New Views of the Magellanic Clouds
IAU Symposium, Vol. 190, 1999
Y.-H. Chu, N.B. Suntzeff, J.E. Hesser, and D.A. Bohlender, eds.

Massive Stars Spectroscopy in the Magellanic Clouds

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Abstract.
Recent results from spectroscopic studies of Magellanic Cloud stars are discussed. Emphasis is placed on how to interpret CNO abundances to examine stellar evolution scenarios. Observed CNO abundances are best explained by the new rotating stellar evolution models (see Langer & Heger, these proceedings). In addition, the Rolleston et al. (these proceedings) abundances for B stars in the Magellanic Bridge are discussed.

1. Introduction

Spectroscopic observations of massive stars are used to study individual stars themselves, but also as probes of their host galaxies, and as test cases for different stellar evolution theories. Simple low (classification) resolution spectra can be used easily for important first estimates of stellar parameters. High resolution spectra and detailed model atmosphere analyses are much more labor intensive but can be used to determine more accurate stellar parameters and individual elemental abundances. To date, detailed atmospheric analyses have been performed for B-type dwarfs, giants, and supergiants, A-supergiants, F-K supergiants, and M-supergiants in the LMC and SMC. These analyses have determined abundances for elements ranging from helium and lithium, through CNO and α-elements, including Fe-group elements, and culminating in abundances for a variety of s-process and r-process elements. Although many individual elemental abundances appear to be contradictory or in poor agreement, most are in excellent agreement between the analyses, but the reader of those papers must first accept the inherent uncertainties in each analysis and must also frequently consider the *differential abundances*, e.g., abundances relative to a standard star, or the abundance ratio between two elements.

2. Spectral Types at Low-Z

The simplest way to learn more about an individual star is to study its spectral type. From this we can learn about its fundamental parameters, e.g., effective temperature, surface gravity, luminosity, and metallicity, and we can determine additional characteristics such as magnetic field strength, rotation rate, and presence of a stellar wind or circumstellar shell. The accuracy with which any one of these parameters can be determined depends critically on the comparison stars calibration scheme. Because of the lower metallicities of the Magellanic Clouds,

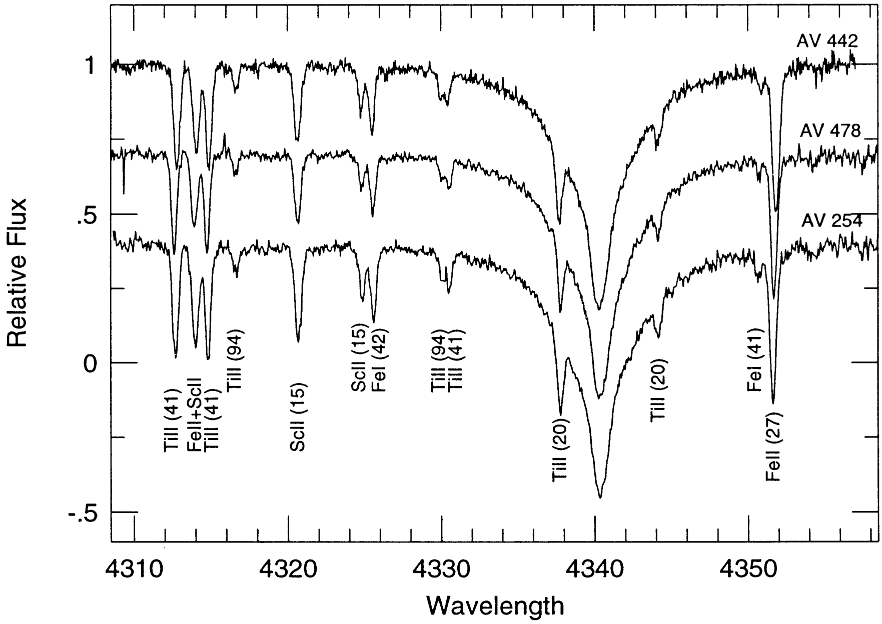

Figure 1. Spectra of three normal SMC A7 Iab supergiants near Hγ. Previously, AV 442 had been reported as a normal A3 Ia star, while the other two had been reported as "anomalous", helium-rich A3 I stars (Humphreys 1983; Humphreys et al. 1991). These claims had been partially based on a comparison of their hydrogen line profiles which are actually, as can be seen in this figure, essentially identical.

new spectral sequences based on stars in the Clouds were developed for bright B stars; in the LMC by Fitzpatrick (1991), and in the SMC by Lennon (1997). These have had two main results. Firstly, Fitzpatrick & Garmany (1990) discovered a feature, a "ledge", in the distribution of B stars in the LMC. This ledge has frequently been interpreted as a mixed population of H-core and He-core burning B-supergiants, providing evidence for blue-loop evolution scenarios for massive stars at low metallicities. Lennon also found evidence for a ledge in his refined, although sparse, SMC data set. Secondly, both Fitzpatrick and Lennon found the first evidence for BN/BC stars in the LMC and SMC, respectively. The mechanism responsible for the N and C line strength differences could be a stellar evolution effect – mixing of CNO-cycled gas into the atmosphere possibly as a previous red supergiant. This effect is thought to be metallicity sensitive, but finding these stars at three metallicities could refute that (partial mixing of gas on the main sequence is discussed below and is another, non-metallicity dependent method of achieving this phenomenon).

