SESSION 2

Rotation in Relation with Abundances and Magnetic Fields

Jose de Medeiros, Claudio Melo, Jose Pereira da Silva and Georges Meynet enjoying Friendship and Astrophysics.

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Abundance Anomalies and Rotation in Main Sequence OB Stars

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Abstract. We review the present status of our knowledge about observational evidence of the influence of rotation on the evolution and chemical surface enrichment of OB Main Sequence stars. We pay special attention to the CNO elements and show that luminosity class IV-V OB stars provide a good reference point for abundance analyses.

While there is clear evidence of rotationally induced mixing in OB stars, we show that fast rotation is not a guarantee of enrichment. A comparison of observed data with present evolutionary models indicates that the observed facts can be explained assuming that the stars are born with a distribution of rotational velocities, and that depending on the stellar mass the surface abundance changes will be dominated by rotation or mass loss. Only the existence of a large number of B supergiants beyond the Main Sequence cannot be explained in this scenario. We show that current evolutionary models including rotation do not adequately account for the transfer of angular momentum from the interior to the surface.

We point out that the difficulty in determining He abundances and in knowing the present or past binary status of many stars leads us to consider the above conclusions as preliminary.

1. CNO Abundances in Nearby OB IV-V Stars

Before we look for CNO abundances possibly related to rotationally induced mixing processes during the evolution of Main Sequence OB stars we have to be sure that there is something that we can call a *normal* abundance composition.

Recently Herrero (2003) has shown that the average CNO abundances of nearby OB Main Sequence stars agree well with those from other objects, like Orion, nearby G-F stars or the recent determinations in the Sun (we have to point out that these new determinations are 3-D simulations while the abundance determinations in OB stars are 1-D calculations). The only exception is the C abundance which might be affected by strong NLTE effects or uncertainties in the model atom. This introduces an additional uncertainty of a factor of two in the C abundance when comparing absolute abundances, although the relative C abundance between two OB stars obtained using the same codes and model atoms should still reflect an actual difference in composition. Table 1 gives an overview of the situation.

Table 1. A comparison of CNO values for nearby objects

Object	C	N	O	References
Sun	8.52±0.06	7.92±0.06	8.83±0.06	Grevesse and Sauval (1998)
Sun	$8.59^{+0.10}_{-0.12}$	$7.93^{+0.10}_{-0.13}$	$8.74^{+0.07}_{-0.09}$	Holweger (2001)
Sun	8.41±0.03	7.80±0.04	8.66±0.03	Allende Prieto et al. (2001, 2002) Asplund (2003)
G-F stars	$8.55^{+0.09}_{-0.11}$		$8.65^{+0.11}_{-0.19}$	Sofia & Meyer (2001)
Orion	8.49±0.12	7.78±0.08	8.72±0.07	Esteban et al. (1998)
B dwarfs	$8.25^{+0.06}_{-0.09}$	$7.81^{+0.06}_{-0.12}$	8.68±0.06	Herrero (2003)

2. Abundance Anomalies in OB Stars

In Fig. 1 we have plotted data for B stars of luminosity class IV–V collected from Gies & Lambert (1992), Cunha & Lambert (1994), Killian et al. (1994) and Daflon et al. (2001). These works constitute our main body of information about absolute CNO abundances in these stars. The figure gives log (N/C) versus log (C+N), where N and C are the number abundances of N and C in the log(H)= 12. scale. We see that most stars cluster around a value of log (N/C)= -0.6 and log(C+N)= 8.40, in agreement with data from Table 1. However, some stars lie at larger N/C ratios, indicating that some mild mixing is possible. Moreover, there seems to be some indication of a gap at about log (N/C)= -0.3. If this gap is real (which we do not consider confirmed by the present data) it could indicate that the mixing at the surface is initiated discontinously, for example a *mixing front* moving upwards could explain the data.

