A-Supergiant Abundances in Local-Group Galaxies

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Abstract. Abundance analyses of A-type supergiants is a tractable and worthwhile problem since these stars can be used as probes of massive-star evolution (by their evolutionary status) and of the chemical evolution of Local-Group galaxies (since they are bright and their spectra sample many elements). Analysis of A supergiants in the Galaxy and SMC shows that high metallicity suppresses blue-loop evolution scenarios, yet partial mixing is indicated in both galaxies in support of the new stellar-evolution models which include rotation. Analysis of a few stars in M31 & M33 shows that we are able to determine abundances of oxygen and α-elements (for comparison with H II-region abundances), but also iron-group and s-process elements. Abundance gradients of these elements can provide new and unique constraints for models of galactic chemical evolution.

1. Introduction

A-type supergiants are young ($\sim 10^7$ yr), massive (5–$25 M_\odot$) stars that have evolved from main-sequence ~B0–B5 stars. Quantitative analysis of these stars is an extremely useful tool since there are many elements sampled in their spectra: light elements (He, B, CNO), alpha-elements (Mg, Si, S, Ca, Sc, Ti), iron-group elements (Cr, Mn, Fe, Ni), and even s-process elements (Sr, Zr, Ba). But also, these stars are extremely luminous, $\log(L/L_\odot) \simeq 3$ to 5, and they are the brightest stars at visual, V, magnitudes which make them the brightest single stars seen in optical surveys of other galaxies.

Can reliable elemental abundances be determined from these stars? Yes! One way is to tailor the analysis to weak lines that form deep in the photosphere, preferably from the dominant ionization state, and then make the standard classical assumptions used in model-atmospheres analyses (hydrostatic and local thermodynamic equilibrium, plane-parallel geometry, full line blanketing, no significant stellar-wind component). Of course, the simplifying assumptions do

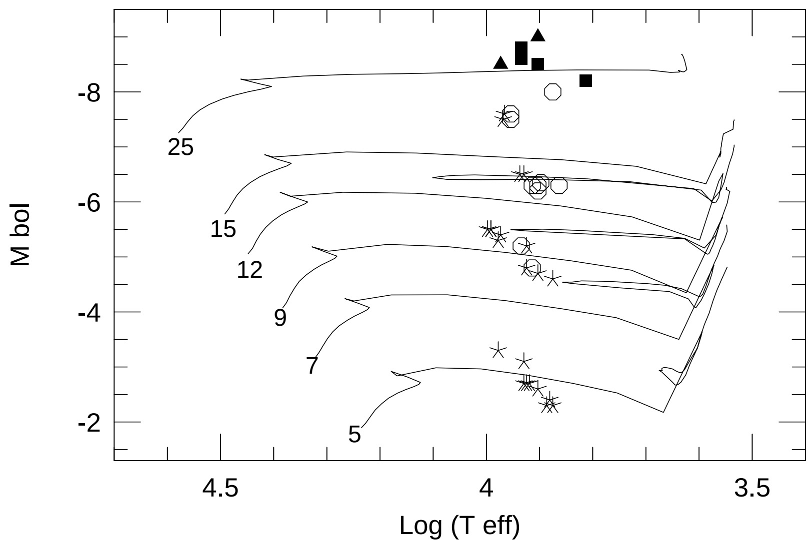

Figure 1. A-type supergiants with detailed atmospheric analyses. Galactic stars (*5-point stars*) from Venn 1995a, b; SMC stars (*open circles*) from Venn 1997; M33 stars (*filled triangles*) from McCarthy et al. 1996; M31 stars (*filled boxes*) from McCarthy et al. 1997. Stellar-evolution tracks for solar metallicity are from the Geneva group (Schaller et al. 1992).

not hold for the analysis of *all* lines, but from empirical studies of Galactic stars, atmospheric parameters and many elemental abundances can be determined with remarkable accuracy ($\pm$0.2 dex; Venn 1995a, b). Including non-LTE *line formation* for some elements (e.g., C I, N I, O I, Mg I; i.e., typically the under-represented ionic species) is an additional step that can alleviate many problems without requiring a fully detailed non-LTE atmospheric analysis. For progress that is being made on fully detailed non-LTE analyses of these stars, see Becker (1998).

