Studies of Blue Supergiants in M31 and M33 with HIRES on the Keck I Telescope

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Abstract. Studies of the visually brightest stars, A- and B-type supergiants, in the Local Group galaxies M31 and M33 have been undertaken with HIRES on the 10-m Keck I telescope. Detailed chemical element abundances are derived from these spectra (as reviewed at this conference by Venn); in this paper, we discuss the Keck observing program and the analysis of the Hα line profile used to determine the stellar wind momentum. The current status of our tests of the Wind-momentum–Luminosity Relation in M31 and M33 is briefly summarized.

1. Motivation

Since 1994 we have been using HIRES, the *HI*gh *R*esolution *E*chelle *S*pectrograph (Vogt et al. 1994) on the 10-m Keck I Telescope, to study the visually brightest stars in Local Group galaxies. With Keck, it is possible to obtain spectra of these blue supergiant stars in M31 and M33 with a dispersion (~0.1Å per pixel) and signal-to-noise quality (S/N > 80 per resolution element) that was previously possible only for stars in our own Galaxy and the Magellanic Clouds. Our motivation for studying these stars is two-fold: (1) the HIRES spectra enable detailed stellar-abundance analyses based on the absorption lines of many chemical elements (see the review in this volume by Venn et al.), and (2) from detailed model fitting of the Hα stellar-wind profile, we can determine the momentum in the radiation-driven wind, which is a function of luminosity.

1.1. Abundance Gradients in Galaxies

By observing a sample of blue supergiant stars distributed across the face of these galaxies, we can study the abundance variations with galactocentric radius outward from the nucleus. Aller (1942) was the first to observe differences in the spectra of extragalactic H II regions at different galactocentric distances (in M33), but he attributed those to differences in stellar UV excitation. Schmidt (1960) argued that *abundance* differences with galactocentric radius *should* exist, but his data from the Palomar 200-inch prime focus spectrograph showed He I $\lambda5876/H\beta$ in M31 was constant. Searle (1971) was the first to measure extragalactic H II region abundance variations with radius, and still today most of what is known about abundance gradients in other galaxies has come from H II region studies.

However, the abundances derived from H II regions are uncertain owing to (i) the possibly non-uniform distribution of gas and dust in the region, (ii) the UV ionizing spectra of the embedded stars, which are in turn a function of metallicity, the number of such stars and their distribution in effective temperature, etc., and (iii) the calibrations of emission-line ratios versus abundances, which also depend upon the electron temperature of the gas. Finally, H II region studies can only determine abundances of light elements such as N, O, Si, and S.

From studies of high-resolution spectra of blue supergiant stars, we can determine the abundances of these and heavier elements such as Mg, Ti, Cr, Fe, the s-process elements, as well as C (see the review by Venn et al. in this volume). The latter are especially important in constraining the nucleosynthesis history of galaxies and models of galactic chemical evolution. A- and B-type supergiants, which are massive stars in a post-main-sequence evolutionary phase, are very young stars (ages $\leq 10^7$ years) whose photospheric abundances should reflect the present ISM abundances where they were born. Indeed, oxygen abundance gradients derived from H II regions and blue supergiant stars agree quite well in M33 and M31, as discussed at this conference by Monteverde and Venn, respectively.

1.2. Extragalactic Distance Determination

The measurement of extragalactic distances is a fundamental problem in observational astronomy (Jacoby et al. 1992). There are only a handful of *primary* distance indicators (e.g., the Cepheid P–L relation, expanding photospheres of Type II supernovae, gravitational lens time delays) which do not require the use of nearby galaxies for calibration. It is our long-term objective to add 'blue-supergiant winds' to the list of primary extragalactic distance indicators, based on the Wind-momentum–Luminosity Relation, or WLR (Puls et al. 1996).

The basic idea behind the WLR is that the mechanical momentum per unit time carried away by the stellar wind, $\dot{M}v_\infty$, should be a function of the photon momentum per unit time supplied by the stellar photosphere (which is proportional to the stellar luminosity), since the stellar wind is radiation-driven. One can determine $\dot{M}$ by fitting the Hα line and v_∞ from the P Cygni lines in the spectrum; applying the WLR then yields the intrinsic luminosity, which in turn yields the distance once the extinction is known. In practice, the method is somewhat complicated by the fact that $\log(L/L_\odot)$ is linearly related to the log of the 'modified wind momentum', $\log \dot{M}v_\infty(R/R_\odot)^{0.5}$, and the slope of this relation is a function of the stellar metallicity (which alters both the stellar UV-flux distribution and the opacity in the wind). However, observations of nearby

O-, B-, and A-type supergiants in our Galaxy and the Magellanic Clouds yield empirical Wind-momentum–Luminosity Relations in excellent agreement with theoretical expectations (Puls et al. 1996) taking metallicity into account.