There is addditional evidence of anomalies in the He, C, N and O abundances of Galactic OB stars. Herrero (2003) has recently reviewed this, but we can cite here the N enhancements found by Schönberner et al. (1988) in stars with strong N lines, the He overabundances found by Herrero et al. (1992) in many O stars (supergiants and fast rotators) and the determinations of CNO in ζ Pup made by Pauldrach et al. (1994, UV analyses) and Kahn et al. (2001, XMM data). These results are consistent with some kind of mixing at the stellar surface. Venn et al. (2002) provide another very important evidence with the B-N connection. They find some stars with normal N and depleted B abundances. While exposition of deep layers through mass-loss could explain N and B depleted stars (that are also observed), stars with depleted B and normal N can only be explained through mixing.

Rapid rotators (that we may arbitrarily identify with stars showing $v \sin i \geq$ 250 km s^{-1}) are at the present Symposium of special interest. Herrero et al. (1992) found that most fast rotators in their sample were He enriched. However, they are difficult to analyze because of multiple blends and very shallow lines, which demand very large S/N and accurate continuum rectification. Thus the

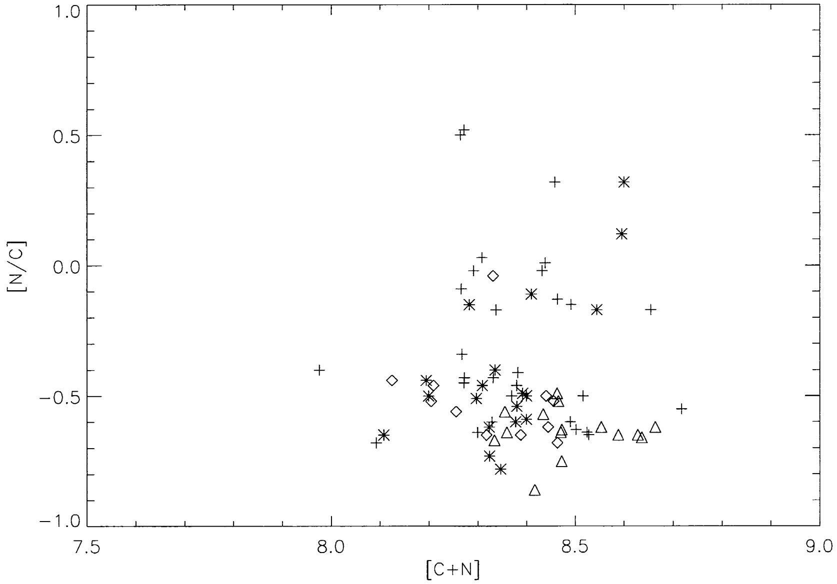

Figure 1. Logarithmic ratio of N to C versus the total number of C and N atoms. Crosses represent data from Gies & Lambert (1992), asterisks from Cunha & Lambert (1994), triangles from Daflon et al. (2001) and diamonds from Kilian et al. (1994)

large, but rather uncertain, He abundances cannot be considered a definitive proof of mixing without independent evidence.

The most complete analysis of a fast rotators' abundances is the one by Villamariz et al. (2002), who analyze HD 191423, an O9 III:n star rotating at 450 km s^{-1}. Villamariz et al. performed a strictly differential analysis. They started with HD 214680 and HD 34078, two slowly rotating O9 dwarfs that formed the baseline in their He and CNO abundances. After that, they analyzed the O9Ib star HD 209975 to see whether the use of planeparallel, hydrostatic models would introduce some bias in the derived abundances. The results indicated that the He and CNO abundances of the supergiant cannot be distinguished from those of the dwarfs within the error bars.

A comparison of the spectrum of HD 209975 degraded to 450 km s^{-1} with the spectrum of HD 191423 immediately indicates that the latter is N richer and C poorer. A detailed analysis of HD 191423 gives then log N= 8.60±0.17, log C= 7.52±0.24 and log O= 8.18±0.48. These values are consistent within the errors with the mild He overabundance found, $\epsilon = \frac{N(He)}{N(He)+N(H)} = 0.12 \pm 0.03$, if they are produced by the exposition of CNO enriched material.