The classical, tailored analyses of 22 Galactic A-type supergiants has shown that abundances of many elements from low-luminosity (type II) stars are consistent with those from higher-luminosity supergiants (types Ib, Iab, and Ia); an HR diagram of the Galactic stars analysed to date is shown in Fig. 1. Since departures from LTE, atmospheric velocity fields, and spherical extension are not predicted to be significant in the low-luminosity stars ($M \simeq 5M_{\odot}$) then this strongly implies that the tailored analysis is sufficient to within the accepted errors (typically $\pm$0.2 dex) for elemental abundance analyses.

For this reason, subsequent analyses of SMC A-type supergiants have concentrated mainly on higher-luminosity stars (see Fig. 1). The SMC analysis has been undertaken to examine the effect of metallicity on the evolution of massive stars (discussed below). The abundances can also be used to constrain the galactic chemical evolution of the SMC. We have also calculated abundances in more extreme Ia supergiants in M31 and M33 (see below). These latter analyses are very exciting to us since they are the first detailed abundance analyses of stars beyond the Galaxy and her satellites (the LMC & SMC). Also, M31 & M33 both have elemental abundance gradients as determined from nebular abundances, which we can examine with the stellar results.

2. Brief Details of the Analysis Techniques and Abundance Results for the Galactic A-type Supergiants

Galactic A-type supergiants have been analysed using Kurucz ATLAS9 model atmospheres and a selective set of weak lines (Venn 1995a, b). The ATLAS9 models, even though in LTE, have the advantage of full line-blanketing, which is critical in modelling the structure of these, the coolest of the hot stars. The selective line list is somewhat empirically based, but basically any weak line that forms deep in the photosphere and represents the dominate ionization state of the element should do. When the line is very strong, then detailed uncertainties in the model-atmosphere structure (such as sphericity) can become important; when the line is formed high in the atmosphere, then neglected non-LTE effects in the outer stellar layers, stellar-wind and velocity-field effects, and microturbulence all become more important; when the line is not from the dominant ionization species, then non-LTE effects can be significant since a small change in the ionization fraction of that species will have a large effect on the number of available absorbing atoms in the atmosphere. For some important elements, lines from only one ionization state may be available, in which case non-LTE line formation is necessary, e.g., for N I (cf. Lemke & Venn 1996).

Atmospheric parameters are determined on the $T_{\rm eff}$–$\log g$ plane from spectral indicators. The $T_{\rm eff}$–$\log g$ plane is necessary since most indicators are sensitive to both parameters as the dominant excitation state of hydrogen changes through this temperature range. I've found that the Hγ line profile and Mg I/II ionization equilibrium are the best atmospheric indicators. Hγ is not too blended with metal lines through the A-supergiant temperature range (Hδ has many more blends), and the wings are not strongly affected by weak stellar winds. The non-LTE calculations for Mg I and Mg II show that those effects are quite small for a select set of lines, thus ionization equilibrium can be reliably calculated from these elements, whereas, e.g., this is not true for Fe I/II, since non-LTE effects for Fe I can be large ($> \pm 0.3$) and varied between multiplets.

Analysis of the 22 Galactic A-supergiants showed that (1) these stars can be analysed reliably, (2) iron-group and α-group elements have similar abundances to other solar-neighbourhood stars, and (3) the CNO abundances are not predicted by the current stellar-evolution scenarios. The CNO abundances are interesting because currently N/C is predicted to be $\sim$0.5–0.6 dex greater than solar, since these stars should have visited the red-giant branch where they would have undergone the first dredge-up of H-burned gas from their stellar interiors. Instead, the ratio is found to be typically 0.3 dex, which is also interesting because it is non-solar, implying *some mixing* of H-burned material has occurred. These results strongly support the new *rotating* stellar-evolution models, where partial mixing may occur in massive stars on the main sequence (cf. Meynet 1998; Langer & Heger 1998; also Denissenkov 1994).

