron-depleted B stars known to date, with special emphasis on the possible role played by magnetic fields to shape their CNO surface abundance pattern.

METHODS OF ANALYSIS

The atmospheric parameters are derived purely on spectroscopic grounds: $T_{\rm eff}$ is determined from the Si ionization balance, $\log g$ from fitting the collisionally-broadened wings of the Balmer lines and the microturbulent velocity from requiring the abundances yielded by the O II lines to be independent of the line strength. All stars are slow rotators and classical curve-of-growth techniques were used to derive the elemental abundances. Fully line-blanketed Kurucz atmospheric models and the non-LTE line formation codes DETAIL/SURFACE have been used (for full details, see Morel et al. 2006).

A POPULATION OF SLOWLY-ROTATING, YET NITROGEN-RICH B DWARFS

The ratios of the CNO abundances ([N/C] and [N/O]) are shown as a function of the boron abundances collected from the literature in Fig.1. Several of our targets have a detected weak magnetic field (e.g. ζ Cas, ξ^1 CMa, τ Sco and β Cep) and are distinguished from the stars without detections using filled symbols. Five stars lacking boron data, but which have been searched for magnetic fields are plotted off scale to the right-hand side of this figure. Three classes of stars with distinct chemical properties, and which may define an evolutionary sequence, can be discerned (see boxes in the upper, left-hand panel):

- **Group I** – These 5 stars exhibit solar [N/C] and [N/O] ratios amounting to about –0.6 and –0.9, respectively (Asplund et al. 2006). This is accompanied by little, if any, boron depletion relative to the meteoritic value ($\log \epsilon$[B]=2.78 dex; Zhai & Shaw 1994). Substantial mixing has not yet taken place.
- **Group II** – Two stars (π^4 Ori and HD 36591) are B depleted by about 2 orders of magnitude, yet have solar N abundances. Shallow mixing has dramatically depleted boron in the superficial layers, but deep mixing is either absent or has yet to bring detectable amounts of CN-cycle burning products to the surface. As can be seen in Fig.1, the chemical properties of these stars are not well reproduced by current theoretical models.
- **Group III** – Another population (8 stars) presents very low B abundances (indeed mostly upper limits) coupled with an N enrichment reaching a factor $\sim$3-4 (the separation between the two subsamples of N-normal and N-rich stars is clearer in terms of the [N/C] ratio, which is the most robust diagnostic for an N excess). This abundance pattern is in agreement with the predictions of evolutionary models, but only for initial velocities exceeding $\sim$200 km s^{-1} (Fig.1). This is well above the true rotation rates of three of these objects (ζ Cas, δ Cet and β Cep, with ΩR in the range 14–55 km s^{-1}), even after accounting for the loss of angular momentum during core-hydrogen burning (the others have $\Omega R \sin i < 51$ km s^{-1}).