Our studies of blue supergiants are also highly relevant to extragalactic distance determinations using Cepheid variables. Cepheid distances are complicated by an unknown – possibly large – dependence of the $P - L$ relation on metallicity. Freedman & Madore (1990) found empirically only a small $P - L$ metallicity dependence from studies of Cepheids in three fields in M31. This result, however, is based on an abundance gradient (for light elements) derived mainly from H II regions. Were the *stellar* metallicity gradient relevant to the Cepheids flatter than that which was assumed, a greater metallicity dependence of the Cepheid $P - L$ relationship would follow. We note that Gould (1994) has re-examined the influence of metallicity on the $P - L$ relation using Cepheids in M31 and the LMC, and he predicts that the distance modulus could vary by 0.56 mag per dex change in metallicity. Clearly, more detailed knowledge of the *stellar* metallicity gradients in galaxies such as M31 and M33 is required in order to address this issue.

Finally, variable extinction in the host galaxies further complicates Cepheid distance determinations. The observed photometric colours of the blue supergiants we study spectroscopically can be compared to the model atmosphere fluxes to determine A_V for each star, in order to assess this problem.

2. Target Selection and Observations

The blue supergiant stars being studied range in spectral type from early-B to mid-F ($T_{\rm eff}$ from 20 000 K to 6500 K). Our work to date has concentrated on the A- and early F-type stars. The stellar luminosities span a range in $\log(L/L_\odot)$ from 4.7 to 6.0 ($M_{\rm Bol} \simeq -7$ to -10) or more. The bolometric corrections are small for stars in this spectral type range, making these supergiants the visually brightest individual stars in their host galaxies, apart from supernovae.

Our initial target selections are based on existing ground-based photometric surveys, including Berkhuijsen et al. (1988; M31, photographic), Magnier et al. (1992; M31, CCD-based), Humphreys & Sandage (1980; M33, photographic), Massey, Armandoroff & Conti (1986; M31, CCD-based), Ivanov, Freedman & Madore (1993; M33, photographic), and Massey et al. (1995; M31 and M33, CCD-based). Where possible, prior to study with Keck HIRES, we confirm the spectral type and galaxy membership of our potential targets using low or moderate-resolution spectra; these are taken either from the pioneering studies in the literature (e.g., Humphreys 1980; Humphreys, Massey & Freedman 1990; Herrero et al. 1994; Monteverde et al. 1996), or else our own unpublished observations with the Palomar 5-m and the WHT.

The Keck HIRES observations span the wavelength range 4300 – 6600 Å in 29 echelle orders with a resolution $R = \lambda/\Delta\lambda = 35\,000$ (for a 1.1-arcsec slit width and a resolution element $\Delta\lambda = 4$ pixels). For a typical $V = 16.5$ mag ($M_V \sim -8$) supergiant star, a signal-to-noise ratio of ~ 80 per resolution element is reached in a 2 hour exposure. Following bias subtraction and flat fielding, careful sky subtraction is necessary to remove a background H II region nebular emission, especially at Hα.