Howarth & Smith (2001) have also analyzed HD 191423 and find very similar stellar parameters to those obtained by Villamariz et al. This is encouraging, as Howarth & Smith include the effect of gravity darkening and geometrical distortion of the surface. Of course, the analysis of Howarth & Smith provides better information, specially in quantities that are radius dependent, like the surface gravity or the local effective temperature, but the average values are very similar. However, Howarth & Smith find a much larger He overabundance

(ϵ=0.20) than do Villamariz et al. This can be due to the neglect of microturbulence in the analysis of Howarth & Smith (see Villamariz & Herrero, 2000, for the effects of microturbulence on the stellar parameters).

A very high He overabundance (ϵ=0.20) is also derived by Howarth & Smith for HD 149757 (O9 Vn, 400 km s^{-1}). Again, the stellar parameters are very similar to those found by Villamariz & Herrero (2003), who however obtain a normal He abundance. In this case we have an easy test: in Fig. 2 we see that the spectrum of HD 149757 is identical in their CNO features to the spectra of the O9 dwarfs HD 214680 and HD 34078 degraded to the appropriate rotational velocity, while the spectrum of HD 191423 shows clearly enhanced N and depleted CO features. In addition, Villamariz & Herrero (2003) have found that HD 15642 (O9.5III:n, $v \sin i$= 350 km s^{-1}) has CNO abundances that are intermediate between those of HD 149757 and HD 191423. These CNO abundances are consistent with a normal He abundance as the one obtained. Therefore the data indicate that, when present, the contamination is consistent with mixed CNO cycled material, but clearly a high rotational velocity does not guarantee a strong mixing. This difference could be attributed to a different age, to a different history or to both.

3. Comparison with Evolutionary Models at Z=0.02

Stellar parameters have been determined for a number of Galactic OB stars. In Fig. 3 we have plotted data for O stars by Herrero et al. (1992, 1999, 2000, 2002), Pauldrach et al. (1994), Howarth & Smith (2001), Bianchi & García (2002), Villamariz et al. (2002) and Villamariz & Herrero (2003) and data for B supergiants by Gies & Lambert (1992), McErlean et al. (1999), Vrancken et al. (2000), Trundle et al. (2002), Smartt et al. (2002) and Urbaneja et al. (2003a). We also plot the tracks for evolutionary models at Z=0.02 without rotation (Fig. 3a, Schaller et al., 1992) and with initial $v_{\rm rot}$ = 300 km s^{-1} (Fig. 3b, Maeder & Meynet, 2000).

We can see a number of features in these plots:

1. there is a large number of He-rich stars as determined from the spectroscopic analysis, larger than can be explained by the non-rotating models. These only predict He enrichment in the Main Sequence for stars with M $\geq$ 85 $M_{\odot}$.
2. many of the He-rich O stars are fast rotators. However, we also find both He-normal fast rotators and He-rich slow (projected) rotators.
3. we do not find very fast rotators at large luminosities (although ζ Pup is at the borderline with $v \sin i$ = 220 km s^{-1})
4. evolutionary models with initial rotational velocities of 300 km s^{-1} can explain the existence of He enriched stars (which should then also show CNO processed material at the surface). However, they fail to explain the existence of early O supergiants (see Walborn & Lennon, these proceedings)
5. O stars with less than about 25 $M_{\odot}$ do not show He enrichment, even if they rotate fast

