I Zw 18: A NEW WOLF-RAYET GALAXY

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ABSTRACT

We report the discovery of broad Wolf-Rayet (W-R) emission lines in the Multiple Mirror Telescope spectrum of the northwest component of I Zw 18, the lowest metallicity blue compact dwarf galaxy known. Two broad W-R bumps at the wavelengths $\lambda4650$ and $\lambda5800$ are detected, indicating the presence of WN and WC stars. The total numbers of WN and WC stars inferred from the luminosities of the broad He II $\lambda4686$ and C IV $\lambda5808$ lines are equal to $17 \pm 4$ and $5 \pm 2$, respectively. The W-R to O stars number ratio is equal to about 0.02, in satisfactory agreement with the value predicted by massive stellar evolution models with enhanced mass-loss rates. The WC stars in the northwest component of I Zw 18 can be responsible for the presence of the nebular He II $\lambda4686$ emission line; however, the observed intensity of this line is several times larger than model predictions, and other sources of ionizing radiation at wavelengths shorter than 225 Å are necessary.

Subject headings: galaxies: irregular — galaxies: ISM — galaxies: stellar content — H II regions — stars: Wolf-Rayet

1. INTRODUCTION

The presence of large numbers of Wolf-Rayet (W-R) stars in star-forming galaxies is well established (Allen, Wright, & Goss 1976; D’Odorico & Rosa 1981; Osterbrock & Cohen 1982; D’Odorico, Rosa, & Wampler 1983; Hutsemekers & Surdej 1984; Kunth & Joubert 1985; Kunth & Schild 1986; Sargent & Filippenko 1991; Conti 1991; Vacca & Conti 1992). These galaxies are often called W-R galaxies and they are of quite heterogeneous types. We focus here on the problem of detection of W-R stars in the low-mass and low-metallicity blue compact dwarf (BCD) galaxies. Systematic spectroscopic studies of BCDs have shown that in the spectra of about one-third of BCDs, broad W-R bumps characteristic of late WN stars are present, mainly at $\lambda4650$ (Izotov, Thuan, & Lipovetsky 1994, 1997b; Izotov & Thuan 1997a). The intensity of these bumps decreases with decreasing metallicity, in agreement with predictions of massive star evolution models and models of evolutionary population synthesis for star-forming regions (Maeder & Meynet 1994; Cerviño & Mas-Hesse 1994; Leitherer & Heckman 1995; Meynet 1995; Schaerer 1996). The lowest metallicity BCD in which W-R stars have been detected has approximately $Z_{\odot}/10$, although BCDs can be as metal-deficient as $Z_{\odot}/50$. Are W-R stars present in these extremely metal-deficient BCDs? In principle, massive stellar evolution theory (e.g., Maeder & Meynet 1994) does predict the evolution of the most massive low-metallicity stars through the W-R stage. However, since the efficiency of mass loss by stellar wind decreases with decreasing metallicity, the total number of W-R stars and the total duration of the W-R phase in a star formation episode are significantly reduced at low metallicities. This trend led Schaerer et al. (1997) to conclude that in some metal-deficient BCDs, weak W-R spectral features are not detected simply because of inadequate signal-to-noise ratio.