More recently, I have determined stellar parameters from detailed model atmosphere analyses of 10 A-type supergiants (Venn 1999) and have found that the problems in spectral typing hot stars extends to the A-types. All the A-type supergiants analyzed had been classified as too hot. In fact, some stars had been classified as anomalous — Humphreys (1983) and Humphreys et al.

(1991) had suggested that the anomalies were due to overabundances of helium in their atmospheres. These stars have identical spectra to simply cooler and less luminous stars, see Fig. 1 for an example. Misclassification of A-stars is easy to do. Line blanketing of the optical spectrum increases, such that hotter A-stars at high-Z mimic cooler A-stars at low-Z (carefully examining ionization ratios can help to avoid this problem).

3. CNO & Fe Abundances in the Clouds: Stellar and MC Evolution

Elemental abundances in the Magellanic Clouds have two main purposes: to study important metallicity effects on stellar evolution and to study the chemical history of these irregular galaxies.

With respect to stellar evolution, the main elements to be exploited are CNO. CNO are catalysts in H-burning, and any mixing between surface and interior gas results in a distinctive change in the relative ratios of C:N:O. In particular -0.15:$+0.55$:-0.1 are predicted by most theories due to the first dredge-up as a red supergiant star (c.f., Schaller et al. 1992). To use CNO, one must know not only the current abundance in a star, but also the initial abundance that the star had before mixing began. The latter is typically assumed to be the same as the present surface abundances in main-sequence B stars, which have undergone no mixing, and the present abundances in the H II regions. Clearly then, the B stars and H II regions are expected to have similar abundances, which is a reasonable assumption given the short lifetimes of B stars.

In the Galaxy, the B stars in the Orion nebula yield very similar results to the nebular abundance data (see Cunha & Lambert 1994). These abundances for CNO are not the same as solar, however, where the Orion abundances are approximately 0.2 dex less than in the Sun. In the Magellanic Clouds, the lower overall metallicity means that CNO are not similar to Orion or solar abundances (of course), but additionally since each element has a different main nucleosynthetic site then *C and N and O need not have the same underabundance as Fe nor as each other.*

Note: Helium and LiBeB would also be affected by mixing, but have not yet been quantitatively examined because of various difficulties with either non-LTE model atmosphere and line formation effects or because the initial abundances are not well known (e.g., the unmixed Li abundance).

3.1. Present Day CNO in the SMC

Initial CNO abundances in the SMC can be determined by examining abundances from three main-sequence B stars (Rolleston et al. 1993) and from several H II regions (Dufour 1984; Russell & Dopita 1990; Garnett et al. 1995). Adopting [Fe/H]=-0.7 for the SMC, these analysis suggest the best pristine present-day CNO abundances are [C/Fe] ~ -0.5, [N/Fe] ~ -0.8, and [O/Fe] ~ -0.2. (Recall that solar abundances are not similar to Orion abundances, where solar abundances appear $\sim$0.2 dex larger).

CNO abundances have been determined as a dataset for three types of evolved stars; B giants (Jüttner et al. 1992; Lennon et al. 1996; Korn & Wolf in these proceedings), A supergiants (Venn 1999), and F-K supergiants (Luck

