New Nitrogen and Carbon in AF-supergiants

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Abstract. The AF-supergiants in the Galaxy and the SMC allow us to examine predictions from evolution models through their CNO abundances. In these proceedings, we recalculate the NLTE nitrogen abundances in 22 Galactic and 9 SMC A-supergiants using improved atomic data and model atmospheres to compare with new evolution models. The new abundances are higher than previously published values, and suggest that most of these stars have undergone substantial mixing with CN-cycled gas. While there is no clear relationship with mass, there is an apparent relation with metallicity since the SMC stars (including B-stars) have larger nitrogen enrichments. We suggest that rotational mixing is indicated from the main-sequence throughout the supergiant range, with more substantial rotational mixing in the SMC stars. In addition, the SMC AF-supergiants appear to have undergone the first dredge-up during a previous red giant phase, and possibly the Galactic AF-supergiants have as well. All abundances are compared to the new solar abundances from M. Asplund (this conference).

1. Introduction

Reviews on massive star evolution have shown there are a number of observations that suggest an additional parameter affects the evolution scenarios, ranging from blue-to-red supergiant ratios in clusters to CNO abundances in main-sequence and evolved stars; c.f., Maeder & Meynet (2000), Heger & Langer (2000 = HL00), Maeder & Conti (1994). In Galactic supergiants, the N/C ratios have long supported a parameter that varies from star-to-star, like rotation. This is because a variety of N/C ratios have been found within clusters of stars (thus, not natal variations), and because the N/C ratios do not clearly scale with effective temperature, luminosity, or mass.

Evolution models that include effects of rotation emerged in 2000. Not only can rotation help to explain the abundance ratios and certain mass discrepancies, but the new models also predict that massive stars may produce and mix primary nitrogen into their atmospheres (by Meynet & Maeder 2002). The new models have been calibrated based on abundance ratios, masses, rotation rates, and ages.
Figure 1. Boron versus Nitrogen in main-sequence B-type stars from Venn et al. 2002. Notice the extreme range in boron abundances observed at the same low nitrogen abundances.

in the published literature. But they also make definite predictions that can be tested for further refinement.

Unfortunately, one direct test that is difficult to implement is to examine abundance ratios versus rotation rate. Rarely do we know the inclination angle of a rotating star. Also, as $v_{\sin i}$ increases, then the spectral lines become so shallow and broad that the atmospheric analysis becomes quite difficult and less certain. Fortunately, there are other indirect tests.

2. Boron and Rotation

One of the new predictions from stellar evolution calculations that include rotation is that the surface abundances of lithium, beryllium, and boron (LiBeB) will be rapidly depleted before significant mixing of any other material (see Heger & Langer 2000). These elements are fragile and easily destroyed when exposed to hot protons, thus any mixing in the atmosphere will rapidly dilute LiBeB and destroy those atoms that are mixed downwards. This should be detectable in main-sequence stars; but boron is the only element with measurable absorption lines in B-type stars.

Boron has been measured in a handful of main-sequence B-stars (see Figure 1) from the BIII 2066 and BII 1362 resonance lines. Both require UV spectral observations, such as with HST-STIS. There is a large range in the initial boron abundances in main-sequence B-stars, by a factor of 10 to 100. This variation
is not natal since several stars within a single association show this range, for example, the star in the Orion association.

In Figure 1, boron is observed to be depleted before there is any detectable nitrogen enrichment. This matches predictions, as seen from the HL00 model for a 12 $M_\odot$ star at 200 km s$^{-1}$ through H-core burning and three sets of initial abundances [(B, N) = (2.6, 7.6), (2.8, 7.7), (2.8, 7.8)]. Thick lines connect boron abundances for the same stars from different analyses. The boron abundance papers are listed in the legend (see references), the nitrogen abundances are from Cunha & Lambert (1994 = CL94), Gies & Lambert (1992 = GL92), or Vrancken et al. (2000). Currently, the most extreme rotating models suggest that boron can be depleted by a factor of 10 before nitrogen is enriched (e.g., $M = 25 M_\odot$, $v_{\text{rot}} \geq 400$ km s$^{-1}$). The current data (especially star HD 36591 in Ori OB1) suggest even larger depletions are possible before nitrogen enrichment.

These boron depletions in main-sequence B-star, without significant nitrogen enhancements, are unique to rotating stellar evolution models. It is possibly to reproduce a boron-depletion with a nitrogen-enhancement through mass-transfer in a binary system (Wellstein, Langer, & Braun 2001).

