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SPECTRAL MORPHOLOGY AND CLASSIFICATION OF MASSIVE STARS IN THE SMALL MAGELLANIC CLOUD: EFFECTS OF METALLICITY

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RESUMEN

En este trabajo discutimos la morfología espectral de estrellas calientes y luminosas en la Nube Menor de Magallanes y la manera en que la baja metalicidad de esta galaxia ha infuido en la precisión de su clasificación. Demostramos de manera concluyente que el hecho de no haber tenido en cuenta la naturaleza tridimensional de la clasificación espectral (basada en temperatura, luminosidad y metalicidad) ha traído como consecuencia considerable incerteza en la clasificación óptica de supergigantes de los tipos A y B. Mostramos que las sorprendentes diferencias que existen entre los espectros UV de estrellas O en las Nubes de Magallanes y la Galaxia, existen también para las supergigantes más luminosas de tipo B. Demostramos que esta incerteza en la clasificación espectral de las supergigantes de la Nube Menor puede ser un factor que ha influido de manera importante en investigaciones previas sobre el uso de supergigantes azules como indicadores de distancia.

ABSTRACT

In this paper we discuss the spectral morphology of luminous hot stars in the Small Magellanic Cloud and how the low metallicity of this galaxy has impacted upon the accuracy of their classification. We demonstrate conclusively that the neglect of the three-dimensional nature of spectral classification, as represented by temperature, luminosity, and metallicity, has resulted in considerable uncertainty in the optical classification of B-type and A-type supergiants. We show that the startling differences which exist between the UV spectra of O-stars in the SMC and in the LMC/Galaxy also exist for the most luminous B-type supergiants. We demonstrate that this uncertainty in spectral classification for the SMC supergiants may be an important factor influencing previous investigations of the use of blue supergiants as distance indicators.

Key words: **STARS: EARLY TYPE — STARS: FUNDAMENTAL PARAMETERS — STARS: MASS-LOSS – STARS: DISTANCES – SUPERGIANTS — MAGELLANIC CLOUDS**

1. INTRODUCTION

The Small Magellanic Cloud (SMC) is significantly metal poor with respect to the local Galactic environment with approximate relative abundances; $[\alpha, \mathrm{Fe/H}] \sim -0.7$, $[\mathrm{C/H}] \sim -0.8$, $[\mathrm{N/H}] < -0.9$, and $[\mathrm{O/H}] \sim -0.6$ (Venn et al. 1998). It is to be expected that this reduced metallicity has a profound effect upon the evolution of massive stars and upon the morphology of their spectra. This will have important consequences, for example in the interpretation of the spectra of unresolved massive star populations in nearby metal poor starburst galaxies and in distant high redshift star-forming galaxies. Therefore, one might ask: How well do we know and understand the massive star content of our closest resolved metal poor companion galaxy, the SMC? To try to answer this question, the present paper concentrates on the spectral classification and morphology of massive stars in this galaxy.

2. MASSIVE STARS IN THE SMC

Since O-star spectra in the visible domain are distinguished by an absence of metal lines, and are classified using lines of the Hydrogen Balmer series and He I/He II lines, the MK system can be confidently transferred to the SMC. However, when one turns to the ultra-violet regime, the spectral morphology of the O-stars are dramatically different from their Galactic counterparts. As shown by Walborn et al. (1995a) using *HST*/FOS data, and as illustrated in Fig. 1, the wind lines due to resonance transitions of ions such as C IV and N V in

