Spectroscopic Analyses of Galactic O Stars

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Abstract. We present here new stellar parameters for O stars and a preliminary analysis of objects in the Cyg OB2 association, derived from an analysis of the stellar spectra. We place the stars in a theoretical HR diagram and compare with evolutionary tracks. We use this comparison to investigate the possible relation between rotational velocity and helium abundance. A few results for Cyg OB2 are also indicated.

1. Introduction

The spectroscopic analysis of hot, massive OB stars is one of the tools that could help us to answer several open questions concerning our knowledge of the structure and evolution of these stars, and of their mass and energy input to the surroundings, and which are therefore relevant for the structure and evolution of the Galaxy. Furthermore, with 4-m and 10-m telescopes and new detectors it is now possible to observe and analyse the spectra of massive blue stars in nearby galaxies (see Kudritzki 1998, and several contributions in these proceedings), so that a thorough knowledge of their Galactic counterparts will be of major importance. Among the unsolved problems found in OB stars we could mention the 'helium discrepancy' (Herrero et al. 1992), i.e., the fact that a large number of OB supergiants analysed with model atmospheres indicate helium abundances which are well above solar, in disagreement with the predictions of evolutionary models.

The reason for this discrepancy is not clear. Initially, it was thought that the inclusion of winds in the model atmospheres would help to reduce or even render normal the derived helium abundance. The strong influence of the velocity-field parameters on the emergent profiles has been demonstrated by several authors (e.g., Schaerer & Schmutz 1994; Sellmaier et al. 1993; Santolaya-Rey et al. 1997). However, this influence is not enough to explain the helium discrepancy, as has been shown by Herrero et al. (1995), for example. In an analysis of HDE 226868 (the optical counterpart of Cyg X-1), using Unified Model Atmospheres (Gabler et al. 1989), these authors found that the helium abundance was the same as that obtained with plane-parallel models. Microturbulence has recently been suggested as the origin of the large helium abundances reported for late-O and early-B stars (McErlean et al. 1997; Smith et al. 1998). However, studies like that of Gies & Lambert (1992) also included large microturbulent velocities and still found large helium abundances for early-B supergiants. Thus, although microturbulence can explain part of the effect, it is still not clear whether there are other physical mechanisms responsible for unexpected early mixing of processed material in these stars (see also Meynet 1998 for a list of facts that seem to point to such processes). These mechanisms may have to be included in the model-atmosphere calculations, or in the evolutionary models, or even in both.

One of the mechanisms so far omitted from standard evolutionary models, and which could contribute to mixing of processed CNO material at the stellar surface, is stellar rotation (see Fliegner & Langer, 1997; Meynet & Maeder, 1997; Langer & Heger 1998; Maeder 1998; Meynet 1998). However, it is clear that any observational analysis will be hindered by the fact that we can only measure the projected rotational velocity. This is especially true if we consider that we are actually working with small-number statistics, because only a limited number of stars have been analysed with spectroscopic techniques.

We present here new observations and analyses that can contribute to an increase our sample of analysed objects, and can thereby help to clarify the possibility of mixing while the stars are still burning hydrogen on the main sequence. In addition, the new observations are made with a different criterion to that followed in our previous studies. Instead of choosing the brightest stars of given spectral types, we have observed stars in Cyg OB2. This can help not only to increase our sample and avoid possible selection effects, but also to study the properties of the upper part of the HR diagram in Cyg OB2.

After presenting the new analyses, we will try to find out whether the available data support the idea that rotation could be related to helium enhancements in massive, hot stars.

2. Observations

The observations of the stars analysed here were carried out with the 2.5-m Isaac Newton Telescope[1] in two runs. In the first (1992 August), bright stars of different O spectral subtypes were observed. In the second (1995 August), stars in Cyg OB2 were observed. The Intermediate Dispersion Spectrograph was used with the H2400B and the R1200B gratings (the latter only for some stars in Cyg OB2) and the 235-mm camera, which resulted in spectral resolutions of 0.6 and 1.3Å FWHM, as measured from Cu–Ar arc lines.