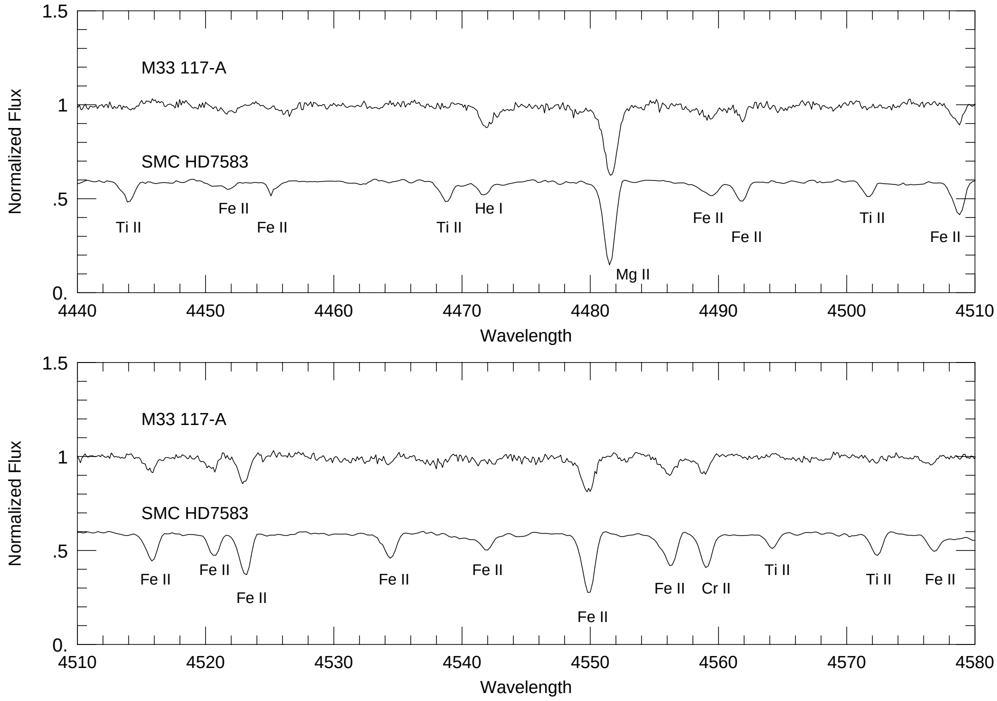


Figure 1. Sample of two orders from the HIRES spectrum of star 117-A in M33 (1 hr exposure) compared to the SMC star HD 7583 (metallicity one tenth solar).

The remaining data reduction steps follow standard procedures (see also McCarthy, 1990; McCarthy & Nemec 1996) including optimal extraction, continuum normalization by polynomial fitting and, for broad features, further normalization based on the average of continuum fits in adjacent orders, and Th-Ar wavelength calibration. Equivalent widths of metal absorption lines are measured by non-linear least-squares fitting of a Gaussian profile to the line and the local continuum. Formal errors in the equivalent width are derived from the covariance matrix of the fit for each line; typical errors are $\pm 10\,\mathrm{m\AA}$. Figure 1 illustrates the quality of the HIRES spectra for the most metal poor of the stars observed to date, star 117-A in M33.

3. Analysis

The results to date of abundance analyses of the A supergiants in M33 and M31 were reviewed at this conference by Venn (see also McCarthy et al. 1995, 1998). The remainder of this review will focus on the analysis of the Hα line for the stellar wind parameters and the wind momentum.

We fit the Hα P-Cygni emission line profile in the Keck HIRES spectrum of each blue supergiant using sophisticated *unified model atmospheres* (Santolaya-Rey, Puls & Herrero 1997), which are based on the radiation-driven wind theory of Kudritzki et al. (1989). These models are spherically extended, in NLTE

