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STELLAR ABUNDANCES AND WINDS OF A-TYPE SUPERGIANT STARS IN M33: FIRST RESULTS FROM THE KECK HIRES SPECTROGRAPH[1]

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ABSTRACT

In this Letter, we report the first results of detailed analyses of A-type supergiants in M33 from high-quality Keck HIRES echelle spectra. The two stars, designated 117-A and B-324, now constitute the most distant stars for which detailed abundances have been measured. We find 117-A is metal-poor (roughly 1/10 solar), resembling an early A supergiant in the SMC. B-324 has P Cygni–like profiles for most of the metal lines, but fitting only the photospheric component yields metal abundances similar to solar. These two stars are located at distinctly different galactocentric distances in M33; comparing their abundances shows that the metallicity gradient of this galaxy, previously reported only from H II–region surveys, is also qualitatively apparent in these stars.

Estimates of the stellar-wind parameters for these stars yield mass-loss rates of $\sim 2.5 \times 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$ for 117-A and $\sim 1.2 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$ for B-324 from the Hα line profiles. When we examine the location of these stars in the wind momentum–luminosity plane, we find that they are in excellent agreement with the loci of luminous blue stars in the Galaxy, LMC, and SMC, taking into account differences in metallicity.

Subject headings: galaxies: abundances — galaxies: stellar content — stars: abundances — stars: mass loss — supergiants

1. INTRODUCTION

We have recently undertaken a study of A-type supergiants in the Local Group spiral galaxies M33 and M31 with the 10 m Keck I telescope and HIRES spectrograph. With Keck, it is possible to obtain spectra of similar dispersion (~0.1 Å pixel^{-1}) and signal-to-noise ratio quality (S/N ≥ 80 per resolution element) as previously only possible for supergiants in the Galaxy and Magellanic Clouds. Using the visually brightest (A type) supergiant stars in these external galaxies, elemental abundances in stars (based on stellar model atmosphere analyses) can be compared to those in H II regions (based on nebular photoionization models), and the list of elements studied can be extended to include Fe, Ti, Cr, Mg, Si, and C, among others. Through the study of these additional elements, new insights can be gained into the nucleosynthetic history and chemical evolution of spiral galaxies other than our own.

Furthermore, recent advances in the theory of stellar atmospheres and winds (see, e.g., Kudritzki, Lennon, & Puls 1995; Kudritzki et al. 1992) have made it possible to derive the luminosities of blue supergiant stars using the wind momentum–luminosity relationship (WLR; Fig. 1) with an accuracy that may rival that of the period-luminosity relationship for Cepheids. The new WLR method relies on the fact that luminous, hot stars have winds driven by radiation pressure through the metal lines; the strength of these winds depends primarily upon the star's luminosity and atmospheric chemical composition. The preferred technique requires the derivation of the stellar parameters (temperature, gravity, and composition) spectroscopically from optical absorption lines, then modeling the Hα line profile provides the mass-loss rate. Combining the spectroscopically determined stellar and wind parameters with an empirically calibrated WLR then allows one to derive the intrinsic luminosity, from which the distance follows once the extinction is known. Inherent in the use of the spectroscopic WLR method is that one also obtains the extinction toward each object by comparing its observed and intrinsic colors, as derived from the model atmosphere analysis.

The importance of metallicity in the stellar atmosphere to the WLR method, as predicted theoretically and subsequently observed, is illustrated in Figure 1. Clearly, the WLR is well defined once metallicity is taken into account. Conversely, proper application of the WLR requires knowledge of the stellar metallicity, which H II–region studies suggest depends on galactocentric distance within a given galaxy.