3. CNO in Intermediate-Mass Supergiants

Another prediction of the rotating models is that there should be a wide range in the C and N abundances in evolved massive stars if these stars had a range in rotational velocities on the main-sequence. This has been seen and is well documented for Galactic stars in the literature, e.g., in O-stars (Herrero et al. 1992) in B-supergiants (McErlane et al. 1999, Lennon et al. 1988) and in A-F supergiants (Venn 1995). More recently, Smartt et al. (2002) found that Sher 25, an evolved early B-supergiant surrounded by nebular ejecta, has only a small nitrogen enrichment, incompatible with the predicted first dredge-up abundances.

The fact that many of the N/C ratios in these stars ranged from solar ratios to only slightly enriched supports the idea that it is rotation that affects these abundances. Another possibility has been that the N/C ratios are affected by surface mixing and the first dredge-up during a previous red giant phase; in this case, we expect an offset in the mean N/C ratio (of $\sim +0.5$ dex for stars $\geq 10 M_\odot$), which has not been seen in the literature until now (below).

In most of the supergiants, non-LTE corrections have had to be applied to the C, and especially the N, abundances. The non-LTE corrections result in N/C ratios in Galactic supergiants that show no relationships with effective temperature, luminosity, or mass. And a variety of N/C ratios are often found for stars in the same OB association. Thus, the variations in N/C are best attributed to star-to-star variations, such as rotation.

**New Solar Abundances:** Before proceeding with a comparison of N/C ratios, it is important to notice that the solar abundances have been significantly improved through the 3-D convection models by M. Asplund and collaborators. In this conference proceedings, new solar CNO abundances are presented, showing excellent agreement between a variety of abundance indicators for each element. In the rest of this paper, we will adopt these new solar abundances; $12 + \log (C, N, O, Fe) = (8.41, 7.80, 8.66, 7.45)$. 
Table 1. Galactic Nitrogen Abundances: $12 + \log(N/H)_{\text{NLTE}}$

| HD    | NEW       | OLD       | HD    | NEW       | OLD       |
|-------|-----------|-----------|-------|-----------|-----------|
| 87737 | 8.54 ±0.03 (3) | 8.09 ±0.06 | 34578 | 8.33 ±0.04 (3) | 7.97 ±0.14 |
| 46300 | 8.28 ±0.14 (8) | 7.85 ±0.10 | 147084 | 8.44 ±0.10 (3) | 8.23 ±0.12 |
| 161695| 8.48 ±0.11 (8) | 8.03 ±0.11 | 58585 | 8.26 ±0.16 (3) | 8.16 ±0.16 |
| 195324| 8.67 ±0.02 (4) | 8.14 ±0.10 | 222275 | 8.51 ±0.03 (2) | 8.31 ±0.25 |
| 207263| 8.43 ±0.05 (3) | 8.04 ±0.04 | 67456 | 8.19 ±0.02 (2) | 8.06 ±0.22 |
| 175687| 8.26 ±0.01 (3) | 8.29 ±0.07 | 36673 | 8.19 (1) | 8.30 ±0.13 |
| 3940  | 8.15 ±0.02 (3) | 7.75 ±0.11 | 148743 | 8.19 ±0.13 (3) | 7.99 ±0.19 |
| 14489 | 8.01 (1) | 8.01 | 6130 | 8.00 ±0.14 (9) | 7.98 ±0.12 |
| 13476 | 8.34 ±0.06 (2) | 7.96 ±0.08 | 25291 | 7.96 ±0.11 (7) | 7.85 ±0.11 |
| 15316 | 8.35 ±0.03 (3) | 7.96 ±0.12 | 196379 | 7.61 ±0.20 (11) | 7.57 ±0.20 |
| 210221| 8.63 ±0.20 (2) | 8.19 ±0.04 | 59612 | 8.57 ±0.02 (2) | 8.29 ±0.12 |

4. New Nitrogen Abundances

Much of the sample for the N/C ratios in Galactic supergiants comes from the A-F supergiants (Venn 1995). Since then, new collisional excitation data has become available for NI (Frost et al. 1998), which does affect the non-LTE corrections (Przybilla 2002, and this proceedings), particularly for the hotter stars. This atomic data was sorely needed for the most reliable nitrogen abundance determinations since the collision excitation cross-sections were the most significant source of uncertainty in the Lemke & Venn (1996) nitrogen model calculations in A-stars. Now, the new atomic data shows that the NI level populations are more collisionally coupled, which reduces the NLTE corrections (which increases the NI abundances).