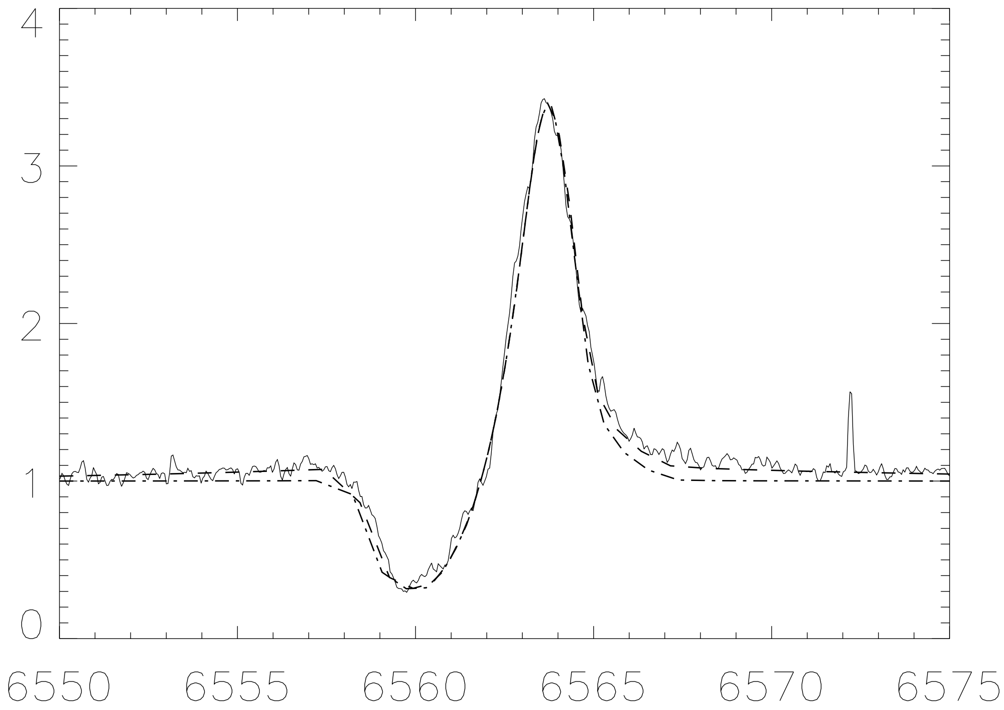


Figure 2. The influence of incoherent electron scattering on the Hα profile of star 41-3654 in M31. The dot-dashed profile neglects electron scattering, while the dashed profile takes it into account properly as a *photospheric* effect (from McCarthy et al. 1997).

radiative equilibrium, and smoothly transition from the quasi-hydrostatic photosphere to the supersonic stellar wind, $v(r) = v_\infty(1 - b/r)^\beta$, by choosing b so that the wind speed $v(r)$ is less than one tenth the sound speed at the base of the wind. Additionally, the models now include the effects of incoherent electron scattering, which raises the far wings of the line profile *in the photosphere* (Figure 2). It is important to emphasize that the observed P-Cygni emission profile is formed far out in the wind, where the electron optical depth is much too small for Thomson scattering to be important.

Prior to fitting the Hα line profile, the stellar parameters $T_{\rm eff}$, $\log(g)$, and the metallicity are determined in the course of the abundance analysis (based on Kurucz LTE model atmospheres). Since the hydrodynamic unified model atmospheres do not account for line blanketting, we adopt a slightly hotter effective temperature to compensate for the missing backwarming of the photosphere when working with the unified models.

The stellar wind parameters to be determined from Hα then are the mass loss rate ($\dot{M}$), the terminal velocity (v_∞), the exponent (β) of the wind velocity field, and $v_{\rm turb}$, an additional non-thermal broadening of the atomic absorption coefficient due to turbulence in the wind. The microturbulence parameter affects the wavelength position of the emission peak, as first detected in the UV spectra of O stars and explained by Hamman (1980, 1981a, 1981b). We illustrate the

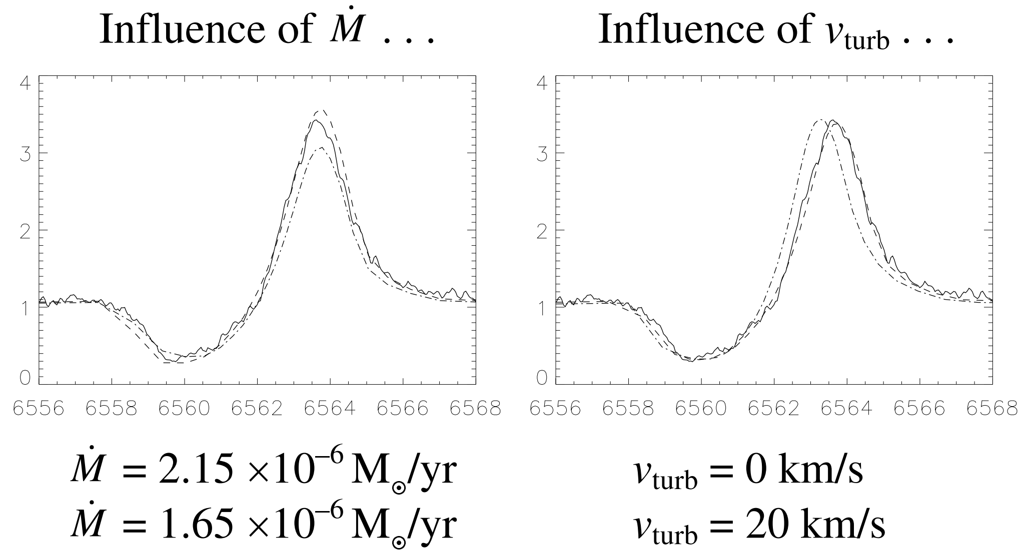


Figure 3. Hα profile fitting to the Keck HIRES spectrum of M31 star 41-3654, illustrating the sensitivity of the fit to the stellar wind parameters $\dot{M}$ (left) and $v_{\rm turb}$ (right). The best fit is obtained for the parameters $\dot{M} = 1.9 \times 10^{-6}\, M_{\odot}\ {\rm yr}^{-1}$ and $v_{\rm turb} = 20\,{\rm km\,s}^{-1}$.