In this Letter, we report our first results from Keck for two A-type supergiants in M33, which now constitute the most distant stars for which detailed abundances have been measured. The two stars, designated B-324 and 117-A, are located at distinctly different galactocentric distances in M33, allowing us to probe the metallicity gradient of this galaxy, previously reported only from H II–region surveys (Henry & Howard 1995; Scowen, Dufour, & Hester 1992; Zaritsky, Elson, & Hill 1989; Vilchez et al. 1988). Finally, we present Hα line-profile analyses for their stellar-wind momenta sufficient to place the M33 stars in the $\log \dot{M} v_{\infty} R^{0.5}$–$\log L$ plane for comparison against the WLRs empirically calibrated in our Galaxy, the LMC, and the SMC.

2. OBSERVATIONS AND REDUCTIONS

The two M33 stars described here were first cataloged by Humphreys & Sandage (1980): star "A" in association 117 (117-A) is located ~20′ (4.5 kpc) from the center of M33; blue star 324 (B-324) is located in association 67 much closer to the

[1] Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

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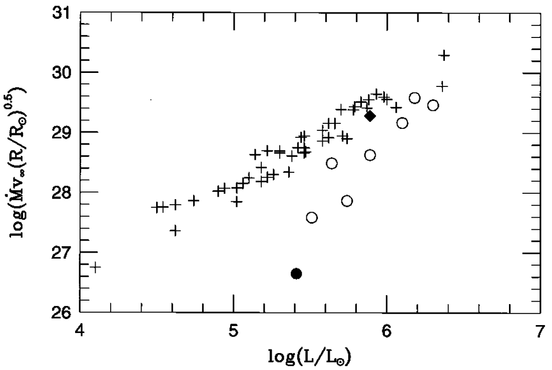

FIG. 1.—The wind momentum–luminosity relationship (y-axis in cgs units). Plus signs represent O stars and AB supergiants in the Galaxy (Puls et al. 1995; Lennon et al. 1994; Kudritzki et al. 1995), and open circles O stars in the SMC (Puls et al. 1995). The diamond represents B-324, and the filled circle 117-A.

center of M33 (6′, or 1.3 kpc). These stars were selected as initial targets on the basis of the previous, medium-resolution spectral survey by Herrero et al. (1994), which confirmed that they are very likely isolated stars because all lines present are consistent with a single stellar temperature. Star 117-A was classified as spectral type A0 Ia-O, while the weak Fe II P Cygni lines found in B-324—likely "one of the most intrinsically bright stars known in the optical"—defied classification attempts at 2.0 and 6.0 Å resolution in their red and blue spectrograms, respectively.

The 10 m Keck I telescope and HIRES spectrograph (Vogt et al. 1994) were used to observe these two M33 stars on 1994 December 24 (UT) in 0.″85 seeing. Five 30 minute exposures of B-324 ($V = 15.2$ mag) were taken through a 1.″1 slit (giving $R = \lambda/\Delta\lambda = 35{,}000$, with 4 pixels per $\Delta\lambda$ resolution element), yielding a combined S/N > 100 pixel^{-1} (S/N > 200 per resolution element) after co-addition. These were followed by a 1 hr observation of 117-A ($V = 16.6$ mag), which yielded S/N ≥ 40 pixel^{-1} (S/N ≥ 80 per resolution element). The wavelength range spanned 4300 Å ≤ λ ≤ 6700 Å in 30 echelle orders; wavelength coverage was not complete for λ > 5000 Å. Slit length was limited to 7.″0 to prevent overlapping orders at the short-wavelength extreme.

The CCD echelle spectrograms were reduced using a set of routines written for echelle data reduction (Tomaney & McCarthy 1995) under the FIGARO package. Even though the stars are isolated and not within H II regions, the HIRES spectra revealed significant broad (>300 km s^{-1}) nebular Balmer, [N II], and [O III] emission, easily recognizable in the two-dimensional CCD data. Moreover, the nebular emission showed a great deal of structure in both the spatial and velocity (spectral) directions, as well as variation from exposure to exposure for B-324 owing to the fact that the fixed Nasmyth slit of HIRES rotates on the sky. This nebular contamination was removed from the stellar spectra prior to extraction by fitting low-order polynomials in the spatial direction to "sky apertures" by using the routines REGPIC and SKYFIT from the FIGARO-compatible PAMELA package by Horne and Marsh (Horne 1986; Marsh 1989).