In this conference proceedings, we present a new table of nitrogen abundances for the A-F supergiants; see Table 1. These new results include the updates to the corrections calculated by NP (see Przybilla 2002 for a detailed description), which makes a substantial difference to the hotter supergiants, yielding higher nitrogen abundances. Only the NI \(\lambda\lambda 7440\) and \(\lambda\lambda 8700\) multiplets, and \(\lambda 8629\) line are included in these new NLTE calculations. The new NLTE corrections do not significantly affect the cooler stars since their NI atomic levels are already more closely collisionally coupled. Thus, similar calculations to those in Venn (1995) have been used for the six coolest stars (which include more lines). We have also recalculated the ATLAS9 model atmospheres using the most recent unix version. This has only a minor effect on the final abundances. The old abundances from Venn (1995) are also shown for comparison. The average nitrogen abundance has significantly increased, and the distribution in abundances with effective temperature is shown in Figure 2. Note that Asplund’s solar abundances listed above are used in these new figures.

In Figure 2, there is no clear trend in the N abundances with temperature above 8000 K. All stars show similar large N enrichments. The coolest stars show smaller N enrichments though, with one star (HD196379) showing no indication of internal mixing. We also show the NLTE CI abundances from Venn (1995), as well as new NLTE CII abundances in three stars from Przybilla (2002). The carbon abundances in the cool stars are from the weak \(\lambda 7115\) multiplet and show
Figure 2. The NLTE C and new NLTE N abundances in AF-supergiants. For C, filled circles include the CI $\lambda 7115$ results from Venn (1995), and hollow circles represent the more uncertain CI $\lambda 9100$ results (and their corresponding N/C ratios). Filled triangles are the NI and CII results from Przybilla (2002). Dashed lines show first dredge-up predictions for 9 to 20 $M_\odot$ stars above solar (the dotted line).

very small NLTE corrections. However, the carbon abundances in the hotter supergiants (hollow circles) are from the strong $\lambda 9100$ multiplet which have very large, and less certain NLTE corrections. In general, the N enrichments are accompanied by smaller C depletions, as expected in CN-cycled gas. Finally, the N/C ratios are shown. The N/C ratios scatter about the predicted first dredge-up abundances (on the red giant branch) for 9 to 20 $M_\odot$ stars from the non-rotating evolution tracks of Schaller et al. (1992).

5. SMC Abundances

We have also recalculated the NLTE NI abundances in the SMC AF-supergiants from Venn (1999). Metallicity has a negligible effect on the statistical equilibrium of nitrogen in these atmospheres. The new SMC NI abundances are listed in Table 2 and plotted in Figure 3. Nearly all stars have higher nitrogen abundances from the new calculations. For only the two coolest stars, where the levels are more closely collisionally coupled, have we used similar calculations from Venn (1999, which also include more lines). Like with the Galactic stars, the new NLTE nitrogen abundances are higher than the published values, and there continues to be no clear trend in the abundances with temperature. Also like the Galactic stars, one very cool star shows no significant nitrogen enrich-
ment. Notice that the initial [N/Fe] ratio for SMC stars is significantly below solar (dotted line) because of the different chemical evolution of this galaxy.

Table 2. SMC Nitrogen Abundances: $12 + \log(N/H)_{\text{NLTE}}$

| AzV | NEW                | OLD          | AzV | NEW                | OLD          |
|-----|--------------------|--------------|-----|--------------------|--------------|
| 110 | 7.84 ±0.06 (2)     | 7.64 ±0.18   | 254 | 7.28 (1)           | 7.13 ±0.27   |
| 298 | 7.72 ±0.07 (2)     | 7.65 ±0.21   | 442 | 7.55 ±0.20 (3)     | 7.32 ±0.21   |
| 136 | 7.73 ±0.05 (3)     | 7.26 ±0.07   | 213 | 7.79 ±0.18 (4)     | 7.74 ±0.22   |
| 463 | 7.07 (1)           | 6.92 ±0.25   | 174 | 6.79 (1)           | 6.76         |
| 478 | 7.87 ±0.07 (3)     | 7.61 ±0.16   |

5.1. Primary Nitrogen?

That the SMC nitrogen abundances are so much larger than the first dredge-up predictions (indicated by the solid line in Figure 3) suggests these stars have undergone excessive mixing. Even if these are post-RGB stars, their nitrogen indicates even more mixing as predicted by the new rotating evolution models. Does this mean that there is primary nitrogen in the atmospheres of these metal-poor supergiants (as predicted for metal-poor stars by Meynet & Maeder 2002)? At present, we can only say that the metal-poor SMC stars have more nitrogen in their atmospheres. Its nucleosynthetic history is an open question.