The reduction of the spectra was performed using a standard procedure: bias substraction, flat-field division, spectrum extraction, wavelength calibration, and continuum rectification. Typical S/N ratios are 150–200. We corrected for radial velocities using photospheric metal lines, discarding strong lines when these seemed to be contaminated by the stellar-wind velocity field.

3. Spectral Analysis

The analysis of the spectra has been conducted following the same procedures as in Herrero et al. (1992). Briefly, the rotational velocities are first determined, using metal lines. Then the observed line profiles of H and He are compared

[1]The INT is operated on the island of La Palma by the RGO in the Spanish Observatorio de El Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

to theoretical ones, broadened with the appropriate rotational velocity and instrumental profile (which is assumed to be gaussian). The theoretical profiles are calculated from H/He model atmospheres, with plane-parallel geometry, in hydrostatic and radiative equilibrium, and including line blocking in the line formation for some models. This is needed for temperatures around 40 000 K or above, or comparatively low gravities, as has been shown by Herrero (1994). From this comparison we obtain the effective temperature, gravity, and helium abundance. Finally, knowing the distance and the apparent magnitude, we can calculate the stellar radius using eqn. 1 in Herrero et al. (1992).

In Table 1 we give the parameters derived for the stars observed in 1992. The apparent magnitudes and distances have been taken from Garmany & Stencel (1992) or Humphreys (1978). For a few objects, preliminary parameters were given by Herrero (1994). For a comparison, we also list those values in Table 1. These stars were observed mainly to complement the data given in Herrero et al. (1992) for high luminosities (around $10^6 L_\odot$).

Table 1. Atmospheric parameters for the stars observed in 1992. Gravities are not corrected for centrifugal force; ϵ is $n(\mathrm{He})/(n(\mathrm{He}) + n(\mathrm{H}))$, where n represents the abundance by number. The last column gives the temperatures, gravities, and helium abundances given by Herrero (1994).

Star	$T_{\rm eff}$ (kK)	$\log g$	ϵ	$R/R_\odot$	$v_{\rm e} \sin i$ (km s^{-1})	H94
HD 15558	46.5	3.70	0.07	21.9	120	(48.0, 3.75, 0.07)
HD 15629	48.0	3.80	0.09	14.0	90	(47.0, 3.75, 0.07)
HD 14947	45.0	3.50	0.15	16.2	140	(43.5, 3.45, 0.15)
HD 210839	41.5	3.40	0.25	20.2	250	
HD 5689	40.0	3.40	0.25	7.7	250	
HDE 338926	34.0	3.00	0.15	24.1	130	
HD 192660	30.0	3.05	0.08	34.6	90	

We should note a problem with HD 5689, which has been classified as O6 V by Garmany & Vacca (1991). Assuming that it belongs to the Cas OB7 association, Garmany & Stencel (1992) derive an absolute magnitude of 4.19, which is barely consistent with the O6 V classification. Humphreys (1978) gives an absolute magnitude of 4.9, consistent with the classification by Garmany & Vacca, but only because the distance to Cas OB7 she derives is a 40% larger. In addition, both absolute magnitudes are inconsistent with our gravity, which corresponds more to a giant (particularly taking into account the correction to the gravity due to the centrifugal force). Adopting the data from Garmany & Stencel leads to the anomalously small radius listed in Table 1. Thus the data for this particular star have to be considered suspect.

For the stars in Cyg OB2 we took the distance modulus and apparent magnitudes (corrected from extinction) from Massey & Thompson (1991), who give $(m - M)_0 = 11.2 \pm 0.2$. With these data, we were able to determine the stellar parameters from the spectral analysis of 19 stars in the association.

In Cyg OB2 we have a few supergiants with comparatively low temperatures. For stars in this region a problem was found by Herrero et al. (1992; and previously noted by Lennon et al. 1991) when performing the spectral analysis: the singlet He I λ4922 and 4387 lines give different results. He I λ4922 (which was the preferred line in the work by Herrero et al.) indicates lower temperatures and larger helium abundances than does He I λ4387. The effect was found to be significant only for the one star below 30 000 K in the Herrero et al. sample, for which the derived helium abundance would be $\epsilon = 0.18$ or $\epsilon = 0.09$ when using He I λ4922 or λ4387, respectively.