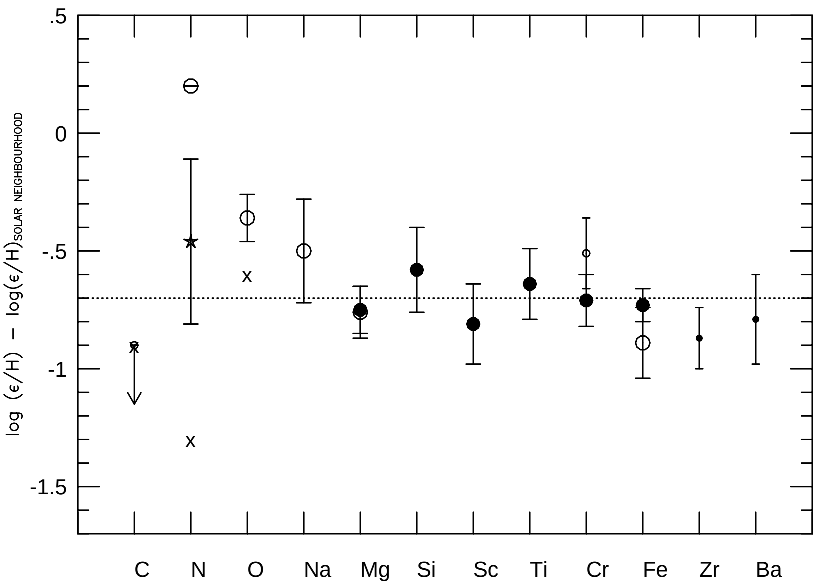

Figure 2. SMC Abundances. Open/filled circles represent neutral/ionized species, and the size of the circle represents the number of stars used in that average (small = 3–5 stars, large = 7–10 stars). Non-LTE nitrogen is shown by a star (with errorbars), and 'X' symbols refer to nebular and B-dwarf CNO abundances (see Table 1).

3. SMC Elemental Abundances and Rotational Mixing

Analysis of SMC A-type supergiants was undertaken to study differences in stellar evolution of massive (10–25$M_\odot$) stars due to metallicity. Several differential studies from F–K and B-type supergiants have been undertaken in the past with inconsistent results for some elements, like carbon, or without being able to sample other elements, like nitrogen. Since the A-type supergiants sample light elements (like the B stars) and heavy elements (like the F–K stars), as well as each of CNO, then analysis of these stars provides an excellent bridge between these various data sets, as well as providing new, systematic and quantitative, abundance data.

I have gathered high-resolution spectroscopic data from the ESO 3.6-m telescope using CASPEC between September 1995 and January 1996. The first result from my analysis is that all previous spectral types are significantly hotter than those indicated from the resultant atmospheric parameters. This is not due to uncertainties in the model-atmosphere analyses of these metal-poor stars, but due to difficulties in spectral typing when applying the MK classification system (Galactic metallicity standards) to the SMC stars. This was also discussed for SMC B stars by Lennon (1997) and by Fitzpatrick & Bohannan (1993) for LMC B stars.

The abundances from the SMC stars (shown in Fig. 2 relative to the solar neighbourhood, e.g., CNO from B-dwarfs and H II regions, all other elemental abundances from the Sun) show that alpha- and iron-group elements share a similar underabundance, $[\alpha, \mathrm{Fe/H}] \sim -0.7 \pm 0.1$. The s-process elements appear slightly more underabundant than the iron group, contrary to the F–K-supergiant results from Hill (1997), though in agreement with the results from Russell & Bessell (1989). The high [Na/Fe] abundance is reminiscent of Galactic A-supergiant results, which may be due to a combination of effects (e.g., non-LTE line formation is not included for Na I, and processes such as granulation are neglected; cf. Venn 1995b and references therein).

The CNO abundances are the most interesting to examine for stellar-evolution effects, but these are also the most complicated elements to interpret because we need to know what their pristine abundances were. This is not so easy, since (1) main-sequence B stars are very faint and currently there are very few reliable elemental abundance determinations for these stars, and (2) CNO do not scale with Fe in a galaxy's chemical evolution. I have attempted to ascertain the best initial, main-sequence abundances of CNO for the A supergiants analysed by examining the nebular abundances for CNO in the SMC and comparing those to differential abundances from three B dwarfs in the SMC; see Table 1.