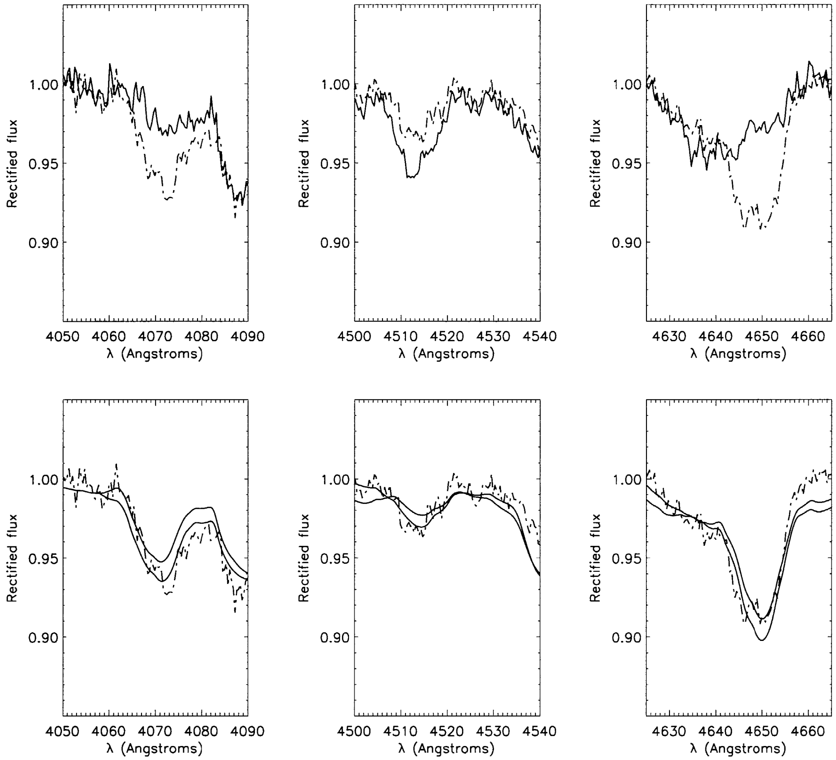

Figure 2. *Upper panel*: comparison of CNO lines in HD 149757 (dash-dotted line) with those of HD 191423 (solid line); *Bottom panel*: same comparison in HD 149757 (dash-dotted line) and the slowly rotating O9 dwarfs HD 214680 and HD 34078 (solid lines, degraded to 400 km s^{-1}). The zones shown contain lines of C (around 4070, 4650), N (around 4511-15) and O (around 4072, 4650)

6. there are more B supergiants beyond the Main Sequence than can be explained by evolutionary models, both with and without rotation, even taking into account that we are not using statistically complete samples.

Points 1 through 5 can be explained assuming that

- single O stars of a given mass are born with a distribution of rotational velocities.
- very massive stars ($M \geq 60\ M_\odot$) can be dominated during their evolution either by mass loss or by rotation. In the first case, the star can move significantly away from the ZAMS. In the second case, it will always stay close to the ZAMS.
- for intermediate mass stars ($25\ M_\odot \leq M \leq 60\ M_\odot$) rotation, rather than mass-loss, is the dominant cause of altered surface composition (if the rotational velocity is large)
- low massive stars ($M \leq 25\ M_\odot$) do not change their surface chemical compositions, either by mass loss or rotation, implying that a minimum mass is required for the rotational mixing to operate or that time scales become longer with decreasing mass