Several recent observations of low-metallicity BCDs have suggested that massive stars with mass loss are indeed present in galaxies with heavy element abundances less than $Z_{\odot}/20$. Imagery of I Zw 18 with the Hubble Space Telescope (HST) by Hunter & Thronson (1995) has resolved its northwest and southeast components into stars, with the brightest star having $V \sim 22$ mag. Those authors attempted to find W-R stars using a narrowband image in the He II $\lambda4686$ line and detected only two marginal W-R candidates. They expected a large population of W-R stars, given the presence of a large number of red supergiants, and thus concluded that I Zw 18 is not a BCD with many Wolf-Rayet stars. Recently, Izotov & Thuan (1997b), from 4 m Kitt Peak Mayall Telescope spectrophotometry of I Zw 18, noted that WC stars are possibly present in the northwest component. Finally, Thuan & Izotov (1997) have found evidence for stars with mass loss through the presence of P Cygni profiles in the UV HST spectra of two
and Tol 1214
2
channel of the MMT spectrograph using a highly optimized
1997 April 29 and 30. Observations were made with the blue
with the Multiple Mirror Telescope (MMT) on the nights of
properties of W-R stars in the BCD. We summarize our
later studies (Davidson, Kinman, &
ferred to subsequently as the brighter northwest and fainter
distance of 5
Martin (1996), Izotov et al. (1997b), and Izotov & Thuan
metal abundance by Searle & Sargent (1972). Later studies by
formation. It was first recognized to have an exceptionally low
spectrophotometry of I Zw 18. We show that W-R stars of
different types are clearly present in this galaxy.
I Zw 18 is a BCD undergoing an intense burst of star
search for stellar populations with mass loss in very metal-
other very metal-deficient galaxies, SBS 0335−052 (Z_\odot/40)
and Tol 1214−277 (Z_\odot/23). In this Letter we continue our
stellar populations with mass loss in very metal-
deficient BCDs. We present high signal-to-noise ratio optical
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was oriented in the direction with position angle P.A.
ionization of I Zw 18 (northwest) I Zw 18 (southeast)
Table 1
Emission-Line Intensities
| Ion            | I Zw 18 (northwest) | I Zw 18 (southeast) |
|----------------|---------------------|---------------------|
|                | F(λ)/F(Hβ)          | I(λ)/I(Hβ)          |
| 3727 [O ii]    | 0.228               | 0.238               |
| 3868 [Ne iii]  | 0.143               | 0.148               |
| 3889 He i + H8 | 0.102               | 0.195               |
| 3968 [Ne iii]  | 0.134               | 0.222               |
| 4010 Hβ        | 0.196               | 0.276               |
| 4340 Hγ        | 0.410               | 0.472               |
| 4363 [O iii]   | 0.069               | 0.068               |
| 4471 He i      | 0.022               | 0.021               |
| 4868 He n (nebular) | 0.041  | 0.040               |
| 4866 He n (W-R) | 0.063               | 0.062               |
| 4861 Hβ        | 1.000               | 1.000               |
| 4959 [O iii]   | 0.731               | 0.690               |
| 5007 [O iii]   | 2.197               | 2.069               |
| 5086 C iv (W-R)| 0.035               | 0.031               |
| 5876 He i      | 0.074               | 0.066               |
| 6563 He n      | 3.163               | 2.743               |
| 6678 He i      | 0.030               | 0.026               |
| 6717 [S ii]    | 0.024               | 0.021               |
| 6731 [S ii]    | 0.019               | 0.016               |
| 7065 He i      | 0.026               | 0.022               |
| 7135 [Ar iii]  | 0.019               | 0.016               |
| C(Hβ) dex      | 0.101               | 0.100               |
| F(Hβ) Å        | 2.36                | 1.70                |
| EW(Hβ) Å       | 56                  | 129                 |
| EW(absorption) Å | 2.9                  | 3.9                |

* In units of 10^{-14} ergs s^{-1} cm^{-2}.

Spectrophotometric observations of I Zw 18 were obtained
along with a 300 groove mm^{−1} grating in first order and an
L-38 second-order blocking filter. This yields a spatial scale
along the slit of 0.3 pixel^{−1}, a scale perpendicular to the slit of
1.9 Å pixel^{−1}, a spectral range of 3600−7500 Å, and a spectral
resolution of about 7 Å (FWHM). For these observations,
CCD rows were binned by a factor of 2, yielding a final
sampling of 0′.6 pixel^{−1}. The observations cover the full
spectral range in a single frame that contains all the lines of
interest and have sufficient spectral resolution to distinguish
between narrow nebular and broad W-R emission lines. The
total exposure time was 180 minutes and was broken up into
six subexposures, 30 minutes each. All exposures were taken at
small air masses (1.1−1.2), so no correction was made for
atmospheric dispersion. The seeing was 0′.7 FWHM. The slit
was oriented in the direction with position angle P.A. = −41°
to permit observations of both northwest and southeast components.
The spectrophotometric standard stars EG 247 and
HZ 44 were observed for flux calibration. Spectra of He-Ne-Ar
comparison lamps were obtained after each subexposure to
provide wavelength calibration.

The two-dimensional spectra were bias subtracted and
flat-field corrected using the IRAF.3 For the northwest
component, the extracted one-dimensional spectra cover the
brightest part of the galaxy with a spatial size of about 5′.
Similar procedures were used for the southeast component,
resulting in one-dimensional spectra covering a region 5′wide
at a distance of 5′.8 from the northwest component. The
extracted spectra from each frame were then co-added and
calibrated to absolute fluxes.

The observed line intensities have been corrected for inter-

3 IRAF is distributed by the National Optical Astronomy Observatories,
which is operated by the Association of Universities for Research in Astron-
omy, Inc., under cooperative agreement with the National Science Foundation.
stellar extinction using the reddening law by Whitford (1958). Hydrogen lines have been also corrected for underlying stellar absorption, with the equivalent width for hydrogen absorption lines derived self-consistently together with the extinction coefficient from the observed intensities of all hydrogen lines. We show the observed $F(\lambda)/F(H\beta)$ and extinction and absorption-corrected $I(\lambda)/I(H\beta)$ line intensities for the northwest and southeast components in Table 1, along with the extinction coefficient $C(H\beta)$ and the equivalent width of the hydrogen absorption lines, the observed flux, and equivalent width of the $H\beta$ emission line. The uncertainties for the tabulated relative line intensities are about 0.5% for the strongest lines and about 10%–15% for the weakest lines.