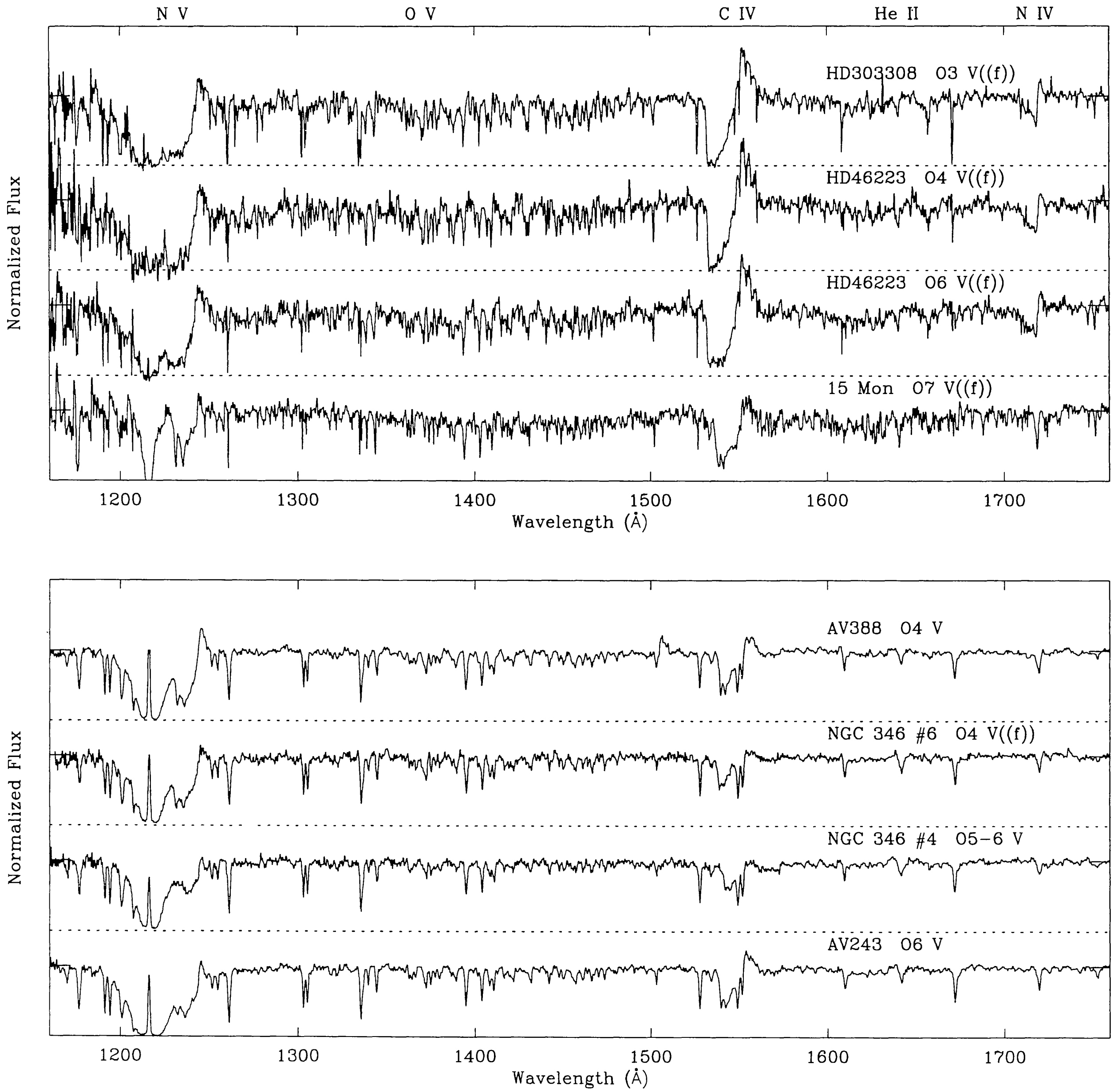

Fig. 1. Comparison of UV spectrogams of O-type dwarfs in the Galaxy (top panel) and SMC (bottom panel). The apparent emission feature near 1500 Å in AV 388 is an artifact. Stellar wind features are identified at top of the upper panel as follows; N V $\lambda\lambda$ 1239, 1243; O V λ 1371; C IV $\lambda\lambda$ 1548, 1551; He II λ 1640; and N IV λ 1718. Note the relative strengths of the wind features in the Galactic O4–O6 stars compared to the SMC stars. Galactic data have been taken from Walborn, Nichols-Bohlin, & Panek (1985) and the SMC data are described in Walborn et al. (1995a).