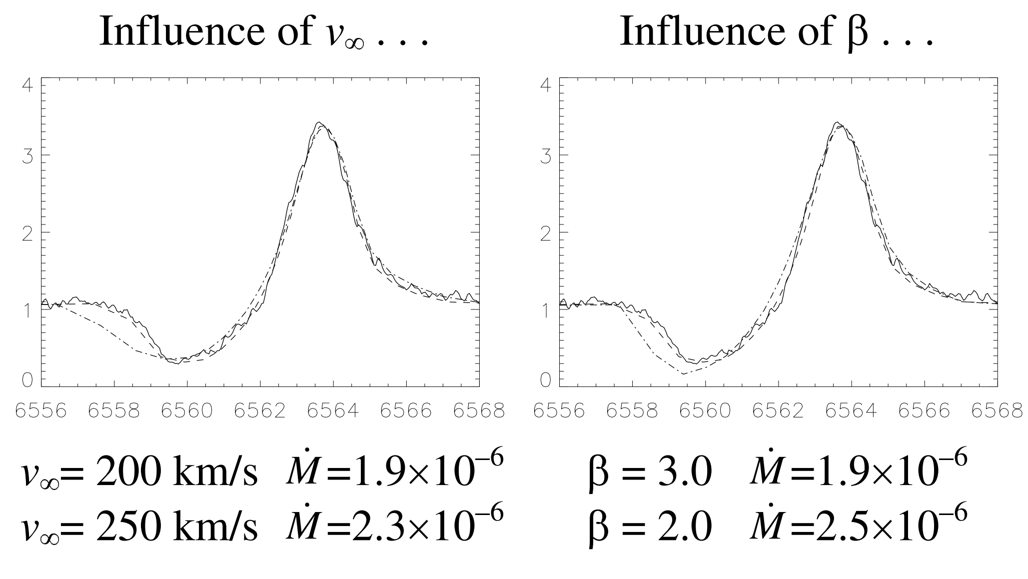
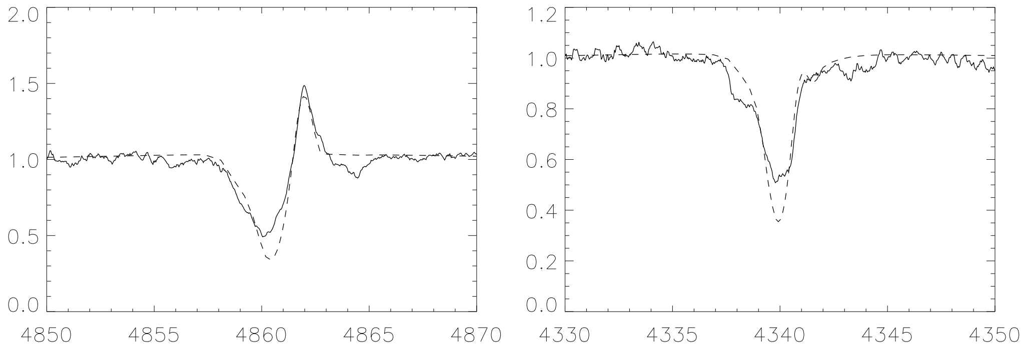


Figure 4. Hα profile fitting to the Keck HIRES spectrum of M31 star 41-3654, illustrating the sensitivity of the fit to the stellar wind parameters v_{∞} (left) and β (right). Note that in each case the mass loss rate has been adjusted in order to best fit the emission peak.

influence of of $\dot{M}$ and $v_{\rm turb}$ on the Hα profile fits to 41-3654 in Figure 3. Clearly if the other parameters (v_∞ and β) were known, $\dot{M}$ could be determined to better than 10%.