Here we find the same effect: for stars below 30 000 K in Cyg OB2, we obtain lower temperatures and larger helium abundances when using the He I λ4922 line. This effect can be explained, at least in part, by including microturbulent velocities in the line-formation calculations and during the formal solution, as has been shown by McErlean et al. (1997) and Smith et al. (1998). Note also that the effect of microturbulence has not been analysed in stars earlier than O9. Thus for these stars the derived helium enrichment could be a consequence of neglecting microturbulence in the analysis, which could then affect the results and discussion which follow.

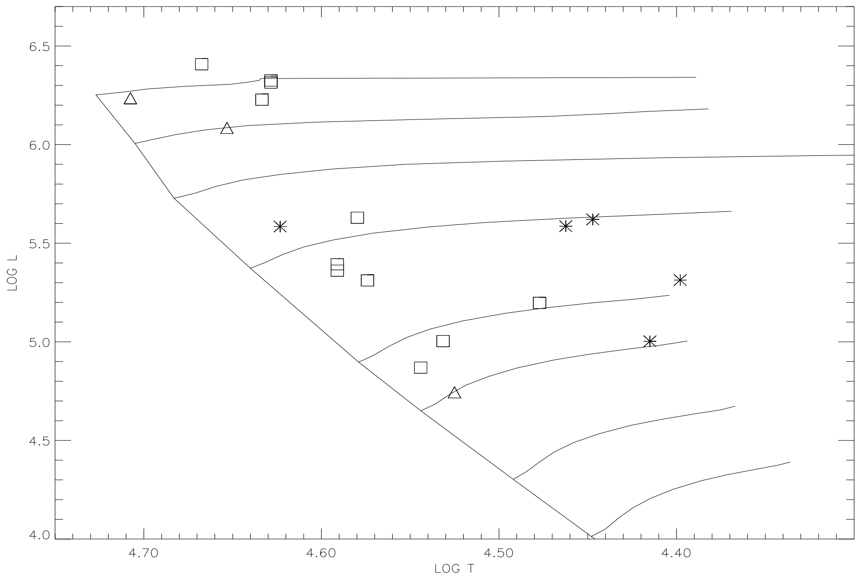

Figure 1. The HR diagram obtained for Cyg OB2. Evolutionary tracks are from Schaller et al. (1992). Squares indicate stars with solar helium abundance; ($\epsilon < 0.12$); asterisks, enhanced helium abundances ($\epsilon \geq 0.15$); and triangles, intermediate valuess ($0.12 \leq \epsilon < 0.15$).

4. The HR Diagram

Using the data obtained in the previous section we can place the stars on a theoretical HR diagram and compare with evolutionary tracks. For such comparison we use the models given by Schaller et al. (1992). In Fig. 1 we show the HR diagram obtained for Cyg OB2 using the analysed stars, with different symbols representing different helium abundances.

The first thing we can see is that the theoretical ZAMS seems to be shifted to higher temperatures compared to the observations. This effect is the same as that found by Herrero et al. (1992) for the stars analysed there. However, we want to emphasize that the stars in Herrero et al., which were compared to evolutionary tracks from Maeder (1990), do not show the effect when compared to the tracks by Schaller et al. used here. Thus the stars from Fig. 1 would show a displacement of nearly 4000 K when compared to the Maeder et al. evolutionary tracks.

The second thing we can see is that there are only five stars showing clear helium enhancements. Of these, four are the coolest stars in the sample (having effective temperatures below 30 000 K). They show the inconsistency between the results derived from He I λ4387 and 4922 lines referred to in the previous section. Thus only one star lying in the region where both lines give the same results has an enhanced helium abundance; this star rotates (in projection) at 135 km s^{-1}. At this point, it is interesting to note, for the later discussion, that none of the analysed stars in Cyg OB2 rotates with a projected rotational velocity larger than 180 km s^{-1}.