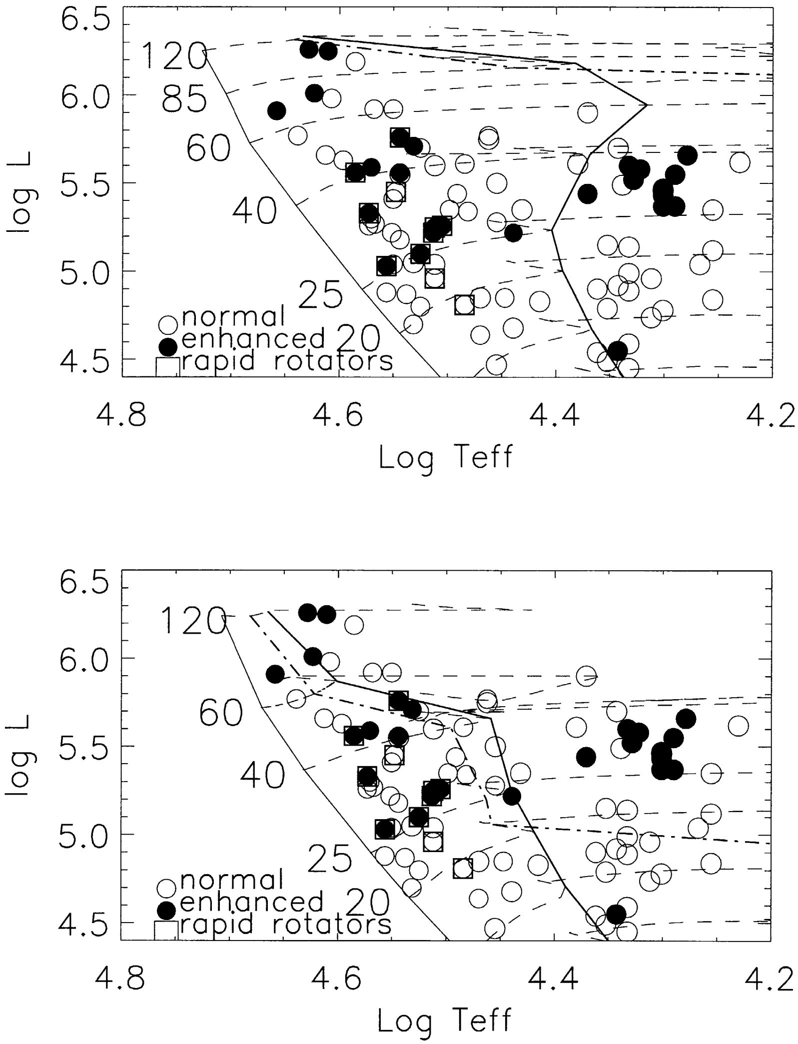

Figure 3. *Upper*: HR diagram with non-rotating tracks at Z=0.02 from Schaller et al (1992). Initial masses are quoted to the left of the ZAMS. The TAMS is indicated by the solid thick line. The dot-dashed line marks the positions where the stars first show He enrichment at the surface according to the evolutionary tracks. Open circles indicate He normal composition for O stars and CN normal composition for B stars, while filled circles indicate He or CN contamination respectively. Symbols inscribed within a square indicate fast rotators. *Lower*: same as the upper figure but using models with rotation (initial rotational velocity: 300 km s−1) by Maeder & Meynet (2000)