Table 1. SMC nebular and B-dwarf abundances

Elem.	Nebulae			B stars					Adopted
	D84	RD90	G96	Gal.	+	R93	=	Diff.	
C	7.3*	...	7.4	8.2		−0.8		(7.4)	7.3
N	6.5	6.6	6.3	7.8		<−0.9		(<6.9)	6.5
O	8.0	8.1	8.1	8.7		−0.6		(8.1)	8.1

D84 = Dufour 1984; RD90 = Russell & Dopita 1990;
G96 = Garnett et al. 1996; R93 = Rolleston et al. 1993.
*Recalculated with new C atomic data (Dufour 1990).

Comparing these pristine abundances to the SMC A-supergiant results shows that only my upper limit to C is in agreement with the adopted initial abundances. The A-supergiants' O abundance is slightly too large, by ∼0.2 dex or $\sim 2\sigma$, but the O I lines are predicted to have a −0.1 to −0.2 dex non-LTE correction (Baschek et al. 1977), which accounts for this discrepancy (this difference was also seen in the Galactic A-supergiant LTE oxygen abundances).

Nitrogen abundances are not in agreement with the adopted initial abundances. The present-day N abundance is extremely low in the SMC, yet the A-supergiant abundances range from slightly to grossly enriched in this element. This range in N is more difficult to interpret then in the case of the Galactic stars. The histogram in Fig. 3 shows that the range is wider (it is also important to note that no other element studied here has such a wide range in abundances from star to star) and no star was found with the adopted pristine N abundance. Only 10 A supergiants in the SMC have been analysed, compared with 22 in the Galaxy; nevertheless, these abundances do suggest a somewhat different stellar-evolution history – that the SMC stars have been more mixed with CNO-cycled gas. How might this happen? Two possibilities are (1) that these stars have undergone the first dredge-up *AND* have been affected by ro-

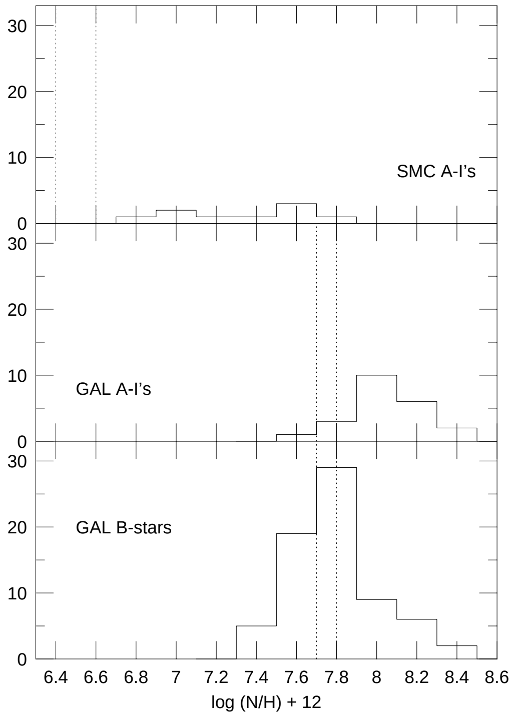

Figure 3. Histogram of nitrogen abundances in SMC and Galactic A-type supergiants and Galactic B-dwarf stars. The breadth of these distributions is significantly greater than 1σ of the errors of most other elements. In the Galactic stars, this is interpreted as evidence of partial mixing of CNO-cycled gas by rotation on the main sequence; these stars have *not* been red supergiants. In the SMC, the interpretation is more complicated; probably these stars have undergone the first dredge-up, as well as star-to-star variation brought on by rotational mixing.

tational mixing when on the main sequence, or (2) that the SMC stars have higher 'typical' main-sequence rotation rates, so that rotational mixing is more efficient than in Galactic stars. Without additional evidence, e.g., B-dwarf CNO abundances or the distribution of rotational velocities in SMC versus Galactic B dwarfs, then I suggest that *the SMC A supergiants probably have undergone the first dredge-up.*