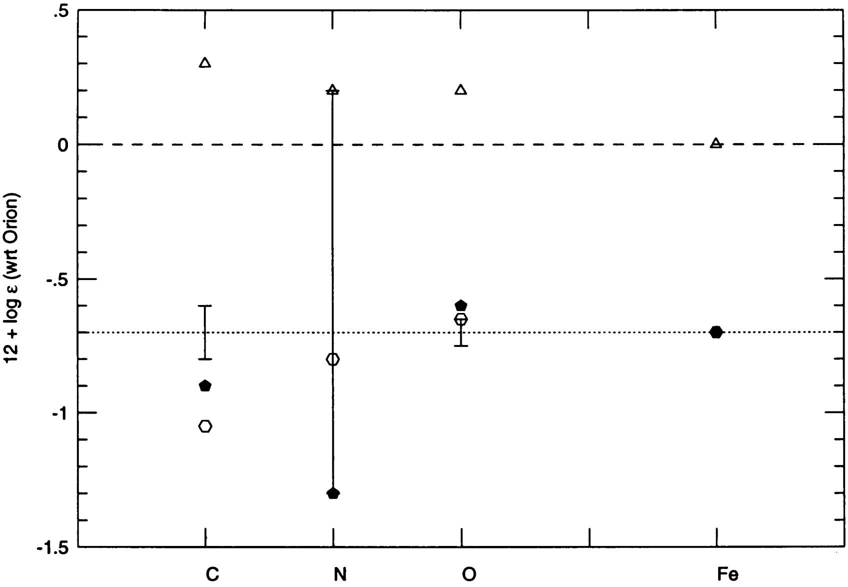

Figure 2. SMC abundances for CNO – present-day (*filled pentagons*), first-dredge-up predictions (*hollow six-sided symbols*), and the range in the abundances determined from evolved stars (see text for references). The initial abundances are dissimilar from the Fe underabundance (*dotted line*). Note also that solar abundances are dissimilar to those from Orion B star and nebular analyses which are used here at the best reference abundances (*dashed line*).

& Lambert 1992; Hill et al. 1997; Luck et al. 1998). These analyses have found [C/Fe] ~ −0.2 to −0.4, [N/Fe] ~ −1.5 to 0.0, and [O/Fe] ~ −0.2.

The first dredge-up predictions are essentially metallicity independent and are shown in Fig. 2 (relative to the present-day CNO abundances). Surprisingly, nitrogen has been so slow in its interstellar enrichment in the SMC that [N/Fe] ~ 0 *after the first dredge-up and not before, as has often been assumed in the past.*

Comparing the CNO abundances in evolved stars to the present-day abundances is still confusing though. The CNO abundances do not reflect the initial abundances nor the first dredge-up abundances. Examining N specifically shows that N ranges from the initial (nebular-like) abundance through the first dredge-up enrichment and on to ~2x the predicted enrichment! This range in the N abundances is much larger than the predicted uncertainties in the analyses (even the expected non-LTE effects). [The high carbon abundance observed in the evolved stars, opposite to the predictions of the first dredge-up, may reflect uncertainties in the initial, nebular, abundance adopted, possibly due to dust grain formation].

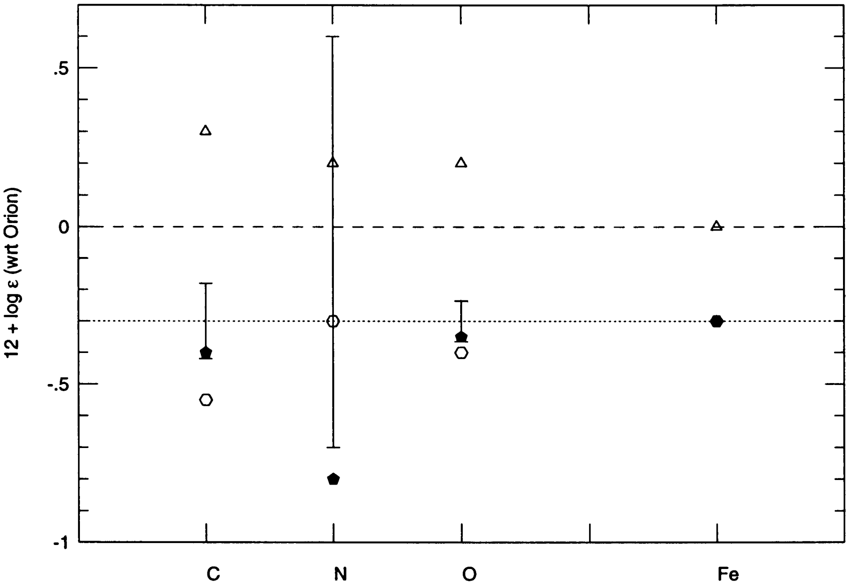

Figure 3. LMC abundances for CNO – symbols same as in Fig. 2.

3.2. Present Day CNO in the LMC

The present-day CNO abundances in the LMC can be estimated from the analyses of several H II regions (Dufour 1984; Russell & Dopita 1990; Garnett et al. 1995) and from 2 B dwarfs (Rolleston et al. 1996; Korn & Wolf in these proceedings). Again, CNO need not have the same LMC underabundance as Fe, although the underabundances of O and Fe are about the same relative to the Orion nebular and stellar abundances, i.e., [O/Fe] ~ −0.2. C and N are more underabundant than Fe, with [C/Fe] ~ −0.4 and [N/Fe] ~ −0.6. These present-day abundances are shown in Fig. 3.