The third interesting aspect in the HR diagram of Cyg OB2 is that the most luminous stars show normal (or about normal) helium abundances, in spite of the fact that they are the most rapidly evolving stars. Clearly, if any mixing processes are active here, they still have not had time to bring newly-formed helium to the surface. The fact that stars of this luminosity still exist in Cyg OB2 gives an age estimate for the cluster, derived from the evolutionary tracks, of about 1.5 Myr. This age is inconsistent with that derived by Torres-Dodgen et al. (1991), since for the minimum age of 3 Myr they suggest these stars should have reached the Wolf-Rayet phase, or should at least show strong evidence of advanced evolution.

Now we put together the data from Herrero et al. (1992), the stars from Table 1, and those from Cyg OB2. The corresponding composite HR diagram is shown in Fig. 2, where again we compare with tracks from Schaller et al. (1992). However, we now distinguish the rapid rotators, and the stars that could be rapid rotators (by diamonds). We consider that a star is rotating 'rapidly' when its measured projected rotational velocity is at least 250 km s^{-1}, and we consider that the object is a 'probable' fast rotator when this measured value exceeds 160 km s^{-1}, which is $250 \times \langle \sin i \rangle$ for random orientations of the rotation axes.

We inmediately see that most fast rotators (8 out of 11) show enhanced helium abundances, and that another two have an intermediate helium abundance. In particular, note that only one of the objects for which a normal helium abundance was derived has a projected rotational velocity exceeding 160 km s^{-1} (and not by much – it has $v_e \sin i = 180$ km s^{-1}). Of course, we should remember that this could be just by chance.

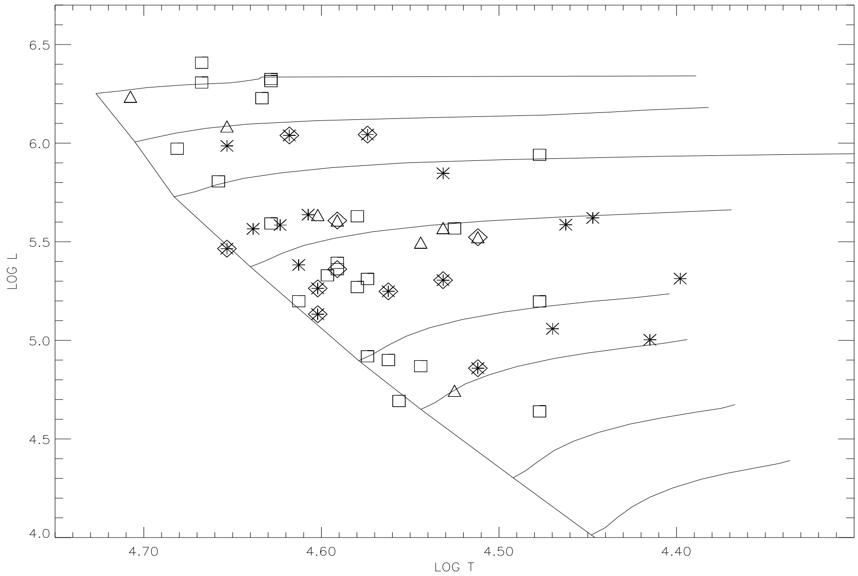

Figure 2. The composite HR diagram for all data. Evolutionary tracks are from Schaller et al. (1992). Fast rotators and probable fast rotators have their symbols enclosed by diamonds.

5. On the Relation Between Rotational Velocity and Helium Abundance

The possible observational relation between rotational velocity and helium abundance was already noted by Herrero et al. (1992). Actually, the idea that possible variations in surface abundances (He, CNO) are related to the rotational velocity is an old one (see for example Maeder 1987; Langer 1992; Dennisenkov 1994; Fliegner & Langer 1997; Meynet & Maeder 1997; and references in all these papers, as well as contributions in these proceedings). Is there then a correlation between the helium abundance and the rotational velocity of the stars?

In Fig. 3 we show the observed helium abundance vs. $v_e \sin i$. No clear correlation or pattern is seen, apart from the fact that no low helium abundances are found at large projected rotational velocities. However, these does not mean that there is no correlation between both quantities.