3. WOLF-RAYET STARS IN I Zw 18

In Figure 1 we show the spectra of the northwest and the southeast components of I Zw 18. The W-R broad lines and strong narrow He ii $\lambda 4686$ emission line are clearly present in the spectrum of the northwest component. Thus, I Zw 18 is the lowest metallicity galaxy where W-R stars are detected. In contrast, in the spectrum of the southeast component, W-R emission lines are not convincingly detected. The weak emission seen at the wavelength $\lambda 4700 \text{Å}$ is nebular emission from the [Fe iii] $\lambda 4658$, He ii $\lambda 4686$, and [Ar iv] $\lambda 4471$, 4740 lines. The appearance of a broad underlying emission feature here most probably arises from the blending of the wings of the individual nebular line profiles, but a very small contribution from W-R stars cannot be excluded. The detection of the C iv $\lambda 5808$ broad line in the northwest component suggests the presence of early WC stars, while the other broad lines are, most likely, evidence of early and late WN stars. The formation of C iv $\lambda 5808$ by WN stars can be ruled out because of its large FWHM ($\sim 80$ Å), which corresponds to early-type WC stars (Smith, Sharaf, & Moffat 1990). The approximate number of O and W-R stars in the northwest component can be estimated as follows. The observed fluxes of the C iv $\lambda 5808$ and broad He ii $\lambda 4686$ emission lines are $8.3 \times 10^{-16}$ and $1.49 \times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$, and that of H$\beta$ $\lambda 4861$ integrated along the slit is $4.93 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$. Correcting for interstellar extinction $C(H\beta) = 0.13$ dex for the northwest component and adopting a distance $D = 10.8$ Mpc (for the redshift $z = 0.00274$ of the northwest component with $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$), we derive the following luminosities: $L(C$ iv $\lambda 5808) = 1.27 \times 10^{37}$ erg s$^{-1}$, $L(\text{He } II \ \lambda 4686) = 2.84 \times 10^{37}$ ergs s$^{-1}$, and $L(H\beta) = 9.26 \times 10^{39}$ ergs s$^{-1}$. Assuming that only one-half of the light in H$\beta$ is contained within the slit width of 1.5, we derive finally $L(H\beta) = 1.85 \times 10^{39}$ ergs s$^{-1}$. This value agrees well with that derived by Hunter & Thronson (1995) from the HST Ha image. Adopting a value of $Q_e = 49.05$ (Vacca & Conti 1992) for the logarithm of the number of Lyman continuum photons emitted per second by an O7 V star and assuming Case B recombination and an instantaneous burst of star formation, we derive $N(O7V) = 381$. To derive the total number of O stars, we need to take into account the age of the stellar population and the initial mass function (IMF) slope. A measure of the age of the burst of star formation is the equivalent width of the $H\beta$ emission line. The low equivalent width of 56 Å in the northwest component of I Zw 18 corresponds to an age of 4–5 Myr, assuming a Salpeter IMF (Leitherer & Heckman 1995). This value is in good agreement with the results of direct HST photometry of the brightest stars by Hunter & Thronson (1995). They found stars as old as 5 Myr in the northwest component. Then, the total number of O stars is about 3 times larger (Schaerer 1996) and is equal to about 1100. This approximate value is in good agreement with the number of O stars of 1300 derived by Hunter & Thronson (1995) from the luminosity function.

The number of W-R stars is estimated from the luminosity of the W-R emission features. While the main contribution to the $\lambda 5808$ emission is from WC4 stars, the emission in the $\lambda 4650$ feature is produced by W-R stars of different types. However, the observed flux ratio, $f(\lambda 4650)/f(\lambda 5808) \sim 3$, is significantly greater than that expected for WC4 stars (Smith et al. 1990). Therefore, the dominant contributors to the broad He ii $\lambda 4686$ emission are WNL stars. The moderate spectral resolution and line blending, however, prevent drawing more decisive conclusions about the origin of the $\lambda 4650$ bump. The derived number of WNL stars should therefore be considered as only indicative. Adopting the luminosity of a single WC4 star in the C iv $\lambda 5808$ line as equal to $2.5 \times 10^{39}$ ergs s$^{-1}$, and that of a single WNL star in He ii $\lambda 4686$ as equal to $1.7 \times 10^{39}$ ergs s$^{-1}$ (Conti 1991; Vacca & Conti 1992), we derive the following numbers of stars: $N(WC4) = 5 \pm 2$, $N(WNL) = 17 \pm 4$. This gives $N(W-R)/N(O) = 0.02$ and $N(WC)/N(WN) = 0.3$.