6. More Rotation? First Dredge-Up?

A comparison of the N abundances in Galactic B-stars, Galactic AF-supergiants, and SMC AF-supergiants is shown in the histograms in Figure 4. Clearly the new Galactic AF-supergiant results are offset from the initial (solar and B-stars) N value by ~0.5 dex. This was not seen in the previously published results (dashed line, where the mean nitrogen abundance was close to the initial N abundance). In the SMC, the same broad distribution in nitrogen is seen as before, but now with more stars at higher values.

In Maeder & Meynet’s review (2000), their Figure 6 shows that a large spread in the N abundances in the A-F supergiants are expected through varia-

![Figure 3](image-url)  
Figure 3. New NLTE NI abundances in SMC AF-supergiants. Old results from Venn 1999 are shown by small dots. The initial [N/Fe] ratio indicated by dotted line. First dredge-up predictions by a solid line.
tions in the rotational velocities. This spread can be larger in higher mass stars or lower metallicity stars. We certainly see a larger spread in the SMC stars versus the Galactic stars, and we expect this is due to metallicity since the stars have similar mass ranges (see Figure 5).

Since all of the AF-supergiants exhibit significantly enriched N abundances, and the metal-poor SMC stars show the largest enrichments of all, then these results suggest:

(a) All of the stars had very high rotation rates (>300 km s⁻¹) on the main-sequence. This does not seem likely since the samples include a lot of stars and the mean $v_{\sin i}$ values for these stars when on the main-sequence (B2-type) is only $\leq 200$ km s⁻¹ (e.g., Fukuda 1982, de Jager 1980).

(b) The stars have higher masses than expected. This is possible, but unlikely. The stars appear to range in mass from 5 to 25 M$_\odot$ based on a comparison with standard evolution tracks (Figure 5), and even if those tracks are not appropriate (e.g., rotational mixing can affect the post-main sequence evolution) there does not appear to be a relationship in the N or N/C ratios with mass.

(c) Rotational mixing is more efficient than currently predicted.

(d) The stars have undergone the first dredge-up during a previous red giant phase. This certainly supports the N and N/C ratios observed, but since

Figure 4. Histogram of NLTE nitrogen abundances in Galactic B-stars (GL92, CL94), and Galactic and SMC A-type supergiants. The old histogram results from Venn (1999) are indicated by the dashed line. The initial solar and SMC ISM nitrogen abundances are indicated.
rotational mixing must also happen on the main-sequence (to explain the boron dispersion in main-sequence B-stars), then the scatter in the N abundances and N/C ratios could be attributed to early rotational evolution effects in addition to first dredge-up abundances. In the SMC, additional mixing beyond the first dredge-up predictions is clearly indicated. [Of course, the few coolest stars with low N (SMC) or N/C ratios (Galactic) could not have undergone the first dredge-up yet and must be evolving directly from the main-sequence].

Either of the last two options is likely given the current theoretical models. In addition, post-RGB evolution is indicated for blue supergiants (from a He-burning sequence parallel to the main-sequence) in metal-poor Local Group dwarf irregular galaxies from deep and accurate HST colour-magnitude diagrams (e.g., Dohm-Palmer et al. 1997 (SexA), 1998 (Gr8); Tolstoy et al. 1998 (LeoA)). Thus, excessive N enrichments in the SMC AF-supergiants are most simply explained as post-RGB first dredge-up abundances. But if we also consider the range in the nitrogen abundances, and the SMC B-star nitrogen enrichments, then main-sequence rotational mixing, as well as RGB convective mixing, are both indicated in metal-poor stars.

Is the first dredge-up indicated at Galactic metallicities? The new AF-supergiant nitrogen abundances do cluster around the first dredge-up predictions. But we also know now that rotational mixing is important in interpreting abundance ratios, in SMC supergiants and in Galactic main-sequence stars (e.g., boron). Thus, the Galactic AF-supergiants may also have been RGB stars in
their past, but it is also possible that their [N/C] ratios could be explained by excessive rotational mixing alone.

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