Suppose that we have a perfect correlation between both quantities, given in a simple way: above a critical value (let say, in a completely arbitrary way, 300 km s^{-1}) the helium abundance increases linearly with the rotational velocity. Following Conti & Ebbets (1977), we assume that the O stars have a bimodal distribution of rotational velocities (for luminosity class V or classes I and III), which peak at 200 and 400 km s^{-1}, with dispersions of 30 and 140 km s^{-1}, and a macroturbulence of 30 km s^{-1}, which is actually seen in the spectra as a minimum rotational velocity. Note that all these are *unprojected* values. If we now have a sample of stars (distributing dwarfs, giants, and supergiants according to their actual relative numbers) we can associate a given rotational

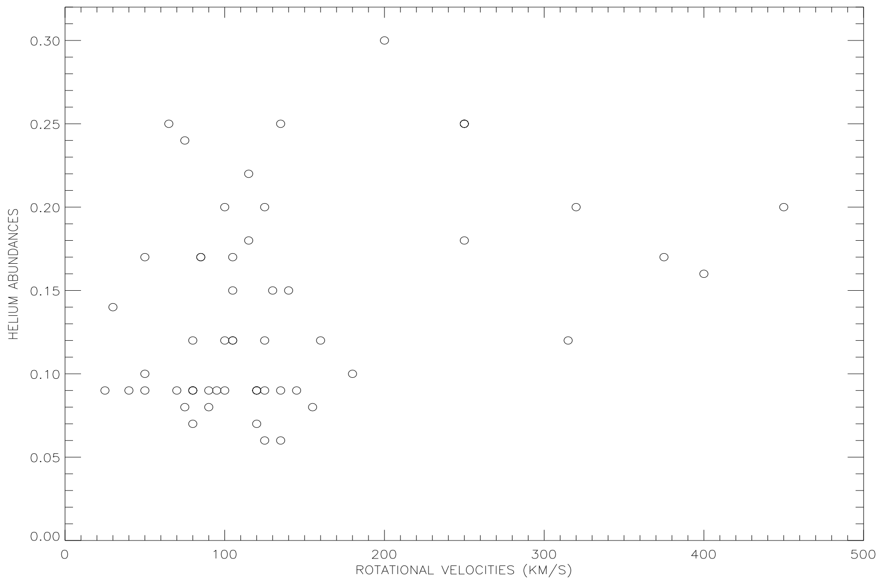

Figure 3. The observed relation between helium abundance and projected rotational velocity.

velocity to each star according to the probability given by the model described above. The resulting relation is as simple as two straight lines intersecting at 300 km s^{-1}.

However, if we now project the rotational velocities of the stars randomly, the result would be the one shown in Fig. 4, where we have plotted 10 000 points following the model described above. Picking out about 50 stars would result in a distribution similar to the one displayed by Fig. 3. This is clearly seen when comparing both figures, with the main concentrations at solar abundances and no points with large rotational velocities and low abundances.

Of course, this is not a proof for any relationship between rotational velocity and helium abundance. It only shows that the observed diagram, as devoid of pattern as it may appear, is actually compatible with the idea of such a correlation. This is even more true if we consider a couple of effects that could also obscure a possible relation – for example, the fact that there could be a minimum time needed for the mixing, or that the stellar rotational velocity could change during evolution, or the as yet unconsidered role of macroturbulence. Clearly, more work will be needed in the future to clarify the possible relation between these two important quantities.

6. Conclusions and Future Work

The main conclusions of this work are the following (remembering that the individual data for Cyg OB2 are still not definitive, although general facts shouldn't change):