O-type dwarfs in the SMC are startlingly weaker than in their Galactic (or indeed LMC) counterparts. Walborn et al. (1995b) subsequently pushed this study into the 900–1200 Å region using the *Hopkins Ultraviolet Telescope* (*HUT*) during the Astro-2 mission. Clearly, if one were to rely on these data for classification purposes, the classification process would be three-dimensional; effective temperature, luminosity, and *metallicity*. This was realized by Walborn (1977, 1983) when he used the He I/He II reference frame to classify B0 supergiants in the SMC using their visible spectra and found an inconsistency with the silicon reference frame which can also be

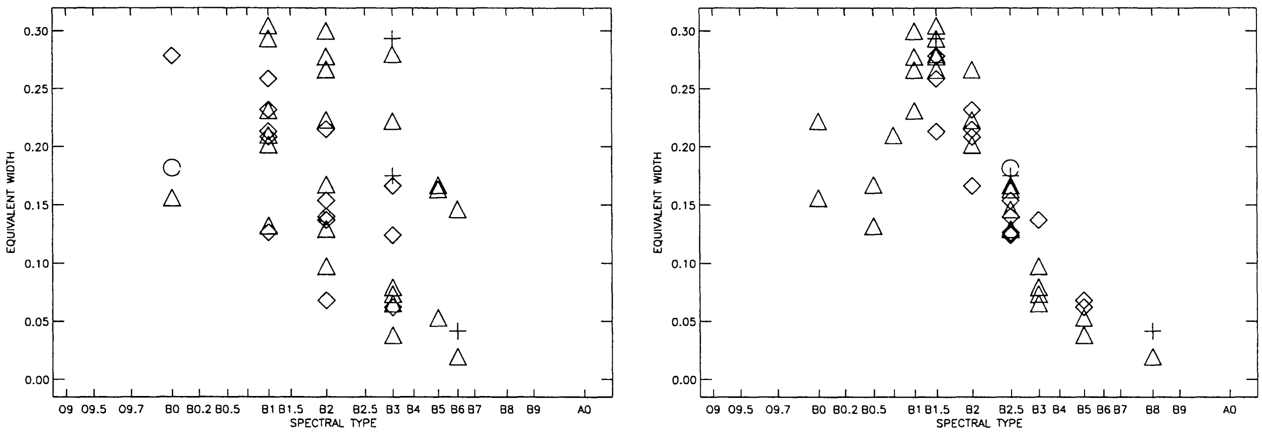

Fig. 2. Comparison of the run of the Si III $\lambda 4553$ line with spectral type; left panel, using previously published optical classifications (old) and; right panel, using the classifications from Lennon (1997). Symbols refer to different sub-classes; Ia^{+} as $+$, Ia as $\triangle$, Iab as $\diamond$, and Ib as O. Note the vastly improved correlation of equivalent width using the new classifications, similar improvements are found by Lennon (1997) for lines of other ions such as He I, C II, N II, O II and Mg II.

used for these stars. This lead Walborn to introduce spectral types such as, for example, B0 Iaw(IV) for a metal weak (w) B0 Ia supergiant with metal line strengths comparable to a Galactic B0 IV star. An alternative view is that classification of such an object using the metal line ratios within the MK system would result in the wrong luminosity class being assigned. Such an object would then appear to be too bright if observed in an external galaxy whose distance was known independently of the implied spectroscopic parallax.

The question of the applicability of the MK system to the classification of B- and A-type supergiants in the SMC was largely brushed aside in more general spectroscopic surveys (Ardeberg & Maurice 1977; Azzopardi, Vigneau, & Macquet 1975; Humphreys 1983). There were some notable exceptions to this; we have already mentioned Walborn (1983) but this was restricted to a small number of the earliest B-type supergiants having He II in their spectra. Dubois, Jaschek, & Jaschek (1977) on the other hand attempted a more general study using the Balmer decrement and the He I lines for spectral type and the Balmer lines for luminosity classes, but with mixed success. More recently, Lennon (1997) re-classified a sample of more than 60 B-type supergiants in the SMC using superior quality data such that the weak metal lines could be reliably observed and measured. This paper devised a self-consistent set of criteria for classifying stars using line ratios defined for standard stars within the framework of the SMC metallicity. A subsequent mapping of these new spectral types to MK spectral types was then performed with the constraint that the *trends* of line strengths versus spectral type for MK standard stars were reproduced. In Fig. 2 we show the success of this procedure, and the marked improvement over previous work, in terms of consistency. Lennon (1997) found that approximately 75% of the stars required new spectral types, necessitating some revision of the observational HR-diagram.

