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THE VLT FLAMES SURVEY OF MASSIVE STARS: ROTATION AND NITROGEN ENRICHMENT AS THE KEY TO UNDERSTANDING MASSIVE STAR EVOLUTION

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ABSTRACT

Rotation has become an important element in evolutionary models of massive stars, specifically via the prediction of rotational mixing. Here we study a sample of stars, including rapid rotators, to constrain such models and use nitrogen enrichments as a probe of the mixing process. Chemical compositions (C, N, O, Mg, and Si) have been estimated for 135 early B-type stars in the Large Magellanic Cloud with projected rotational velocities up to ~300 km s^{-1} using a non-LTE TLUSTY model atmosphere grid. Evolutionary models, including rotational mixing, have been generated attempting to reproduce these observations by adjusting the overshooting and rotational mixing parameters and produce reasonable agreement with 60% of our core hydrogen burning sample. We find (excluding known binaries) a significant population of highly nitrogen-enriched intrinsic slow rotators ($v \sin i \lesssim 50$ km s^{-1}) incompatible with our models (~20% of the sample). Furthermore, while we find fast rotators with enrichments in agreement with the models, the observation of evolved ($\log g < 3.7$ dex) fast rotators that are relatively unenriched (a further ~20% of the sample) challenges the concept of rotational mixing. We also find that 70% of our blue supergiant sample cannot have evolved directly from the hydrogen-burning main sequence. We are left with a picture where invoking binarity and perhaps fossil magnetic fields is required to understand the surface properties of a population of massive main-sequence stars.

Subject headings: stars: early-type — stars: rotation — stars: abundances — stars: evolution — Magellanic Clouds

1. INTRODUCTION

Stellar rotation in massive stars has been adopted in recent theoretical models to, for example, predict the correct blue-to-red supergiant ratio (Maeder & Meynet 2001), the progenitors of gamma-ray bursts through homogeneous evolution (Yoon & Langer 2005), and Wolf-Rayet populations as a function of metallicity (Meynet & Maeder 2005; Vink & de Koter 2005). However, the consequent surface enrichment of helium and nitrogen through rotational mixing is poorly constrained by observations (Daflon et al. 2001), with the mixing typically calibrated from studies of either main-sequence stars with low projected rotational velocities (Korn et al. 2002) or evolved supergiant stars (Venn 1999). The former are biased toward slow rotators while the latter have evolved beyond the core hydrogen burning phase. The analysis of an unbiased sample of fast-rotating core hydrogen burning stars in order to properly calibrate the predicted rotational mixing efficiency was a strong driver for a large survey of O- and early B-type stars in our Galaxy and the Magellanic Clouds (Evans et al. 2005, 2006). Hunter et al. (2007) and Trundle et al. (2007) (hereafter Papers I and II, respectively) have presented chemical abundances for the narrow-lined objects (predominately slow rotators) in the LMC sample. Here we extend the study with the chemical analysis of the faster rotating stars.

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2. OBSERVATIONS AND MODEL ATMOSPHERE ANALYSIS

High-resolution ($R \sim 20{,}000$) spectra from the Fiber Large Array Multi-Element Spectrograph (FLAMES) at the European Southern Observatory Very Large Telescope were obtained for some 750 O- and early B-type stars located toward clusters in our Galaxy and the Large and Small Magellanic Clouds (LMC and SMC, respectively). A discussion of target selection, observational details, and initial data reduction can be found in Evans et al. (2005, 2006). In this Letter we discuss the LMC early B-type stars, using nitrogen as a probe of chemical enrichment.