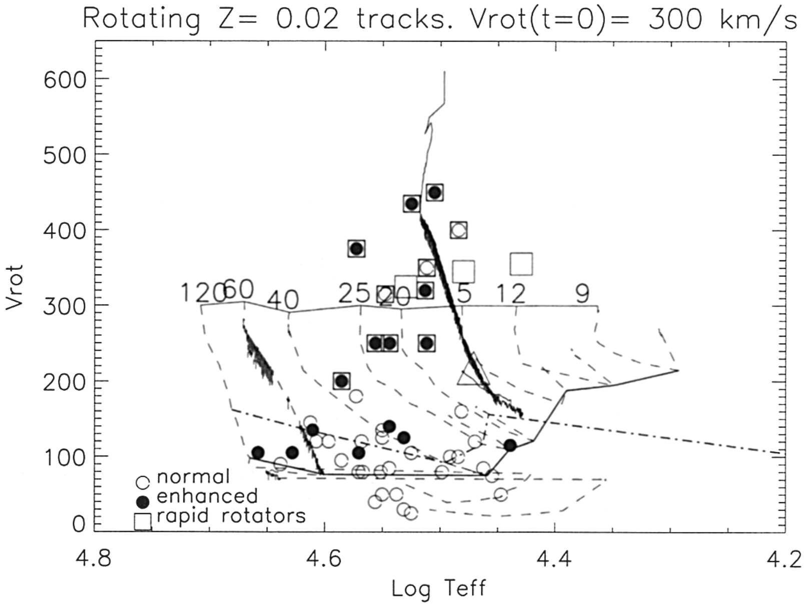

Figure 4. Rotating tracks of massive stars at Z=0.02 by Maeder & Meynet (2000) in a log $T_{\rm eff}$ - $v_{\rm rot}$ diagram. The tracks start with $v_{\rm rot}$= 300 km s^{-1}. The stellar symbols, the numbers, the thick solid line and the dash-dotted line have the same meaning as in Fig. 3. The track for M= 20 $M_\odot$ and $v_{\rm rot}$= 611 km s^{-1} is also plotted (it has been smoothed). The large open triangle marks the point where He enrichment at the surface just begins for this model. The open large squares mark the positions where this He enrichment begins for the models calculated by Heger & Langer (2000) with M= 20, 15 and 12 $M_\odot$ and initial $v_{\rm rot}$= 307, 323 and 328 km s^{-1} respectively.

Point 6, the existence of a large number of B supergiants beyond the TAMS, cannot be explained by this scenario, although we have shown elsewhere (Lennon et al., 2002; Herrero, 2003) that the observed range of N abundances of B supergiants is correctly predicted by the evolutionary models with rotation, once the abundances have been scaled to correct initial values. One possibility is that the bump formed by the TAMS towards the red is shifted to lower luminosities.

The position of the B supergiants on the HR diagram is not the only problem that we have to face in a comparison of evolutionary models versus spectroscopic results. A second one is the rate at which angular momentum is transferred from the interior to the surface. This is illustrated in Fig. 4, which generalizes a result found by Howarth & Smith (2001). In this figure we have plotted the tracks with rotation from Maeder & Meynet (2000) for models with initial rotational velocity of 300 km s^{-1} together with the position of the observed O stars in a log $T_{\rm eff}$ - $v_{\rm rot}$ diagram. As the stars evolve, they loose angular momentum and rotate more slowly, becoming cooler at the same time. This is therefore an appropriate evolutionary diagram to study the predictions of the models with rotation. We note however that we compare observed *projected* and theoretical *unprojected* rotational velocities.

We see that the models can account for the existence of slowly rotating stars with He enhancement, but paradoxically *evolutionary models with rotation* *cannot account for the existence of fast rotators with He overabundance*: by the time they show He enhancement they should rotate with moderate rotational velocities.

Of course, the fact that we derive projected rotational velocities in excess of 300 km s^{-1} for half of the fast rotators suggests that the initial velocities could be larger. We have also plotted the track calculated for a model of 20 $M_\odot$ and v_{rot} = 611 km s^{-1} at t=0. We see that this improves the situation but still a large number of stars show too large overabundances in early stages of evolution.

If we use the models calculated by Heger & Langer (2000) the situation is reversed: these models can account for He enriched fast rotators, but they keep rotating fast and thus they cannot account for slow rotators showing CNO processed material.

Thus the conclusion is that models calculated by Maeder & Meynet should spend more time rotating at large rotational velocities, while models from Heger & Langer should spend less time rotating at large velocities. In the first case, either more efficient transport from the interior to the surface or less efficient loss of angular momentum from the surface is required. This loss could naturally be provided by polar-enhanced anisotropic winds (Maeder, 2002). Models by Heger & Langer seem to require a less efficient transport of angular momentum from the interior or a more efficient loss of angular momentum from the surface.

A word of caution should be mentioned here. Many of the fast rotators we have used for the conclusions above may be binaries or have had a binary past (some of them are runaways). Since we do not know the status and history of each individual object our conclusions should be regarded with caution.

4. CNO Abundances in Stars in Nearby Galaxies

The number of quantitative analyses of massive OB stars in nearby galaxies is rapidly increasing. It includes analyses in the Magellanic Clouds, the local spirals M31 and M33 and even the first analysis of two B supergiants beyond the Local Group, in NGC 300 (Urbaneja et al., 2003b). However, only the analyses of MC stars can actually be presently used for studies of abundance anomalies related to rotational mixing.

The subject has been reviewed very recently by Herrero (2003) and thus we will only comment here that the evidence from these extragalactic analyses is consistent with the scenarios, problems and conclusions outlined above. Additional work presented at this Symposium (see contributions by Crowther & Evans and Heap & Lanz) also point in the same direction.

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