Meynet (1995) presented new evolutionary population-synthesis models based on the most recent grids of stellar models computed at the Geneva Observatory. He studied the effects of changes in the rates of mass loss by stellar winds on the
massive star populations born in a starburst. According to Maeder & Meynet (1994), the high mass-loss rate stellar models are to be preferred over the standard ones on the basis of comparisons with the observed luminosities, chemical compositions and number statistics of W-R stars in zones of constant star formation rate. In starburst galaxies, the presence of WC stars at very low metallicity is predicted only by models of massive star evolution with enhanced mass loss (Meynet 1995), while the models with standard mass-loss rates derived by de Jager, Nieuwenhuijzen, & van der Hucht (1988) and scaled with metallicity as $Z^{1/2}$ fail to produce WC stars at the metallicity of I Zw 18. Therefore, the detection of WC stars in I Zw 18 gives strong support to the idea of enhanced mass loss in massive low metallicity stars. Furthermore, we find satisfactory agreement between the observed and theoretical W-R/O and WC/WN ratios at the metallicity of I Zw 18. Meynet (1995) has calculated evolutionary population synthesis models only for metallicities as low as $Z_{/0.20}. At this metallicity, assuming an instantaneous burst of star formation and an IMF $dn/dM \propto M^{-2}$ for the massive stars, his models predict W-R/O $\approx 0.035$ and WC/WN $\approx 0.5$ for peak values. Scaling these values as $Z^{1/2}$ to the I Zw 18 heavy element abundance $Z_{/50}$ gives W-R/O and WC/WN ratios close to those derived from the observations.

The detection of WC stars in I Zw 18 can help resolve the long-standing problem of the origin of the strong nebular He II $\lambda$4686 line in the northwestern component, which is several orders of magnitude greater than predicted by photoionized H II region models. Schaerer (1996) has shown that WC stars can significantly increase the ionizing flux shortward of 228 Å, thus leading to the formation of a He ii$^{+4}$ zone in the H II region and increasing the recombination He II $\lambda$4686 emission line luminosity by several orders of magnitude. However, this model predicts the maximum value of the nebular He II $\lambda$4686 emission-line intensity to be only about 1%-2% that of H$\beta$ when the age of the star-forming region is not greater than 3 Myr. The He II line intensity is expected to decrease from this maximum value for a somewhat older stellar population like the one in I Zw 18. This is in contrast to the observed intensity of the nebular He II $\lambda$4686 emission line in the northwestern component of I Zw 18, which is 4% that of H$\beta$, larger than the predicted peak value. Furthermore, this model fails to explain the presence of strong He II $\lambda$4686 emission line in the galaxies where WC stars have not been detected (Izotov et al. 1997a). We therefore conclude that, in addition to WC stars, some other source of ionizing radiation at wavelengths shorter than 228 Å must be invoked.

4. CONCLUSIONS

We have obtained high signal-to-noise ratio spectrophotometric observations of I Zw 18, the most metal-deficient BCD known, in an attempt to detect the broad low-intensity emission lines of W-R stars. We have obtained the following results:

1. Broad emission lines at wavelengths of approximately $\lambda$4650 and $\lambda$5800 have been detected in the spectrum of the northwestern component of I Zw 18, implying the presence of WN and WC stars, while in the younger southeast component these lines are absent. Thus, I Zw 18 is the lowest metallicity Wolf-Rayet galaxy known to date.

2. The total numbers of WNl and WC4 stars in I Zw 18 are 17 ± 4 and 5 ± 2, respectively, and the total number of O stars is about 1100. The existence of WC stars at the very low metallicity of $Z_{/50}$ in I Zw 18 confirms predictions of massive stellar evolution models with enhanced mass-loss rates (Meynet 1995), while the models with standard mass-loss rates fail to explain the presence of WC stars in I Zw 18. The observed W-R/O and WC/WN ratios of 0.02 and 0.3, respectively, are in satisfactory agreement with evolutionary population synthesis models based on stellar evolution models with enhanced mass loss and extrapolated to the metallicity of I Zw 18. Although the WC stars detected in I Zw 18 could be responsible for the presence of the strong nebular He II $\lambda$4686 emission line, the observed value of the nebular He II $\lambda$4686, 4% that of H$\beta$, is several times larger than theoretical predictions. We conclude that additional sources of ionizing radiation at wavelengths shorter than 228 Å need to be present.

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