A grid of non-LTE TLUSTY model atmospheres (Hubeny & Lanz 1995; Dufton et al. 2005) has been used to calculate the atmospheric parameters and chemical compositions (C, N, O, Mg, and Si) of our targets as described in Papers I and II and in Hunter et al. (2008, hereafter Paper III). We have fitted the lines with rotationally broadened profiles to estimate the equivalent widths (EWs), since at significant rotational velocities (>50 km s^{-1}) the line shape is rotationally dominated. For those objects in which no nitrogen features could be identified, an upper limit to the nitrogen abundance was estimated by placing an upper limit on the equivalent width of the strongest N II line in our spectral range, which is located at 3995 Å (Paper I).

The mean abundances of C, O, Mg, and Si are in excellent agreement (within 0.05 dex) with the LMC baseline abundances given in Paper I. However, the mean nitrogen abundance is 0.36 dex higher than its baseline abundance, indicating that nitrogen enrichment has occurred in many of the stars. In addition the scatter in the nitrogen abundances is over a factor of 2 larger than that of the other elements, indicating that different levels of enrichment explain the mean nitrogen abundance, rather than systematic errors. Since nitrogen is an important element in the CNO cycle, the surface nitrogen enrichments can be used as a measure of the mixing efficiency.

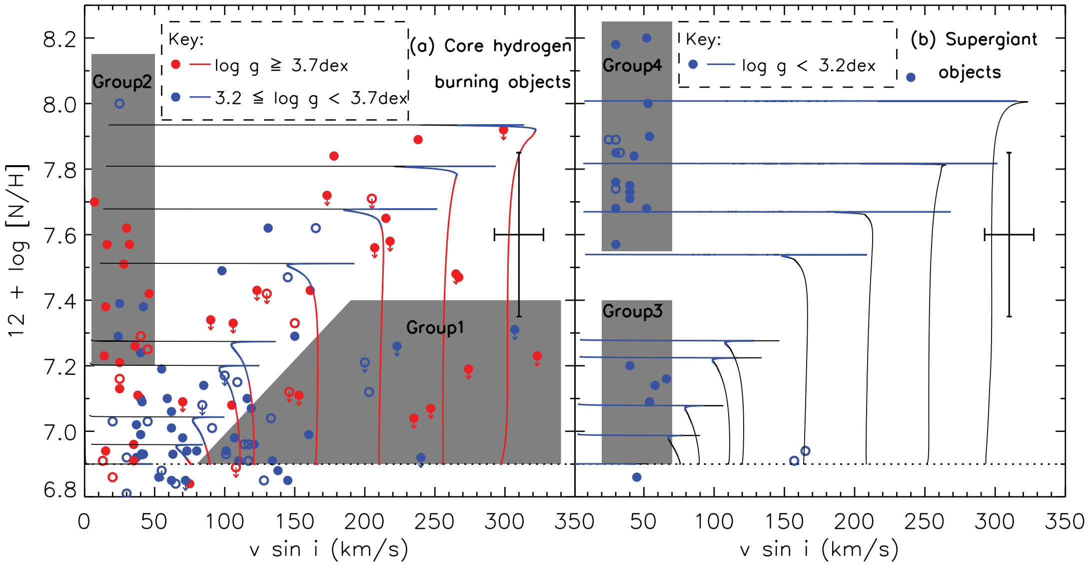

FIG. 1.—Nitrogen abundance (12 + log [N/H]) against the projected rotational velocity ($v \sin i$) for (*a*) core hydrogen burning and (*b*) supergiant objects. *Open symbols*, radial velocity variables; *downward arrows*, abundance upper limits; *dotted line*, LMC baseline nitrogen abundance. The mean uncertainty in the nitrogen abundance is 0.25 dex while that in $v \sin i$ is 10%, and these are illustrated. These errors are largely independent of rotational velocity since the systematic uncertainties are comparable to the measurement errors. The bulk of the core hydrogen burning objects occupy a region at low $v \sin i$ and show little or modest nitrogen enrichment. The tracks are computed for an initial mass of (*a*) 13 $M_\odot$ and (*b*) 19 $M_\odot$, corresponding to the average mass of our non-supergiant and supergiant stars, respectively, and their rotational velocity has been multiplied by $\pi/4$. Although the plot contains stars with a range of masses, comparison of the tracks shown in (*a*) and (*b*) show that any mass effect is negligible compared to the abundance uncertainties. In (*a*) the surface gravity has been used as an indicator of the evolutionary status and the objects (see key) and tracks have been split into red and blue to indicate younger and older stars, respectively. However, this is illustrative only, since the evolutionary status is obviously continuous and not discrete. Gray shading in (*a*) highlights two groups of stars which remain unexplained by the stellar evolution tracks. In (*b*) gray shading highlights the apparent division of the supergiants into two distinct groups. The surface gravity estimates of many of the objects in group 3, and the two apparently rapidly rotating unenriched supergiants, are consistent with being in the core hydrogen phase within their uncertainties.