Independent corroboration of these findings is represented by the work of Neubig & Bruhweiler (1997). These authors also devised a self-consistent classification scheme for O and B stars *in the SMC*, but using low resolution UV spectra from the *IUE* archives. Their scheme uses metal line strengths and, like Lennon (1997), it is independent of the MK system although it is defined such that there is good correlation with optical classifications. Whilst Neubig & Bruhweiler find a good correlation between UV and optical spectral types (their Fig. 7), it is clear that this is markedly better for the O-stars than for the B-stars. This is not too surprising for the O-stars since, as we have already discussed, their optical spectra may be classified independently of metallicity. The deterioration of their correlation for the B-stars on the other hand, is a direct result of the greater uncertainty in the *previous* optical classifications based upon the MK system. We demonstrate this in Fig. 3 where, for that subset of B-stars considered by both Neubig & Bruhweiler (1997) and Lennon (1997), we compare correlations of the UV spectral types with previous optical spectral types and Lennon's new optical spectral types. For the early B-type stars the correlation is clearly much better using the data of Lennon, confirming that the results of both Lennon (1997) and Neubig & Bruhweiler (1997) are more accurate than those published previously.

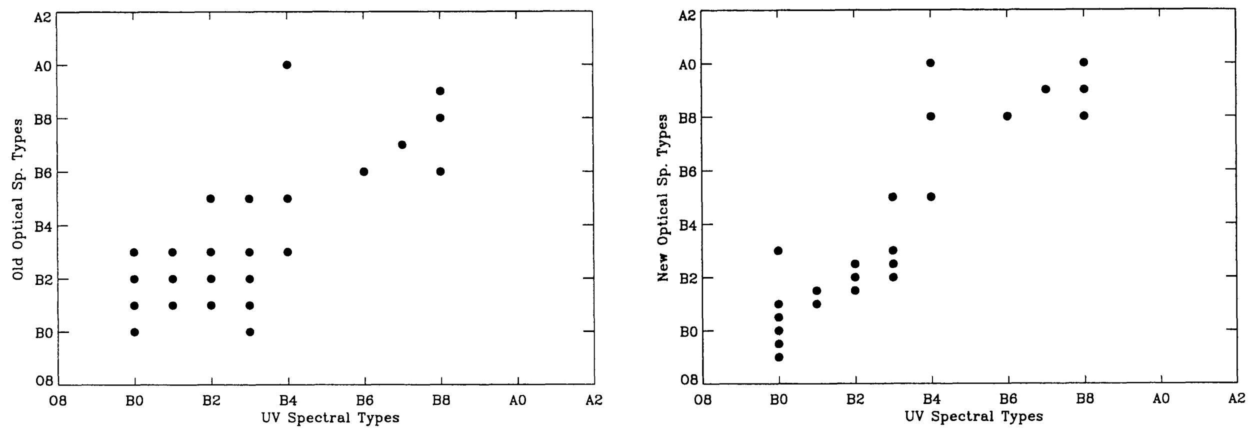

Fig. 3. In the left panel we show a comparison of the previously published B-supergiant spectral types with the UV spectral types of Neubig & Bruhweiler (1997). Note the large scatter at early types between B0 and B3. In the right panel we demonstrate the improved correlation when we compare these UV spectral types with the classifications from Lennon (1997). Note the outlyers in the right-hand panel at B4–B8 and B4–A0, these are the double point B4–A0 in the left-hand panel (stars AV 270 and AV 297). In both cases the results of Lennon (1997) agree better with previously optical types.