These abundances can also be interpreted in the context of the galactic chemical evolution of the SMC, since each of these elements (iron-group, α-group, s-process elements, CNO) have different nucleosynthetic sites. Here, I will limit my comments on this topic to only four points. First, the same metal underabundances have been found in this study as have been reported from cooler-supergiant studies; the depletion of iron at [Fe/H]$=-0.65\pm0.1$ dex is secure. Secondly, it is interesting that α-elements share the same underabundances as the iron group in the SMC, whereas in the Galaxy [α/Fe] is typically $+0.2$ to $+0.4$ dex (Edvardsson et al. 1993). Thirdly, the abundances of s-process elements found here are not consistent with all other studies, which are most likely due

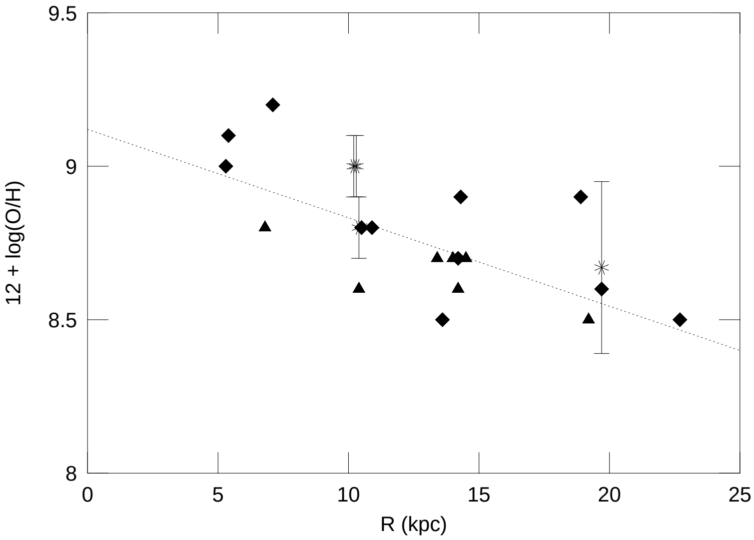

Figure 4. Oxygen abundances in M31. Nebular and supernovae abundances are noted by diamonds (Blair et al. 1981, 1982) and triangles (Dennefield & Kunth 1981). Stellar abundances determined here are shown with stars and error bars. To within errors, these four stars agree with the nebular oxygen abundance gradient, determined as -0.03 dex kpc^{-1}.

to uncertainties in each of the analyses that warrant improvements. Fourthly, the upper limits on carbon found here are in agreement with the nebular abundances. Previous high carbon abundances from F–K supergiants (Russell & Bessell 1989) appear to have been due to uncertainties in their analysis.

4. M31 Elemental Abundances and Galaxy Evolution

Examining stars in galaxies beyond the Clouds is a new and exciting line of research made possible by the large 8–10-metre-class telescopes. Heavy-element abundances can now be determined quantitatively from stars, and light-element abundances can be compared between stellar and nebular results. At present, we have obtained and analysed Keck I HIRES spectra for four isolated A-type supergiants in M31 (see also McCarthy et al. 1998). Three of these stars have similar galactocentric distances, near $R_{\rm g} = 10$ kpc, while the fourth is further out, near $R_{\rm g} = 20$ kpc. (This fourth star is located in Baade's Field IV, which is an important field for Cepheid studies and calibrations, also, and we are able to improve on the reddening estimate to stars in that neighbourhood).

Nebular abundance determinations have suggested that there is a strong O/H abundance gradient in M31 (see Fig. 4). We have determined stellar oxygen abundances (also plotted in Fig. 4), and they are in agreement with the nebular slope, although our uncertainties are significant.