Figure 4 illustrates the effects on the Hα line profile of increasing the terminal velocity of the wind versus the effect of reducing the β exponent of the velocity field. In both cases these changes decrease the density in the wind for a given mass loss rate (since the equation of continuity must hold), so that to maintain a fit to the Hα emission peak requires increasing the mass loss rate. When this is done (as in Figure 4), the differing effects on the blue wing of the P-Cygni absorption profile can be distinguished: changing v_∞ changes the slope of the blue wing while changing β alters its depth without changing its slope. Therefore it is possible to determine a unique solution for both the β and v_∞ parameters of the velocity field, together with $\dot{M}$ and $v_{\rm turb}$, from a detailed study of the Hα profile observed at high resolution and signal-to-noise ratio.

Finally, as a consistency check, the stellar wind model which best fits the Hα profile is compared to the observed Hβ and Hγ profiles, as in Figure 5. The shapes of the Hβ and Hγ profiles are well-reproduced by the models (note that Hγ is blended with metal absorption lines), except in the absorption line core where the observed profiles show a weak wind contamination not reproduced by the models. To obtain a better fit would require some fine tuning of the density structure of the wind just above the photosphere, but this would have no effect on the determination of the wind momentum.



$$\dot{M} = (1.90 \pm 0.25) \times 10^{-6}\ \mathrm{M_\odot/yr} \qquad v_\infty = 200 \pm 25\ \mathrm{km/s}$$

$$\beta = 3.0^{+1.0}_{-0.5} \qquad v_{\rm turb} = 20 \pm 5\ \mathrm{km/s}$$

Figure 5. Unified model profiles compared to the observed Hβ and Hγ profiles using the model stellar wind parameters (shown inside the box) which best fit the Hα profile.

4. Results

The Hα profiles of four M31 and M33 blue supergiants have been analyzed to date (McCarthy et al. 1995, 1997), and the results are summarized in Table 1.

Note that the mass loss rates span a range of over two orders of magnitude, while the remaining stellar wind parameters are quite similar. The terminal velocities are consistent with previous results on A supergiants (Stahl et al. 1991, Lamers et al. 1995). The β exponents of the velocity fields are large compared with previous findings for O- and B-type supergiants (see Puls et al. 1996), but similar β values were found for A-type hypergiants by Stahl et al. (1991).

Table 1. Stellar-Wind Parameters

Star Name	$\dot{M}$ ($10^{-6}\,M_{\odot}$ yr^{-1})	β	v_{∞} (km s^{-1})
M31: 41-3654	1.90 ± 0.25	$3.0^{+1.0}_{-0.5}$	200 ± 25
M31: 41-3712	1.10 ± 0.20	$2.0^{+1.0}_{-0.5}$	200 ± 25
M33: B-324	12.0 ± 2.0	$4.0^{+0.5}_{-1.0}$	150 ± 25
M33: 117-A	0.03 ± 0.003	$4.0^{+0.5}_{-1.0}$	200 ± 25

The locations of the four M31 and M33 stars from Table 1 in the Wind-momentum–Luminosity plane are shown in Fig. 6. Note that the wind-momentum of the metal poor M33 star 117-A is in excellent agreement with the SMC stars O stars shown, as expected from its metallicity (see also Fig. 1).

5. Conclusions and Future Plans

In McCarthy et al. (1997) we demonstrate that the residuals in the Wind-momentum–Luminosity plane between our M31 stars and the WLR defined by Galactic A and B supergiants translate into distance modulus errors of $\Delta\mu = +0.31$ and -0.50 mag for 41-3654 and 41-3712, respectively. These distance uncertainties are comparable to those obtained from the $P-L$ relation for individual Cepheids, and from a sample of 20 A supergiants one could determine a galaxy's distance modulus to an accuracy of $\Delta\mu \sim \pm 0.1$ mag.

Our first objective is to increase the sample of blue supergiants observed with Keck HIRES, not only to test this claim regarding the WLR as a distance indicator but also to map in detail the element abundance gradients in M31 and M33. On the theoretical side, a parallel effort has been undertaken to better understand the application of the WLR to stars over a large range of effective temperature; see the discussion at this conference by Kudritzki.