The three-dimensional nature of spectral classification in the UV, as illustrated by Fig. 1, is to a large extent due to the indirect effect of the metallicity on the spectrum through its influence on the stellar mass-loss rate. Typical strong wind lines arise from resonance transitions, and these often saturated lines are more sensitive to wind conditions than to abundance effects. However, since the winds are driven by radiation pressure on the metal lines, the metallicity comes into play indirectly, resulting in the situation that mass-loss itself is a diagnostic of metallicity. This has been discussed more extensively by Haser et al. (1998) who introduced the concept of a *dynamical* metallicity implied by the wind dynamics, as opposed to the more usual *spectroscopic* metallicity derived from spectrum synthesis calculations. Furthermore, they showed that an analysis of the UV spectra of O-stars in the Magellanic Clouds resulted in consistent dynamical and spectroscopic metallicities.

In Fig. 4 we compare high-quality UV spectra of early B-type supergiants in the LMC and SMC. We can clearly see important differences between both sets of data consistent with the previous discussion. For example, there is a complete absence of the N V doublet around 1240 Å in both SMC supergiants whereas it is clearly visible in the LMC stars. Note also the much stronger absorptions longwards of ~1600 Å, due mainly to Fe III lines, in the LMC objects. In general, the P-Cygni wind features in the SMC stars are weaker and narrower than their counterparts in the LMC; the star AV 483 is especially peculiar in this sense as even the C IV line is a weak absorption feature. Such considerations have obvious implications for the interpretation of composite UV spectra of starburts of uncertain metallicity and stellar content.

3. IMPACT ON WIND MOMENTUM LUMINOSITY RELATIONSHIP

It has been suggested that the relationship between stellar mass-loss rate ($\dot{M}$) and luminosity (L), as expressed by the wind momentum – luminosity relationship (WLR);

$$\dot{M} v_\infty R_\star^{1/2} \propto L^{1/\alpha} \quad ,$$

can be used as a distance determination method (Kudritzki 1999; McCarthy et al. 1997), applicable to supergiants in nearby resolved galaxies. In the formula, v_∞ and $R_\star$ are the wind terminal velocity and stellar radius respectively, while α is a factor depending mostly on the distribution of line strengths and is typically of order $^2/_3$ for OB stars. In this context, the most promising objects are A-type supergiant stars since they are less affected by crowding than O-stars, they are intrinsically the brightest stars at visible wavelengths and the Hα line is an excellent diagnostic of mass-loss. Tully & Wolff (1984) reached a similar conclusion and proposed