Note that although a corresponding carbon depletion of up to ~0.2 dex would be expected, within the uncertainties in determining carbon abundances (see Paper I), such an effect would be difficult to observe. In Figure 1 the nitrogen abundances are plotted as a function of the projected rotational velocity with the sample being split into two groups: core hydrogen burning objects with surface gravities ≥3.2 dex and supergiants having surface gravities <3.2 dex (see Paper III).

3. STELLAR EVOLUTION MODELS

Comparison with published stellar evolution models such as the Geneva models (Maeder & Meynet 2001) is complicated as no rotating models at the LMC metallicity are currently available. In addition, the initial chemical composition for evolutionary models is often scaled from solar composition, and this is not appropriate for all elements, in particular nitrogen.

New evolutionary models have been calculated (I. Brott et al., in preparation) using the stellar evolution code of Yoon et al. (2006) which includes rotation (Heger et al. 2000) and angular momentum transport by magnetic torques (Spruit 2002). Only two differences apply here: we updated the mass-loss prescription and now use the recipe of Vink et al. (2001) and we disregard the magnetically induced chemical diffusion term of Spruit (2002), which—in contrast to the magnetic angular momentum transport—is not observationally supported, and appears controversial at present (Spruit 2006).

As initial composition we adopted the LMC C, N, O, Mg, and Si abundances given in Paper I and all the other metal abundances decreased by 0.4 dex from the solar composition of Asplund et al. (2005). Based on the recent discussion of the primordial helium abundance (Peimbert et al. 2007), we have updated the initial helium mass fraction for our LMC models to $Y = 25.6\%$, which together with the metallicity of the adopted chemical composition ($Z = 0.5\%$) results in a hydrogen mass fraction of $X = 73.9\%$.

In Paper III we determined that the end of core hydrogen burning occurs at a logarithmic surface gravity of ~3.2 dex. We find that a convective core overshooting of 0.335 pressure scale heights is required to reproduce this result. While this value is larger than what is typically assumed, with consequences for the post–main-sequence evolution which still remain to be investigated, it provides the only way to understand the sharp drop in the rotational velocity distribution of our sample at a surface gravity of 3.2 dex. Evolutionary models neglecting overshooting indicate that the surface nitrogen enrichment is smaller by less than 0.15 dex at core hydrogen exhaustion for a rapid rotator. Hence, our principal conclusions are not significantly affected by the adopted amount of overshooting.

The efficiency of rotationally induced mixing in our models is controlled by the parameter f_c, which is the ratio of the turbulent viscosity to the diffusion coefficient that describes the transport of angular momentum by rotationally induced hydrodynamic instabilities (Heger et al. 2000). The mean projected rotational velocity of the stars shown in Figure 1 is 110 km s^{-1}, with the mean surface nitrogen abundance being 7.2 dex. Although this mean projected rotational velocity is lower than that observed for cluster stars (see, for example, Huang & Gies 2006a), there is no bias toward stars with low rotational velocities. Our stars are a relatively unbiased sample of the true populations, as explained in Evans et al. (2006). This population is dominated by field stars, which are known to rotate slower than cluster stars, and our velocity distribution is comparable to the Galactic field stars of Abt et al. (2002). In addition Be-type stars are excluded, hence our mean velocity is representative only for normal B-type stars and there is no velocity bias for these B-type stars.