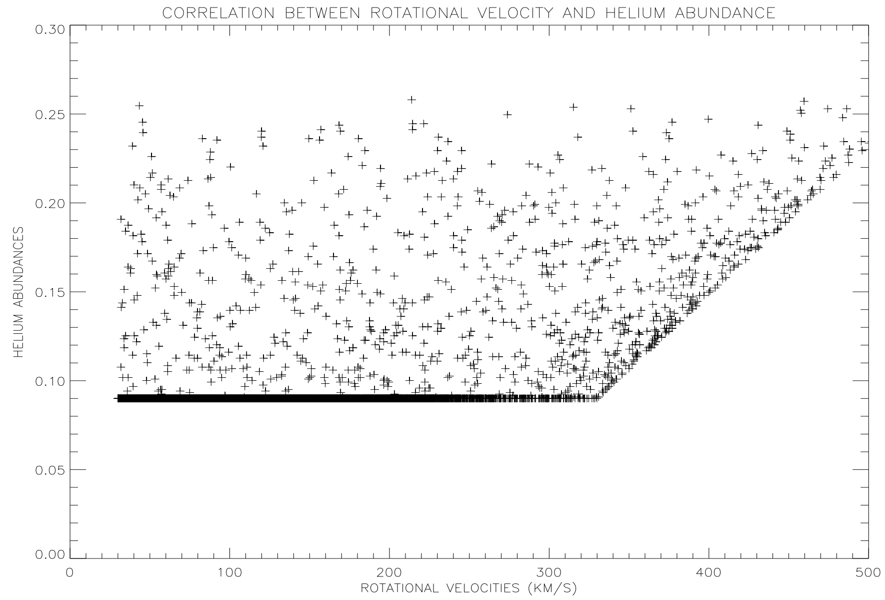

Figure 4. The distribution of Fig. 3 when projecting the rotational velocity randomly over the line-of-sight.

1. The theoretical ZAMS of Cyg OB2 seems to be about 2000 K hotter than the one derived from the spectral analysis.

2. The most luminous stars in Cyg OB2 do not show a helium enrichment

3. Comparison of our data with evolutionary tracks indicates an age of about 1.5 Myr for Cyg OB2.

4. Nearly all O stars which are rapid rotators ($v_e \sin i \geq 250$ km s^{-1}) or possible rapid rotators (160 km s^{-1} $\leq v_e \sin i \leq 250$ km s^{-1}) show some helium enrichment – only one of the intermediate rotators ($v_e \sin i = 180$ km s^{-1}) shows a normal helium abundance.

5. For supergiants below 30 000 K the He I λ4922 line gives lower temperatures and larger helium abundances than the λ4387 line. As has been shown by other authors, this could be a consequence of microturbulence, and the helium abundance could be about normal.

With respect to future work, is clear that the effect of microturbulence on the helium abundances derived for stars hotter than about 30 000 K has to be investigated, as it could be that the large abundances are mainly due to the neglect of microturbulence in the analysis. Rotation can also play a role in the evolution of the stars, and it will be necessary to continue investigating its possible relation with the helium abundance. However, it is difficult to solve the problem only with helium, and abundances and abundance ratios for other elements are a matter of primary importance.

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Discussion

Gies: Could you comment on the state of the 'mass discrepancy' which you identified in your 1992 paper?

Herrero: Well, at the beginning we were really convinced that this was an effect of the wind on the spectroscopic analysis. However, it now seems that this only goes half-way to giving the answer. Allowing for rotation in the evolutionary tracks can explain another little bit of the discrepancy, so I think that, when you consider the errors, the problem is now more or less solved.

Kaper: On the basis of your 1992 results, Blaauw suggested that helium enrichment and rapid rotation might be related with the fact that the rapid rotators are OB-runaway stars. Then the helium overabundance and the rapid rotation might be the result of binary evolution; mass transfer from the initially more massive star supplies both enriched material and angular momentum.

Howarth: Keith Smith and I have been carrying out some analyses of the most rapidly rotating O stars, taking into account the equator-to-pole variations in temperature and gravity. Preliminary results for HD 191423, which is the most rapidly rotating near-main-sequence O-star known, show clearly that it has enhanced helium, and also that it is, in fact, an ON star. Two other well-known rapid rotators, HD 93521 and HD 149757, are clearly *not* ON stars, although the helium analysis is not yet complete.

Kudritzki [to Howarth]: Did you check if you can remove the helium overabundance by using microturbulence?

Howarth: Yes; microturbulence has no important effect on the analysis of 191423.