The spectrum of B-324 shows P Cygni profiles in nearly all spectral lines, both weak and strong. Herrero et al. (1994) noted P Cygni profiles for several weak Fe II lines in the red, and we extend this list to dozens of Fe II lines in the blue, as well as Ti II, Sc II, and Cr II lines. B-324 also has extremely strong stellar Hα emission. The spectrum of 117-A is that of a normal, metal-poor supergiant, with stellar Hα in emission and Hγ in absorption.

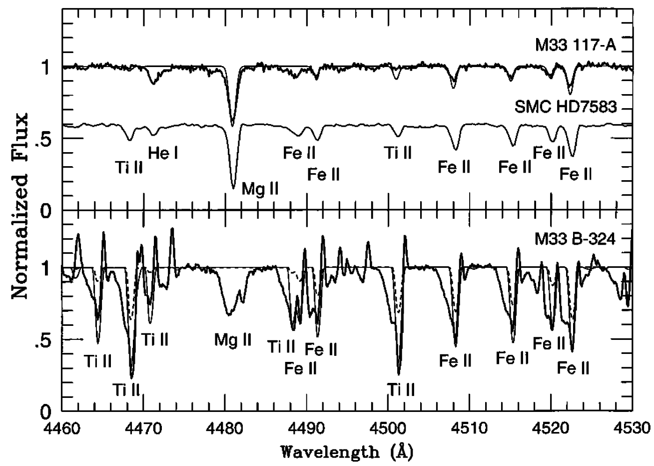

FIG. 2.—*Top*: Representative spectrum of 117-A fit by spectrum synthesis with [Mg/H] = [Cr/H] = −0.7, [Fe/H] = [Ti/H] = −1.0, and no He, compared to the metal-poor SMC A0 Ia0 star HD 7583. *Bottom*: Representative spectrum of B-324, shown with our spectrum syntheses for near-solar abundances (*thin solid line*: [Fe/H] = 0.0 and [Ti/H] = 0.5) vs. 1/10 solar metallicity (*dotted line*).

3. ANALYSIS

3.1. *Atmospheric Parameters and Abundances*

It is clear that 117-A is metal-deficient from a comparison of the stellar spectrum with that of a star of similar spectral type in the SMC, as shown in Figure 2. We have attempted to quantify this metal deficiency by calculating photospheric abundances via a simplified LTE analysis; A-type supergiants are in a regime where non-LTE effects should be considered, yet Venn (1995) has shown that LTE is an adequate description when analyzing *weak* metal lines that form in deep stellar layers. Spherical extension is probably also important and will be considered in future papers, but the metal-line analyses presented here assume plane-parallel model atmospheres.

Comparing this star's spectrum with an SMC spectral sequence (Lennon 1995), we adopted $T_{\rm eff} = 9500$ K, slightly hotter than that of the SMC A0 hypergiant HD 7583, which Husfeld (1993) found to have $T_{\rm eff} = 9400 \pm 250$ K. A fit of the Hγ line wings in 117-A indicates $\log g \sim 1.0 \pm 0.2$ dex, typical of an A0 hypergiant. A line-blanketed, LTE (ATLAS9) model atmosphere was adopted with $T_{\rm eff} = 9500$ K, $\log g = 1.1$, and [M/H] = −1.0. There were not enough lines of any one species in our spectrum for a good determination of the microturbulence; however, our Fe II lines support a value of $\xi = 10 \pm 5$ km s^{-1}, typical of the values found by Venn (1995) for high-luminosity A-type supergiants.