The parameter f_c has been calibrated to reproduce the mean surface nitrogen abundance of the core hydrogen burning stars at core hydrogen exhaustion for a 13 $M_\odot$ model (the mean mass of our non-supergiant stars) initially rotating at 140 km s^{-1} ($110 \times 4/\pi$ to account for random angles of inclination). We find $f_c = 2.28 \times 10^{-2}$, compared to 3.33×10^{-2} adopted previously (Heger et al. 2000). Using these parameters, we computed a grid of models for masses representative of our sample and a range of initial rotational velocities.

4. DISCUSSION AND CONCLUSIONS

In Figure 1 the nitrogen abundances are plotted against the projected rotational velocities for our sample stars, and compared with the evolutionary models. Given the large number of objects in our sample, it is reasonable to assume a random distribution of inclination angles, and hence the rotational velocity of the tracks has been scaled by $\pi/4$. Although we have attempted to constrain the evolutionary tracks to the observations, we are able to reproduce agreement for only 60% of the data (excluding known radial velocity variables).

However, two groups of core hydrogen burning stars in Figure 1*a* stand out as being in conflict with the evolutionary models. Group 1 contains fast rotators which have little chemical mixing. In particular, this group includes fast-rotating single stars with surface gravities indicating that they are near the end of core hydrogen burning (excluding radial velocity variables, this is ~20% of the core hydrogen burning sample.) The gravities used to discriminate these stars have not been corrected for the fact that we may have observed them almost equator-on; i.e., their true polar gravities could be larger, meaning that they are less evolved than our derived gravities imply. However, applying the surface gravity corrections described in Huang & Gies (2006b) would increase the gravities by up to ~0.3 dex for our faster rotators. As the zero-age main sequence gravity of our 13 $M_\odot$ models is about 4.3 dex, and since most of the stellar expansion on the main sequence occurs toward the end of core hydrogen burning, this gravity uncertainty cannot reconcile the situation.

The second discrepant group of stars in Figure 1*a* are the 15 slow rotators ($v \sin i < 50$ km s^{-1}) that show significant nitrogen enrichment. This group also forms ~20% of the nonbinary core hydrogen burning sample. Although it could be argued that they may be fast rotators observed pole-on, statistically this is unlikely. In order to reproduce their mean nitrogen abundance requires a rotational velocity of ~200 km s^{-1}. Using simple geometry to calculate the solid angle restriction that we must impose, i.e., $4\pi(1 - \cos\theta)$, and assuming that we need 15 stars to have this velocity, we expect less than one star to appear with such a low rotational velocity due to random inclinations. The simple corollary of this is that if we have 15 stars with velocities ~200 km s^{-1} populating group 2 through random angles of inclination, over 300 similarly enriched stars with $v \sin i$ values between 150 and 200 km s^{-1} would be expected. Such a population clearly does not exist.

Evolved rapid rotators with low nitrogen enrichment (group 1) may be produced by close binaries with an initial period small enough to ensure tidal locking and slow rotation but large enough for highly nonconservative mass transfer, i.e., with an amount of mass accreted which is sufficient to spin up the star but insufficient to enrich it significantly (Petrovic et al. 2005). However, for many of the evolved stars in group 1, there is no indication of binarity. The single-star nature of these objects would pose a serious challenge to the theory of rotational mixing.