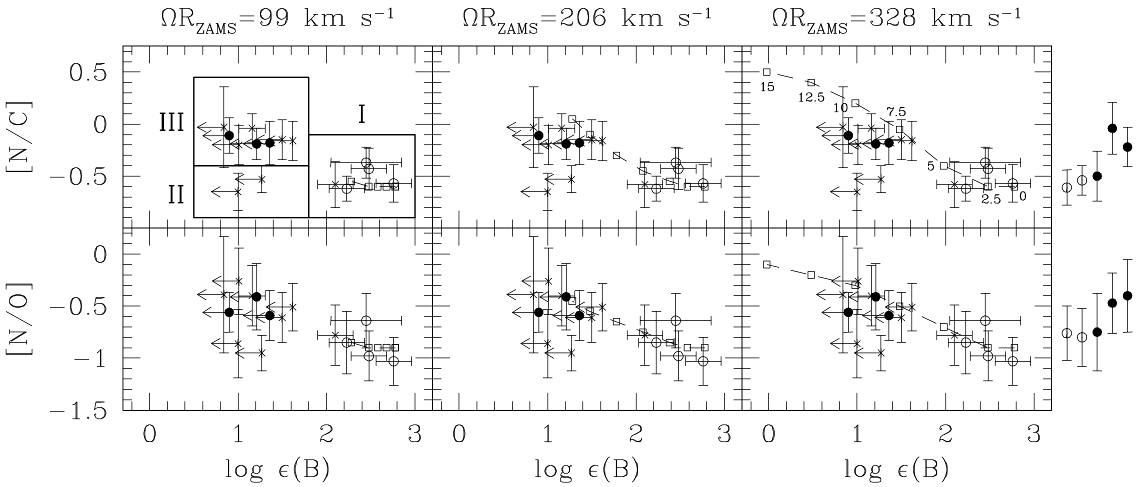

FIGURE 1. [N/C] and [N/O] ratios, as a function of the B abundances (filled circles: stars with a detected magnetic field; open circles: stars with null detections; crosses: stars without magnetic data). The observations are compared with the theoretical predictions of Heger & Langer (2000) for a 12 $M_\odot$ star and three different values of the rotational velocity on the ZAMS: 99 (left-hand panels), 206 (middle panels) and 328 km s^{-1} (right-hand panels). The locus in each panel (dashed line and open squares) defines an age sequence with the time elapsed from the ZAMS increasing leftwards: from t=0 to 15 Myrs (0 to 12.5 Myrs for $\Omega R_{\rm ZAMS}$=99 km s^{-1}) in steps of 2.5 Myrs. The initial [N/C], [N/O], and boron abundances at t=0 have been taken as –0.6, –0.9 (representative of the baseline solar value; Asplund et al. 2006) and $\log\varepsilon$(B)=2.78 dex (meteoritic value; Zhai & Shaw 1994), respectively. The boxes in the upper, left-hand panel delineate the three classes of stars (Groups I, II and III) with different chemical properties (see text).

CONCLUSIONS AND PERSPECTIVES

Evolutionary models incorporating rotational mixing do not predict the N excess observed at the surface of our targets (any carbon depletion is expected to reach levels comparable to the uncertainties, and is indeed not detected). A similar problem may be encountered in low-metallicity environments, such as the Magellanic Clouds (Trundle et al. 2007). Mass transfer processes in close interacting binaries do not appear a viable explanation for the N overabundances observed in our sample. On the other hand, this class of N-rich stars does not seem to be only restricted to large-amplitude pulsators (see Morel et al. 2006), which argues against a pulsational origin. No relationship is found between the occurrence of a nitrogen excess and the evolutionary status, the mass or the rotation rate (Fig.2). This suggests that an additional parameter may play a key role in the appearance of N-enriched material at the stellar surface.

Interestingly, a higher incidence of an N excess in the magnetic stars seems to emerge in our data: all (but one) magnetic stars are N rich, whereas all stars without a magnetic field detection are N normal (Fig.1). Great caution should be exercised at this stage considering the paucity of the magnetic field measurements, but sensitive spectropolarimetric observations of several N-rich stars have recently been carried out using FORS1/VLT (Hubrig et al., in prep.). Should this trend be confirmed, this would open the possibility that even weak surface magnetic fields (at the ∼100 G level) could significantly alter the photospheric abundances of slowly-rotating B stars during the early phases of their