Abundances were calculated from equivalent widths using LINFOR (from the Kiel group), with the exception of Mg, for which we used a spectrum synthesis of the Mg II λ 4481 region (see Fig. 2). We find significant underabundances of all elements, as noted in Table 1. Fe II is ∼1.0 dex less than solar, and our upper limits for Ti II are in agreement with this value. The remaining three elements examined (Mg, Si, Cr) are less abundant than in the Sun by 0.6–0.8 dex. We note that the lines used in the Mg II, Si II, and Cr II abundance determinations have larger χ-values than those used for the Fe II and Ti II calculations, which may suggest an inability of the model atmosphere to accurately represent the uppermost stellar layers (e.g., sphericity and velocity fields). Abundance uncertainties due to errors in the atmospheric parameters are not

TABLE 1

117-A Weak-Line Abundances

Ion	Multiplet	λ (Å)	χ (eV)	log gf[a]	W_λ (mÅ)	log ε	[ε][b]
Mg II......	4	4481.2	8.83	0.97	[c]	6.9	−0.7
Si II........	5	5041.03	10.07	0.17	108	6.8	−0.8
Ti II	19	4395.03	1.08	−0.66	≤30	≤4.0	≤−0.9
Ti II	19	4443.80	1.08	−0.70	≤30	≤4.0	≤−0.9
Cr II.......	44	4558.66	4.07	−0.66	101	5.0	−0.7
Cr II.......	44	4634.10	4.07	−1.24	43	5.1	−0.6
Fe II.......	27	4351.76	2.70	−2.10	155	6.4	−1.1
Fe II.......	27	4416.82	2.78	−2.60	89	6.5	−1.0
Fe II.......	37	4491.40	2.86	−2.70	52	6.4	−1.1
Fe II.......	38	4508.28	2.86	−2.21	98	6.3	−1.2
Fe II.......	37	4515.34	2.84	−2.48	76	6.4	−1.1
Fe II.......	37	4520.23	2.81	−2.60	53	6.3	−1.2
Fe II.......	37	4522.63	2.84	−2.03	151	6.4	−1.1
Fe II.......	37	4555.89	2.83	−2.29	141	6.6	−0.9
Fe II.......	38	4576.33	2.84	−3.04	42	6.6	−0.9
Fe II.......	38	4583.83	2.81	−2.02	174	6.4	−1.1
Fe II.......	37	4629.34	2.81	−2.37	107	6.4	−1.1
Fe II.......	49	5197.56	3.23	−2.10	122	6.5	−1.0
Fe II.......	49	5234.62	3.22	−2.05	114	6.4	−1.1
Fe II.......	74	6456.39	3.90	−2.30	99	6.9	−0.6

[a] Sources for the oscillator strengths are as follows: Wiese & Martin 1980 (Mg, Si), Martin, Fuhr, & Wiese 1988 (Ti, Cr), and Fuhr, Martin, & Wiese 1988 (Fe).

[b] $[\varepsilon] = \log \varepsilon(X)_* - \log \varepsilon(X)_\odot$, where solar abundances are from Anders & Grevesse 1989.

[c] Mg II is a blend of two lines; the abundance has been determined from a detailed line synthesis.

significant, less than +0.2 dex for $\Delta T_{\rm eff} = +500$ K, $\Delta\log g = -0.2$ dex, and $\Delta\xi = +5$ km s^{-1}.

The metallicity of B-324 is less certain. A simplified LTE analysis of the central absorption of the Fe II and Ti II lines, assuming these are the true photospheric component (as our wind models confirm), supports a solar Fe abundance for this star (Fig. 2). The effective temperature ($T_{\rm eff} = 8000$ K) was estimated from the star's apparent spectral type, roughly A7. The lowest gravity solar-metallicity model at this temperature that we could converge with ATLAS9 had $\log g = 0.9$. We also adopted $\xi = 10$ km s^{-1}, $v \sin i = 40$ km s^{-1}, and gf-values from Kurucz (1988) for the spectrum synthesis. The line fits are not excellent for all the Fe II lines but suggest that a near-solar abundance is preferred over a reduced abundance. A model with $T_{\rm eff} = 7400$ K and $\log g = 0.4$ yielded a similar synthetic spectrum and abundance determination.