Hubble Space Telescope WFPC2 observations will be used to verify that our targets in M31 and M33 are single stars, not unresolved pairs or associations, and at the same time to improve the photometric magnitudes and colours from which we determine reddening (extinction) and place the objects in the wind-momentum–luminosity plane. Future ultraviolet spectroscopy with HST targetting M31 and M33 early-B supergiants will enable us to determine the

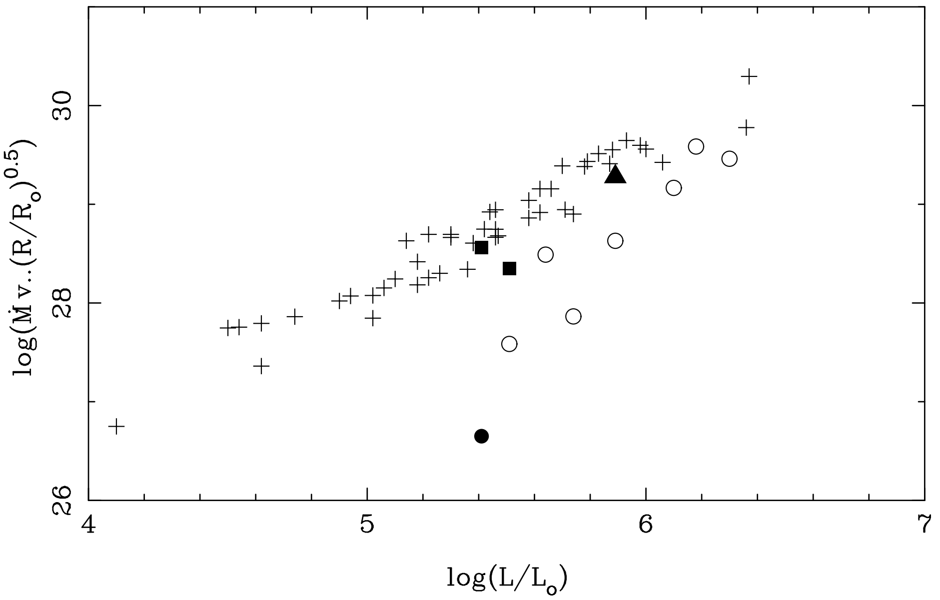


Figure 6. The locations of the M31 supergiants (filled squares) and M33 supergiants B-324 (filled triangle) and 117-A (filled circle) in the Wind-momentum–Luminosity plane, compared to Galactic O stars and AB supergiants (plus signs) and SMC O stars (open circles).

terminal velocities in the winds of these stars, whose Hα lines do not have the well-developed P-Cygni profiles observed in the A supergiants.

Meanwhile we are pushing the limits of the Keck HIRES instrument to obtain spectra of the brightest A-type supergiants in the Local Group dwarf-Irregular galaxy NGC 6822, as well as in NGC 2403 beyond the Local Group ($m - M = 27.5$). Finally, we have also initiated the task of identifying blue supergiants in HST/WFPC2 images of M101 and M100 obtained by the Distance Scale Key Project Team (W. Freedman, PI) to search for Cepheids. Moderate-resolution ground-based multi-slit spectroscopy of these very faint ($V > 20$) blue-supergiant targets is being attempted with the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) at Keck Observatory. We look forward to reporting on our future successes at the next Boulder-Munich Workshop, in a few years.

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Discussion

Schmutz: I was very interested in your remarks about the electron-scattering wings. In my experience with WR stars, as soon as you introduce electron-scattering you find that the model profiles don't fit unless you also introduce clumping. You didn't mention this, so I guess the electron-scattering wings fit okay from the outset, which I find surprising.
McCarthy: Well, we didn't need to use clumping, although of course we could be misled if clumping does exist. Do you want to comment, Rolf?
Kudritzki: [To Schmutz] You assume that all the electron-scattering takes place in the wind, which is not true for these objects; it's a *photospheric* effect.
Schmutz: But in the hotter stars, when you introduce electron-scattering you find that it does not fit...
Kudritzki: My problem is, it fits! [Laughter.] I'm sorry! But the point is that these wings are not formed in the wind but in the photosphere.
Puls: I think there are two things which can be confused here. We are not speaking of coherent scattering, which occurs in your Wolf-Rayet winds and which I agree is a real problem, but the non-coherent redistribution of photons from underpopulated $n = 2$ levels in the photosphere.
Harries: I'm amazed that you can get a unique solution when you have so many free parameters. Do you construct a grid of models and find a χ^2 minimum?
McCarthy: The different parameters affect the profile in different ways, and at our resolution we can constrain each parameter uniquely. [This is illustrated in the written version of the talk.] I forgot to mention in my talk that $T_{\rm eff}$, $\log g$ and the abundances are all separately determined before we undertake the Hα analysis.
Harries: The rotation velocity looks quite low.
McCarthy: From the metal lines, certainly less than 50 km s^{-1}.
Kudritzki: Thirty.