The first dredge-up predictions are essentially metallicity independent and are also shown in Fig. 3. Again, as seen for the SMC, [N/Fe] ~ 0 *after the first dredge-up and not before, as has often been assumed in the past.*

CNO have been determined as a complete dataset for only a few evolved stars in the LMC; for B giants (Korn & Wolf in these proceedings) and F-G supergiants (Luck & Lambert 1992; Hill et al. 1995). In general, the CNO pattern results are similar to the SMC. These evolved stars show [C/Fe] ~ −0.2 to −0.4, [N/Fe] ~ −0.6 to +0.7, and [O/Fe] ~ −0.2. Thus, oxygen is similar to the present-day nebular abundance, carbon ranges from the nebular to the predicted first dredge-up abundance, and nitrogen ranges wildly from the nebular abundance to 2x the first-dredge-up prediction. Again, the range in the nitrogen abundances in these analyses are far larger than the simple model predictions.

3.3. Importance of Rotation on Stellar Evolution

The NLTE CNO abundances from evolved stars in the Magellanic Clouds prove beyond a doubt that the surfaces of these stars have undergone mixing with CNO-cycled gas from their interior. The new question raised by these results is when and how did this happen. Classical stellar evolution models predict first dredge-up mixing as a red supergiant, however the *range* in the CNO abundances do not support this alone. The range in N also shows that star-to-star variations are large – some stars showing extreme mixing and others showing little or none.

Only the newest rotating models predict significant star-to-star variations, e.g., the range in N reflects the range in rotational velocities of these massive stars and thus their success in rotational mixing on or near the main-sequence (c.f., Langer & Heger in this conference proceedings, and references therein). Whether rotational mixing happens alone or in addition to the first dredge-up remains unclear. It is probably the latter because (1) some of the enrichments of N are incredibly large (too large for just one mechanism?), and (2) most stars appear enriched to some degree in the Magellanic Clouds, which is *not* what is seen in the Galaxy (most evolved massive stars do not show strong N enrichments, c.f., Venn 1995 and references therein).

Rotation can have a huge effect on the evolution of massive stars. Theoretical tracks are used to get stellar masses & ages, and the evolution scenario is used to predict the chemical yields from stars. Also the theoretical distribution of massive stars on the HRD is used in galaxy population syntheses. To see an example of rotational effects on the evolutionary track of a 10 $M_\odot$ star, see Fig. 2 in Fliegner et al. (1996). Also, see Langer & Heger (these proceedings) for more details and effects of rotation on stellar evolution.

4. Stars in the Magellanic Bridge

The Magellanic Bridge is a ridge of H I gas between the LMC and SMC, in which evidence for on-going star formation has been found, e.g., from color-magnitude diagrams of associations of young stars (e.g., Irwin et al. 1990). Elemental abundances of normal main-sequence B stars in the Bridge have been performed (Hambly et al. 1994; Rolleston et al., in these proceedings). The abundance results suggest that C, O, Mg and Si in the Bridge B stars are less than Galactic B stars by ~ 1.0 dex. This is a larger underabundance than has been found for SMC B stars of ~ 0.7 dex (Rolleston et al. 1993).

How or why gas in the Magellanic Bridge could be more metal-poor than that of the SMC is a mystery, and currently not predicted from the dynamical models of the Bridge. Enrichment in the SMC to the present-day abundances is thought to have occurred ~2 Gyr ago (e.g., Pagel & Tautvaišienė 1998), and yet the Bridge is thought to be gas pulled out of the SMC ~0.2 Gyr ago (e.g., see Gardiner or Kunkel, these proceedings).

The abundance determinations in the Bridge B stars are very difficult because the stars analyzed so far have essentially no spectral lines for a standard detailed model atmospheres analysis (e.g., where spectral lines from different ionization stages of He or Si are used to constrain atmospheric parameters). This alone is significantly different from SMC B stars analyzed, and qualitatively suggests these stars are truly more metal-poor. Future analysis of additional stars, particularly cooler stars which should have more spectral lines, will provide better abundances of a variety of elements, and thus allow us to further examine the chemical and dynamical formation of the Bridge.

Acknowledgments. Many thanks to Danny Lennon, Robert Rolleston, Norbert Langer, and Michael Lemke for many stimulating and helpful discussions on the Magellanic Clouds and massive star abundance analyses. Much of this work has been carried out at the Universität Sternwarte München thanks to Rolf Kudritzki. Also, thanks to Clare and Evan Skillman for helping me to enjoy Vancouver Island.

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Discussion

Nolan Walborn: It should be noted that Norbert Langer's talk included objects above the 40-50 $M_\odot$ limit for a red supergiant, such as some of the Ofpe/WN9 stars, so clearly their nitrogen enhancements must be due to some other mechanism than dredge-up.

Hans Zinnecker: There is often some confusion about Z, i.e., the heavy element abundance/metallicity. Could we agree to call Z_{CNO} the "heavy element abundance" and Z_{Fe} the "metallicity"?