3.2. *Mass-Loss Rates and Winds*

One of our goals in examining the blue supergiants in M33 is to test the WLR for stars having known distances. We began by adopting a distance modulus to M33 of $\mu = 24.43$ (Rozanski & Rowan-Robinson 1994). This value is likely to be uncertain by ±0.2, considering the range in the distance moduli from different studies (e.g., Freedman 1985; Freedman, Wilson, & Madore 1991). This distance was then used to determine the luminosities and radii of the stars in advance from their effective temperatures, apparent dereddened magnitudes, and model atmosphere fluxes. For 117-A, we adopted $V = 16.34$ mag and $B - V = 0.18$ mag (Humphreys 1980), and for B-324, $V = 15.20$ mag and $B - V = 0.31$ mag (Humphreys, Massey, & Freedman 1990). To determine the reddening, we used an intrinsic $(B - V)_o$ from Lang (1992, p. 150) for the stars' apparent spectral types, yielding $E(B - V) = 0.13$ mag for both 117-A and B-324. Combining the dereddened magnitudes and model atmosphere fluxes for each star, we obtained $R_* = 200\ R_\odot$, $\log (L_*/L_\odot) = 5.4$ for 117-A, and $R_* = 460\ R_\odot$, $\log (L_*/L_\odot) = 5.9$ for B-324. With these intrinsic stellar parameters, we then derived the mass-loss rates from the Hα profiles by fitting theoretical non-LTE (H and He) model atmosphere profiles, including stellar winds and spherical extension (see Puls et al. 1995).

For 117-A, Hα is well represented by a mass-loss rate of $2.5 \times 10^{-8}\ M_\odot$ yr^{-1}, assuming a standard velocity law $v(r) = v_\infty(1 - r/R_*)^\beta$ with $\beta = 4$ and $v_\infty = 200$ km s^{-1}; see Figure 3. These values for v_∞ and β were found to be typical for A-type supergiants from an analysis of Hα and UV Fe II lines by Stahl et al. (1991). In fitting the Hα profile for 117-A, only

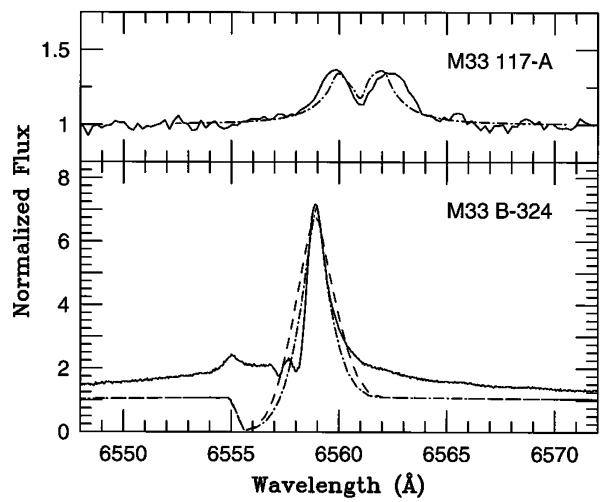

FIG. 3.—*Top*: Hα fit to 117-A based on $v_\infty = 200$ km s^{-1} with $\dot{M} = 2.5 \times 10^{-8}\ M_\odot$ yr^{-1} and $\beta = 4$; a test with $\beta = 2$ and $\dot{M} = 5 \times 10^{-8}\ M_\odot$ yr^{-1} yields a similar profile. *Bottom*: Hα fit to B-324 based on $v_\infty = 150$ km s^{-1} with $\dot{M} = 1.2 \times 10^{-5}\ M_\odot$ yr^{-1} and $\beta = 4$ (*dash-dotted line*) vs. $\dot{M} = 2.0 \times 10^{-5}\ M_\odot$ yr^{-1} and $\beta = 2$ (*dashed line*).

the central absorption is used in determining $\dot{M}$ since the emission wings of the profile are purely photospheric and a typical non-LTE effect (see Hubený & Leitherer 1989).