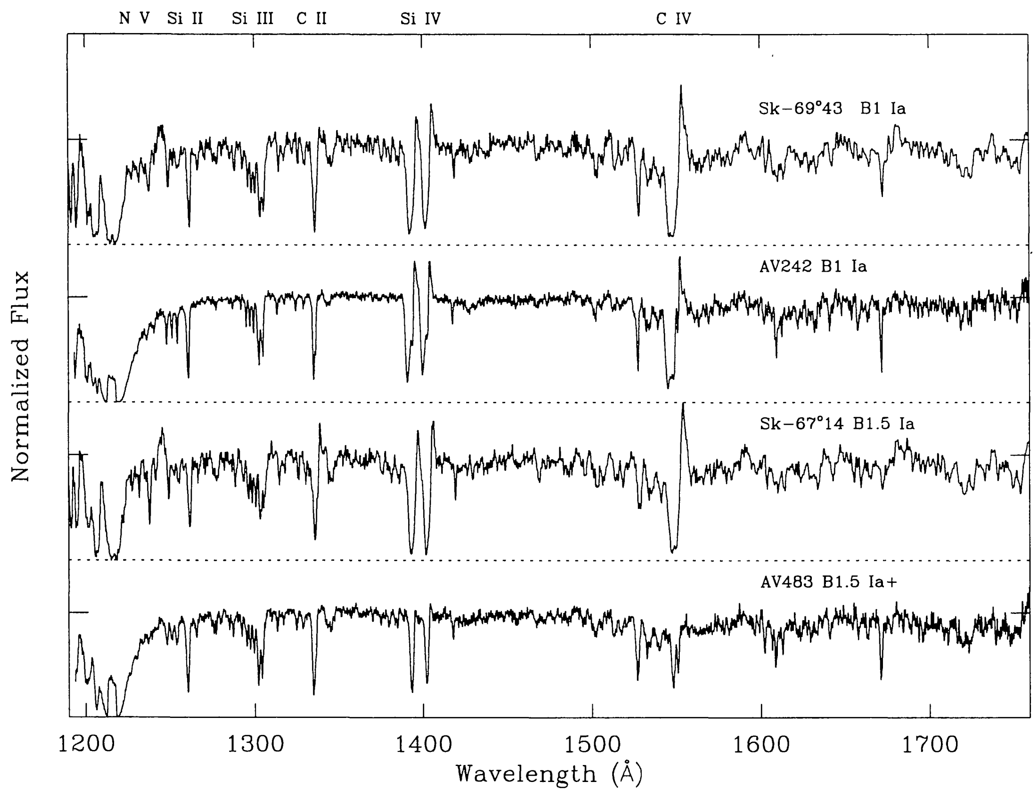

Fig. 4. Comparison of UV spectrograms of the LMC B-type supergiants Sk −69°43 and Sk−67°14, taken with *HST*/FOS, with those of the SMC supergiants AV 242 and AV 483, obtained with *HST*/GHRS. The lines identified at the top of the panel are as follows; N V $\lambda\lambda$ 1239, 1243; Si II $\lambda\lambda$ 1260, 1265; Si III $\lambda\lambda \sim 1300$; C II $\lambda\lambda$ 1334, 1336; Si IV $\lambda\lambda$ 1394, 1403; and C IV $\lambda\lambda$ 1548, 1551. Note the absence of the N V doublet in both SMC stars and in particular the weakness of the Si IV and C IV features in AV 483.

using the known luminosity dependence of the Balmer lines. They surveyed Balmer line profiles for a large sample of B- and A-supergiants in the Magellanic Clouds and, for the LMC, found that there was indeed a tight correlation between Hα and luminosity at fixed spectral type. However, their SMC results were problematical in that they found clear evidence of a shift in scale and a much larger scatter in the SMC. The scale shift they attributed to the difference in metallicity between the LMC and SMC, and the effect that this has on stellar mass-loss rates. The increased scatter in the SMC results however could not be satisfactorily explained and, more seriously, its magnitude was such as to invalidate the use of this technique as an accurate distance determination method. We can illustrate this situation by considering the WLR for A0 supergiants in the LMC and SMC, but first we need to discuss a suitable transformation of the V_0 − Hα relationships of Tully & Wolff into a form analagous to the WLR. We choose to take this route since it gives us an idea of how the observed scatter in the equivalent widths is likely to affect the wind momentum – luminosity relationship.

It is trivial to estimate luminosities and radii, we assume that all A0 supergiants in the sample of Tully & Wolff have identical effective temperatures ($\sim$ 10,000 K) and bolometric corrections ($\sim$ 0.0), and for the distance moduli of the LMC and SMC we adopt values of 18.5 and 19.1, respectively. We can drop the v_∞ dependence here since we assume all stars have the same wind terminal velocity (the exact value is unimportant, rather the difference in real terminal velocities will be a small effect which we ignore). We now need to convert the observed equivalent width into an estimate of the mass-loss rate, for which we need the net Hα emission ($W_{\mathrm{H}\alpha}$), defined to be the total equivalent width minus the photospheric equivalent width. Photospheric Hα lines can be computed using stellar models provided we know the surface gravities of each object. We obtain these using evolutionary tracks to estimate the stellar masses and since we know the radii, the surface gravities. However, as