While binaries might be able to populate group 2 (Langer 2008), another explanation may be more likely. Morel et al. (2006) have analyzed 10 slowly rotating Galactic early β Cephei B-type stars and found a highly enriched group (four out of ten) of which three have detected magnetic fields. Although pulsations in these stars may cause an apparent surface enrichment, Bourge et al. (2007) report that only slight nitrogen enrichments would be expected. As such, assuming that the effect of pulsations is negligible, there appears to be a correlation between magnetic fields and nitrogen enrichment. Indeed, Wolff et al. (2007) have attributed the large number of slow rotators often seen in massive star populations to magnetic locking of the star to the accretion disk during the star formation process and Alecian et al. (2008) also show a correlation between slow rotation and magnetic fields for magnetic A- and B-type stars. Hence we postulate that the highly enriched slow rotators in the LMC are analogs of the enriched Galactic magnetic stars. This would imply that, independent of metallicity, a significant fraction of early B-type stars are intrinsically magnetic, analogous to the well-known situation for lower mass stars. In this context, the identification of three He-rich slowly rotating OVz stars in NGC 346 (Mokiem et al. 2006) suggests that the phenomenon of intrinsic magnetic fields in massive stars may not be confined to the B star regime. If these magnetic fields are of fossil origin, i.e., possessing long-term stability (Braithwaite & Spruit 2004), in contrast to the fields produced by the Spruit (2002) mechanism, one may speculate that stars in group 2, and their Galactic counterparts, might be the progenitors of magnetars, analogous to the suggestion of Ferrario & Wickramasinghe (2006) that magnetic white dwarfs evolve from magnetic A, F, and late B stars. While the fossil field hypothesis might well explain the slow rotation, the physical process which leads to the enrichment of nitrogen in the stars of group 2 remains to be identified.

The nitrogen abundances of the supergiants (Fig. 1*b*) appear to fall into two distinct groups, one group having a level of nitrogen enhancement consistent with that seen for the majority of the core hydrogen burning objects (<7.2 dex; group 3), and a second having a much greater level of enrichment (>7.6 dex; group 4). It should be noted that although the group 4 objects appear to be well fitted by evolutionary tracks with initial rotational velocities of 200–300 km s^{-1}, such a rotational velocity distribution for supergiants is inconsistent with that for core hydrogen burning objects and rotation does not increase the blue supergiant lifetime. Hence, the enrichments of the supergiants in group 4 (70% of the nonbinary supergiant sample) are incompatible with the theory of rotational mixing. In addition it should be noted that the lowest gravity stars (<2.8 dex) are all enriched in nitrogen, implying that some evolutionary process not accounted for in the models is responsible for the enrichment.

The simplest way to interpret this would be to characterize group 3 as pre–red supergiant objects, and group 4 as post–red supergiant objects. The nitrogen abundances and rotational velocities in group 4 are indeed consistent with the predictions for a blue loop stage (Heger & Langer 2000). However, we note that our models do not return to the high effective temperatures of the stars in group 4 and hence their position on the H-R diagram cannot be reproduced. As several of the enriched objects show evidence of binarity, mass transfer may also be important (Wellstein et al. 2001).

To conclude, our study cannot provide unambiguous evidence for rotational mixing acting in massive stars. The fast rotators in our sample can be interpreted in two ways. First, as rotationally mixed stars, if the relatively nonenriched stars (group 1) can be explained by binary effects. However, if it were confirmed that these group 1 stars are single stars, then the enriched rapid rotators may need to be understood as binary products—and rotational mixing would be inefficient, or much more complex than described by the present-day shellular models. In addition, the population of intrinsically slow rotators with nitrogen enhancements of up to a factor of ~6 implies that studies of nitrogen enhancements with stellar samples which are restricted to low projected rotational velocities—which applies to most previous works—are not suited for constraining, or motivating, the adoption of rotational mixing in massive stars. Finally, our supergiant sample implies that these stars cannot be considered as representative of the amount of mixing that occurs during the hydrogen-burning main sequence and hence should not be used to constrain this process. In summary, our study provides a challenge to rotational mixing, and provides evidence for two other processes affecting the rotation and the surface abundances of populations of massive stars, likely binarity and magnetic fields.

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