We have also determined the abundances of several other elements, including the first estimates of s-process abundances in a galaxy beyond the Clouds (McCarthy et al. 1997). All elemental abundances are important in the study

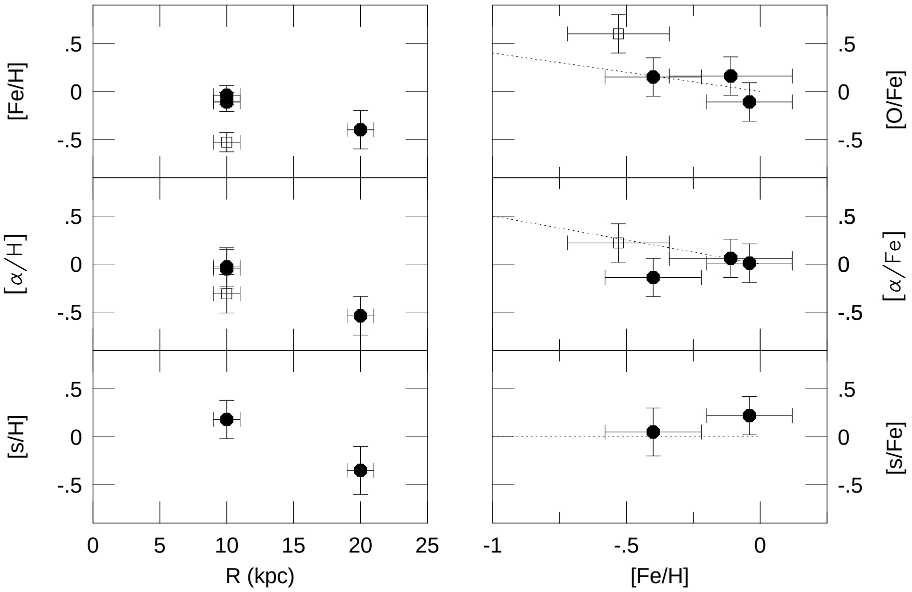

Figure 5. Abundance gradients in M31, useful for galactic chemical-evolution constraints. Panels on the left side show abundance gradients with galactocentric distance in M31 of iron, α-elements, and s-process elements. Panels on the right side show abundance gradients with iron. The dotted lines represent the abundance gradients in the Galaxy (from Edvardsson et al. 1993, corrected for the difference in the size between M31 and the Galaxy). The open box is the 'odd' star 41-3654.

of abundance gradients, which yield important constraints for galactic chemical-evolution models. Although we have only studied four stars at present, we can plot the abundances of several other elements with galactocentric distance. On the left side of Fig. 5, (Fe/H, α/H, and s/H) vs. $R_{\rm g}$ show the differences in metal enrichments with galactocentric distance. Four stars alone cannot be used to make a scientific case; however, we do notice trends in all elements that are similar to the oxygen gradient. On the right side of Fig. 5, ([O/Fe], [α/Fe], and [s/Fe]) vs. [Fe/H] show the differences in timescales for the enrichment of various elements relative to the Fe timescale. Since each element has a different nucleosynthetic site, then these relationships give us information of the star-formation history and mass functions in the galaxy's past. For example, oxygen is expected to come primarily from high-mass stars, whereas iron is enriched in the interstellar medium from the evolution of both high- and low-mass stars; therefore, a high O/Fe ratio shows where (or when) the most recent (or efficient) star formation occurred. Alpha elements are expected to have a similar nucleosynthetic source as oxygen, whereas s-process elements come from intermediate-mass stars that climb the AGB.

Clearly, analysis of more stars, in galactocentric distance and iron abundance, will provide new and unique information for studying the chemical evolution of M31.

5. M31 Odd Star Out

One star in M31, 41-3654, is odd in its abundances. This star shows normal abundances of O, Mg, and Si for its galactocentric distance (and relative to the other stars analysed near $R_g = 10$ kpc); however, the iron-group elements are significantly depleted. Careful examination of the analysis of 41-3654 shows that these depletions are real and cannot be explained by any standard atmospheric uncertainty (even a differential analysis with other supergiants cannot remove the metal underabundances). Furthermore, the star is clearly in M31, since we see Na *D* interstellar absorption at the radial-velocity offset of the galaxy. The iron-group depletions may only reflect typical variations in elemental abundances at a given galactocentric distance as seen in our own Galaxy. For example, significant abundance variations in Fe/H are seen in F–G disk dwarfs by Edvardsson et al. (1993; their stars are all within a 50 pc radius); for stars from 0.6 to 0.8 Gyr, the variation in [Fe/H]$\geq$0.5 dex.