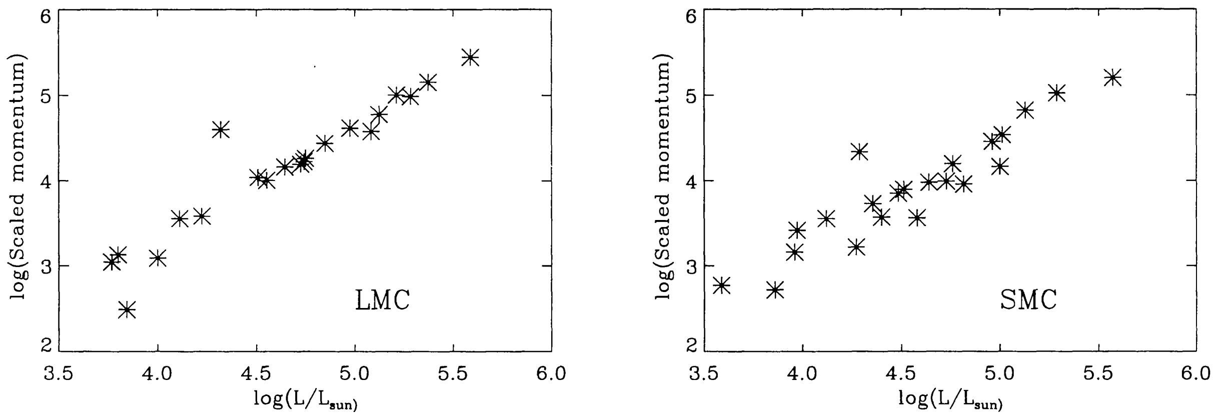

Fig. 5. In the left panel we show a log–log plot of the scaled wind momentum ($\log(W_{\mathrm{H}\alpha}^{3/4} R_\star^2)$), as described in the text, versus stellar luminosity for the sample of LMC A0 supergiants observed by Tully & Wolff (1984). In the right-hand panel we plot the analagous diagram for the SMC. Note that at low luminosities we are susceptible to large cancelation errors since the net emission tends to zero with decreasing luminosity, discrepant points in both diagrams near $\log(L/L_\odot) \sim 4.3$ are real however and are caused by a small number of stars in both galaxies with anomalously strong Hα emission. Aside from these points, there is a much tighter correlation for the LMC compared to the SMC.

it is well established that this method results in severe overestimates compared to results obtained from fitting Hydrogen line profiles, we perform an empirical calibration of the logarithmic surface gravities ($\log g$) using well studied Galactic A-supergiants for which spectroscopic gravities are available in the literature. We effectively normalize our surface gravities to the lower luminosity supergiants. In fact, the correction for photospheric absorption, given that we make such an approximation, is most crucial for the lower luminosity stars. At higher luminosities, where we expect our $\log(L/L_\odot) - \log g$ relationship to be less reliable, this correction is not so important. The quantity $W_{\mathrm{H}\alpha}$ is then related to the mass-loss rate by the following scaling relationship

$$\dot{M} \sim W_{\mathrm{H}\alpha}^{3/4} R_\star^{3/2} \quad ,$$

obtained by Puls et al. (1996) for the optically thick case and a velocity field exponent of $\beta = 1$. Note that this is equivalent to assuming that the Q value, used by Puls et al. as a measure of the wind contribution, and defined as

$$Q = \frac{\dot{M}}{R_\star^{3/2}} \quad ,$$

is just given by

$$Q = W_{\mathrm{H}\alpha}^{3/4} \quad ,$$

Making all these approximations the WLR for the A-supergiants should scale as

$$W_{\mathrm{H}\alpha}^{3/4} R_\star^2 \propto L^{1/\alpha} \quad .$$

The resultant plots for the A0 supergiants observed in the LMC and SMC by Tully & Wolff (1984) are shown in Fig. 5. Note the tightness of the relationship for the LMC compared to the SMC; a least-squares fit of each dataset to a straight line confirms an offset in scale between the two galaxies, also noted by Tully & Wolff from the original equivalent width data.

Puls et al. (1996) have already discussed the observed wind momentum of O-stars in the Magellanic Clouds and its dependence on metallicity, confirming Tully & Wolff's suggestion that this is the cause of the shift in scale between LMC and SMC. Now, we have a possible explanation for the increased scatter in the SMC,