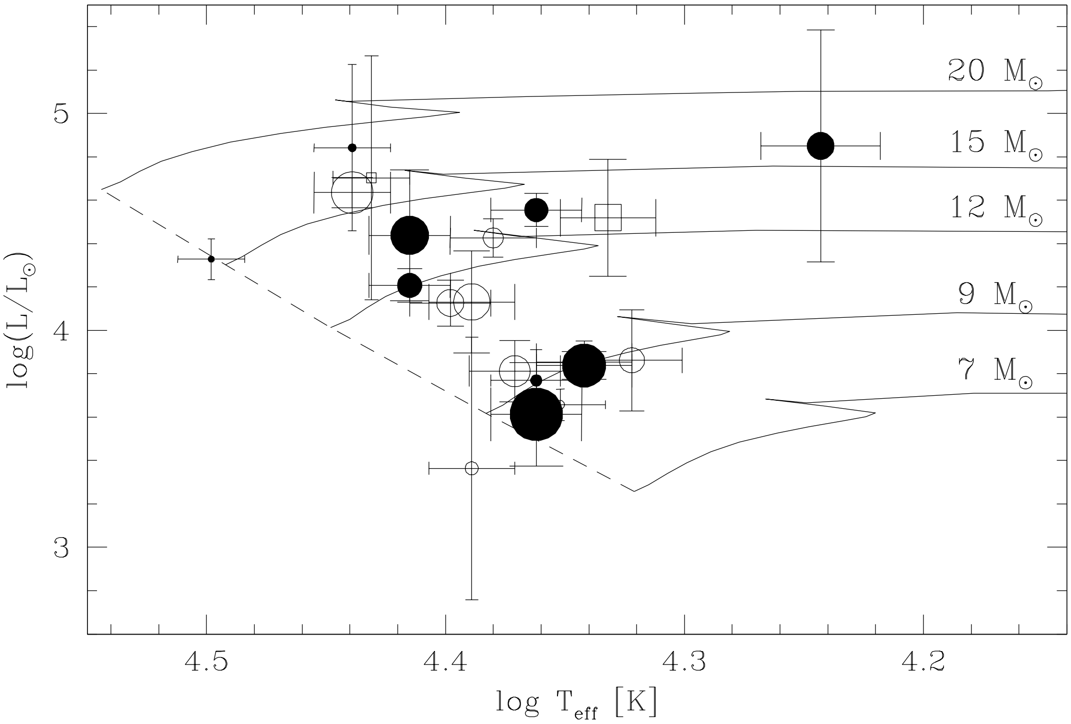

FIGURE 2. Position of the programme stars in the Hertzsprung-Russell diagram using *Hipparcos* parallaxes. Open circles: Group I (B- and N-normal stars), open squares: Group II (N-normal, but B-depleted stars), filled circles: Group III (B-depleted and N-rich stars). The stars lacking boron data (see right-hand side of Fig.1) are included in this figure assuming that the 3 N-normal and 2 N-rich stars belong to Groups I and III, respectively. The size of the symbols is proportional to the $\Omega R \sin i$ values. Geneva evolutionary tracks for solar metallicity and without rotation are overplotted (Schaller et al. 1992). The ZAMS is shown as a dashed line.

evolution. Indeed, the importance of magnetic phenomena is already hinted at by evolutionary models including dynamo-generated magnetic fields (e.g. Maeder & Meynet 2005), although much theoretical work remains to be done (see, e.g. Zahn et al. 2007).

ACKNOWLEDGMENTS

The author acknowledges financial support from the Research Council of Leuven University through grant GOA/2003/04. We are very grateful to C. Aerts, M. Desmet and P. Dufton for kindly providing us with the high-resolution spectra of several of our targets.

REFERENCES

Asplund, M., Grevesse, N., & Sauval, A. J. 2006, Nucl. Phys. A, 777, 1
Gies, D. R., & Lambert, D. L. 1992, ApJ, 387, 673
Heger, A., & Langer, N. 2000, ApJ, 544, 1016
Maeder, A., & Meynet, G. 2005, A&A, 440, 1041
Meynet, G., & Maeder, A. 2003, A&A, 404, 975

Morel, T., Butler, K., Aerts, C., Neiner, C., & Briquet, M. 2006, A&A, 457, 651
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Trundle, C., Dufton, P. L., Hunter, I., Evans, C. J., Lennon, D. J., Smartt, S. J., & Ryans, R. S. I. 2007, A&A, 471, 625
Zahn, J.-P., Brun, A. S., & Mathis, S. 2007, A&A, in press ([arXiv:0707.3287])
Zhai, M., & Shaw, D. M. 1994, Meteoritics, 29, 607