Nitrogen Enrichment in Massive Stars

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Abstract. We present high-resolution spectra of 17 O-type stars in the Small Magellanic Cloud, a low-metallicity galaxy (Z=0.2 Z⊙). We analyzed these spectra using the new, fully line-blanketed NLTE model spectra computed by Lanz & Hubeny (2002). We found that half the program stars show strong enrichment in nitrogen, which we interpret as material processed in the core and brought up to the stellar surface via rotationally induced mixing. We also found that the stars with the highest N abundances are also the stars showing spectroscopic masses much lower than one would derive from their positions on the HR diagram. We interpret both phenomena – enhanced atmospheric nitrogen and low spectroscopic masses – as the effect of rotation.

1. Introduction

The Small Magellanic Cloud (SMC) is a low-metallicity galaxy (Z=0.2 Z⊙) with distinctly non-solar abundance patterns. Typical CNO abundances in HII regions are [C]~7.5, [N]~6.5, and [O]~8.1; which is to say, SMC stars are born with 5–10 times as much carbon as nitrogen, and 30–45 times as much oxygen as nitrogen. Nevertheless, by the time massive SMC stars reach the post-main sequence phase as A-type supergiants, the surface abundance of nitrogen has increased to [N]=7.33 ± 0.35, although oxygen shows no evidence of depletion (Venn 1999). These results raise some basic issues (c.f. Venn, these proceedings): (i) is rotational mixing sufficient to explain the N enrichments, or is a first dredge-up somehow involved? (ii) is the enriched nitrogen primary or secondary? (iii) which is the main source of nitrogen at low Z: massive stars or intermediate mass stars? Such issues must be resolved before we can understand the evolution of nitrogen or infer the IMF of stars in the early universe.

Happily, the tools to address these issues are now within our reach. High-resolution ultraviolet and optical spectra of massive, main-sequence stars in the SMC have been obtained (Walborn et al. 2000). Spectral models of SMC stars accounting in detail for line-blanketing effects in NLTE have now been computed (Lanz & Hubeny 2002). Evolutionary models of massive stars that account for rotation have recently become available (Maeder & Meynet 2001).
In this paper, we present a spectral analysis of 17 O-type stars (all are main-sequence stars) in the SMC based on observations made with HST/STIS, FUSE, and ESO or AAT. We used Lanz & Hubeny's new NLTE photospheric model atmospheres to derive the fundamental properties of each star (Heap et al. 2002) and compared them to the surface properties of evolutionary models. Here, we focus on nitrogen abundances in these stars. Our results are still somewhat preliminary, but we expect no substantive change in the final version.

2. Spectral Analysis

Because the distance to the SMC is well known (m-M=19.0), and the extinction is relatively low both in the Galaxy and SMC, the luminosities, masses, and ages of SMC stars can be determined if their effective temperatures are known. This is an important "if", since \( L_{\text{bol}} \propto T_{\text{eff}}^4 \). A well determined \( T_{\text{eff}} \) is also essential for a reliable determination of nitrogen abundance. For the majority of the program stars, the N abundance has to be derived from NIII lines alone. Since the ionization fraction of NIII plumes toward mid- and early-O stars (Lanz & Hubeny 2002), any overestimate of \( T_{\text{eff}} \) translates to an overestimate of the nitrogen abundance. Similarly, an underestimate of \( T_{\text{eff}} \) can lead to an OC-type spectral classification even when the nitrogen level is normal.

To determine \( T_{\text{eff}} \), we used the time-honored method of ionization balance of the optical helium lines, but we supplemented this method with ionization balance of the UV carbon lines, \( \text{CIV} \lambda 1169/\text{CIII} \lambda 1175 \). The resulting temperatures from the two methods generally agree to about 1,000 K. In addition, there are numerous lines of other elements, such as the Fe IV/V/VI lines, that are useful for consistency checks. We are presently working on ways to use the so-called "Of emission lines" that are pure NLTE effects (not wind emission) to consolidate our estimates of temperature and gravity. The main result of our endeavor is a significantly lower \( T_{\text{eff}} \) scale for O-type stars than previous spectral calibrations, e.g. Vacca et al. (1996).

With the fundamental properties of each star in hand (Heap et al. 2002), we then compared the observed properties to evolutionary models with/without rotation. We find that the observations strongly favor the rotating models, because only the rotating models predict nitrogen enhancements at the stellar surface during the main-sequence phase of a massive star.

3. Results and Discussion

Figure 1 shows the evolution of the surface nitrogen abundance for models with initial masses ranging from 20 to 60 \( M_\odot \). It shows that the more massive the star, the higher the N enrichment, but even the 60 \( M_\odot \) does not achieve a solar level of nitrogen in its main sequence phase. The figure also shows our N abundance estimates for all 17 program stars. Three O stars (white star symbols) have low N abundances typical of SMC nebulae, \([\text{N}] = 6.45\). We interpret such stars as slow rotators. Nine of 17 program stars (black stars) show a solar level of nitrogen, \([\text{N}] = 7.92\), a 30X enrichment factor, and higher than predicted by rotating models. Such high observed N abundances suggest that SMC O stars
Figure 1. Comparison of observed atmospheric N abundances in SMC O-type stars with theoretical surface N abundances from the rotating models of Maeder & Meynet (2001).

generally rotate more rapidly than assumed in the models (ZAMS V\textsubscript{rot}=300 km/s), and/or rotational mixing is more efficient than assumed.

Most, but not all, program stars have spectroscopic masses (M\textsubscript{sp}) that are lower than indicated by their position on the HRD. The mass discrepancy is usually worse for stars with a high N abundance than for stars with their original (low) N abundance. This trend is a sign that rotation is involved, since rotation can cause this mass discrepancy by decreasing g\textsubscript{eff} and therefore M\textsubscript{sp} \propto g\textsubscript{eff} R\textsuperscript{2} and/or by increasing the luminosity (L\textsubscript{ev}).

Both theory and observations suggest that rotation is a more important factor in massive stars of low metallicity (Z). Low-Z stars lose less angular momentum due to their weaker winds (Maeder & Meynet 2001). They may also be born as faster rotators, because they are smaller than their galactic counterparts. Observations support this trend with metallicity in revealing that the fraction of Be stars (rapid rotators) to total (Be + B) stars in clusters increases toward lower metallicity (Maeder et al. 1999).

References

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