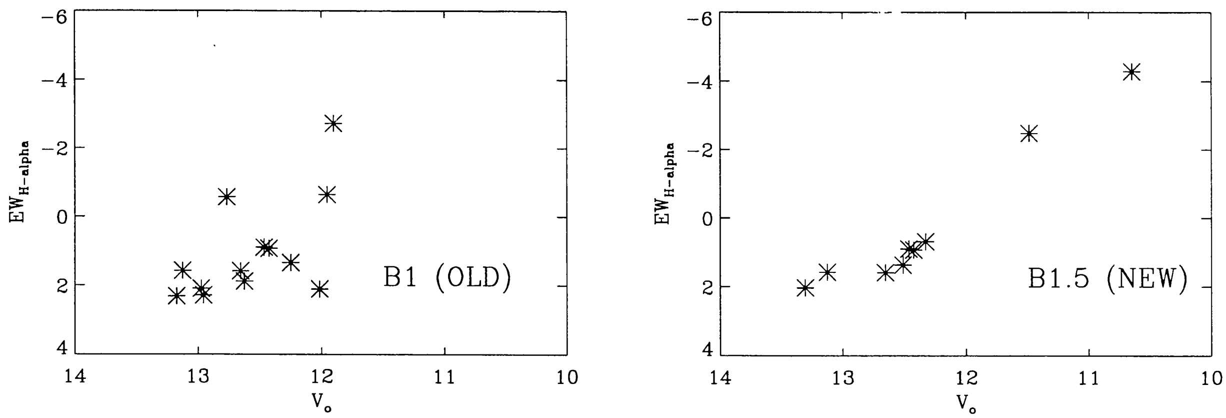

Fig. 6. In the left-hand panel we show the poor correlation between the Hα equivalent width and the dereddened visual magnitude (V_0) for a sample of supergiants in the SMC previously classified as B1. In the right-hand panel we demonstrate the improvement obtained by using the spectral classifications of Lennon (1997), this time for B1.5 supergiants. Note that there is no strict one-to-one correlation between old and new classifications; 50% of the new B1.5 stars were previously classified as B1 stars.

namely the greater uncertainty in the spectral classifications for the SMC compared to the LMC. As has been demonstrated, the older spectral types are unreliable since they do not take the reduced metallicity of the SMC into account. In the LMC on the other hand, Fitzpatrick (1991) showed that the more moderate metal deficiency of the LMC does not lead to any significant difficulty in applying the MK system to the classification of B-type supergiants. Incorrect spectral types will lead to erroneous estimates of effective temperatures, bolometric corrections and photospheric absorption components, all of which increase the scatter in luminosity and wind momentum. While Tully & Wolff (1984) discussed late B-type and early A-type supergiants only, Lennon (1997) concentrated mostly on the early B-type supergiants; therefore, we cannot directly check this hypothesis at present. We note, however, that Venn, Lennon, & Lemke (1996) have found that a number of A-supergiants in the SMC have stellar parameters inconsistent with their spectral types. Nevertheless, here we can perform some comparisons at other spectral types. For this purpose, we consider those stars in the Lennon sample with previous B1 spectral types and with new B1.5 spectral types. These two classes of objects are chosen to provide reasonable sample sizes, in fact half of the B1 sample were re-classified as B1.5 by Lennon. In Fig. 6 we show the observed trends of Hα equivalent width with dereddened visual magnitude. Clearly the correlation is much better using the newer spectral types, supporting our hypothesis that the uncertainties in published spectral types for the SMC contribute significantly to the scatter in Fig. 5 for the SMC.

We note in passing that the trends observed by Tully & Wolff for the LMC in particular, and as presented here for B1.5 stars in the SMC, have an additional very important implication. It is that the well known Hα variability of blue supergiants (Kaufer et al. 1996) does not significantly degrade the correlation between wind momentum and luminosity in this kind of snapshot observing program. In fact, the number of outliers is relatively small and most of these are at low luminosities where one is dominated by cancellation effects caused by subtracting two almost equal numbers; a model photospheric profile and an observed profile which is itself almost completely photospheric. For the more luminous A0 stars ($\log(L/L_\odot) \geq 4.5$) the correlation in the LMC between wind momentum and luminosity is excellent.

4. SUMMARY

We have seen that the low metallicity of the SMC severely compromises much of the classification work that has been done for the B-type and A-type supergiants. Both the optical and UV spectra of these stars exhibit substantial morphological differences compared to their counterparts in both the LMC and the Galaxy. For massive stars the classification process is clearly three-dimensional, depending upon temperature, luminosity, and metallicity. Future work on the SMC is clearly needed and will have repercussions for studies of more distant metal poor star forming regimes such as star bursts and high redshift galaxies.

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