A few more unusual, but interesting, possible explanations for the iron-group depletions in 41-3654 also present themselves. One possibility is that it is located out of the galactic plane – 41-3654 appears spatially located near another star analysed here, 41-3712, which has normal abundances, but if the star is not in the plane, a projection effect could account for the differences. If 41-3654 formed in a thick disk, or in the plane but at a larger galactocentric distance and was later ejected, then these could account for the iron-group abundances. They possibilities do not easily explain the normal abundances of oxygen and the α-elements in 41-3654, though. Another possibility is that 41-3654 is an interarm star, i.e., located between spiral arms in M31 where star formation has been inactive and therefore chemical abundances may be lower. The radial velocity of 41-3654 is significantly different from the nearby star 41-3712 (by 26 km s^{-1}), and it appears to be moving *towards* the star-forming complex that contains 41-3712, ruling against it having been ejected from that region. Mixing processes in the interstellar medium are poorly understood, such that arm-interarm differences may be significant; however, they are not currently observed. The recent analysis of arm versus interarm emission nebulae by Martin & Belley (1996) found that differences in O/H do not appear to exceed 0.6 dex. Mixing timescales in the interstellar medium for oxygen or iron are currently unknown, although we might expect the slow enrichment of iron to occur over a longer timescale that that of oxygen, so that oxygen deviations should always exceed iron variations.

6. M33 Elemental Abundances

We have also had the opportunity to observe and analyse Keck I HIRES spectra for two A supergiants in M33 (see McCarthy et al. 1996). These two stars have very different galactocentric locations: 117-A, a normal A0 Ia supergiant, is located 4.5 kpc from the galactic centre, while B-324, an extreme hypergiant, is only 1.3 kpc away. Spectrum syntheses showed that the more distant star is metal-poor, $\sim$1/10 solar, as expected based on nebular abundances (Vilchez et al. 1988). Unfortunately, the spectrum of B-324 is so hydrodynamically extreme that any classical atmospheric analysis (as done here for abundances) cannot be reliable. Nearly all spectral lines in B-324 show P Cyg-type profiles with extreme blue wings, even for Fe II and Ti II lines. This star is useful for an analysis of its stellar-wind properties (see McCarthy et al. 1998), but its metallicity remains uncertain. We hope to analyse more stars in M33 in the future to further probe the abundance gradient reported for this galaxy from nebular analyses.

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Discussion

Oey: I'm a little confused; in discussing 41-3654, you're suggesting that the arm and inter-arm abundances may be different? But if you have star formation in spiral density waves then presumably...

Venn: ...there's no reason for any difference between arm and inter-arm abundances, right? My suggestion was primarily based on Galactic results.

Dufton [to Oey]: What you suggest is quite correct, but, as I mentioned very briefly in my talk, empirically you do seem to find higher metallicities for stars which lie in the arms than for those which lie between the arms.

Oey: A related interesting point is that you [Venn] also showed a higher scatter at the lower galactocentric radius in M31, which is exactly what Philip showed for the Galaxy.

Schaerer: Your low-metallicity hot star seems to have a metallicity which is slightly higher than SMC, but still fits the wind-momentum–luminosity relation. Is that a problem?

Kudritzki: Yes, that's a real worry, and that was one of the reasons why I had difficulties at first believing the low abundances; but they seem okay, between SMC and LMC. The fact is, this star has a very strong wind, and I would expect it to be below the Galactic WLR, but in fact it's on it. At the moment, I don't understand this.

Venn: I should caution that it's only the iron abundannce that's real low. What if the wind's not driven by iron-group elements, but but α elements? As we've seen, the SMC is equally depleted in α elements as in iron-group elements. Since SMC stars are our calibration for the low metallicity wind-momentum–luminosity relationship, then perhaps we should only be looking at the α element abundances rather than the iron-group abundances.

Conti: Sally almost took the words right out of my mouth about this arm/inter-arm business; it's a nice explanation of the observations, but how does such an abundance segregation get maintained?

Venn: From what I understand at the moment, the whole business of 'pollution' within a galaxy is highly uncertain – I'd say it's an open question. We have thought about other possibilities for 41-3654, such as it being just outside the disk.