The mass-loss rate of B-324 was determined from the central emission feature only, yielding $\beta = 4$ and $\dot{M} = 1.2 \times 10^{-5}\ M_\odot$ yr^{-1}, with $\dot{M}$ determined from the height of the emission peak and β from the width (Fig. 3). We used $v_\infty = 150$ km s^{-1} for this star, as determined from the blueshifts of the optical metal lines (Fe II, Ti II, Sc II, Cr II), and found this to be consistent with the Hα profile fits. The calculated profile does not reproduce the observed Hα profile exactly, though; currently, we do not generate the broad, extended emission wings, and we produce a P Cygni profile absorption trough that is not seen in the observations (Fig. 3). Work is now underway to examine the effects of incoherent electron scattering in reproducing the broad line wings and filling in the calculated absorption trough and will be reported in a future paper. At present, we are satisfied with the less-than-perfect Hα profile fits, in view of our simplifying assumptions.

4. DISCUSSION

The abundance determinations for 117-A (roughly SMC metallicity) and B-324 (roughly solar metallicity) are in good agreement with those found from H II–region studies, although those studies could only provide information on the light elements (such as He, N, O, and S). Our analysis of these supergiants has yielded abundances for Fe-group and α elements. While abundance gradients have been determined in many galactic disks, suggestions that the gradients become flatter at large galactocentric distances (see Zaritsky 1992) have been disputed recently by Henry & Howard (1995), who maintain that the observational data are consistent with a gradient of constant exponential slope. From the linear radial [N/H] and [O/H] decreases summarized by Vilchez et al. (1988), abundances change with galactocentric distance on the order of 0.4 dex between the locations of our two blue supergiants. Meanwhile, adopting an exponential gradient as done by Henry & Howard (1995) results in a decrease of ~0.6 dex between the same two points. Even though we expect young, massive supergiant stars to reflect the abundances of the interstellar medium, our steeper gradient of ~1.0 dex over 3.0 kpc does not contradict the slope of the H II–region gradients since our stellar abundances are somewhat uncertain at present. Also, our α-element abundances for 117-A are less underabundant than the Fe-group elements, suggesting that the slope in the light elements may be more gradual and therefore more similar to the H II–region gradient values. The abundance of oxygen in the H II region IC 142 (Vilchez et al. 1988), which is located close to B-324, is roughly solar and in good agreement with our Fe estimate, even though we had no O I features from which to determine the oxygen abundance in this star. We note that elemental-abundance gradients in the Galaxy as determined from stars, H II regions, and planetary nebulae are often in disagreement (see, e.g., Rolleston, Dufton, & Fitzsimmons 1994; Kilian, Montenbruck, & Nissen 1994), although in the Galaxy it is the H II regions that show the higher gradients. A significant dispersion in the abundances at any galactic location is likely (as seen in the Galaxy). We plan to observe and analyze more blue supergiants in M33 and extend our work to stars in M31, seeking a more detailed picture of abundance gradients, nucleosynthesis, and chemical evolution in spiral galaxies.

Finally, this initial empirical test using M33 supports the WLR. Adopting the luminosities, radii, mass-loss rates, and v_∞ values for B-324 and 117-A found in § 3.2 above, we place the two supergiants in the modified wind momentum–luminosity plane of Figure 1 as shown; note that these stars lie exactly on the expected calibrations for their metallicities (i.e., Galactic and SMC). While this result is encouraging, we have made several simplifying assumptions that require further study. In addition to analyzing more stars in M33 and M31, we are working to improve the model atmospheres for the metallicity, Hα line profile, and mass-loss rate calculations and to examine the general properties of A-type supergiant winds (e.g., v_∞, β, clumping properties) in more detail.

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