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Hot, Massive Stars in I Zw 18

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Abstract: We present the far-ultraviolet spectrum of the northwest component of I Zw 18, a blue compact galaxy having a very low metallicity. The spectrum is compatible with continuous star-formation over the past ~ 15 Myr (CSF age), and a very low metallicity, $\log Z/Z_{\odot} \sim -1.7$, although the stellar surface may be enhanced in carbon. Stellar winds are very weak, and the edge velocity of wind lines is very low (~ 250 km/s).

1 Introduction

Blue, compact, dwarf galaxies (BCD's) are primitive galaxies: they are low-mass galaxies that have converted only a small fraction of their gas mass into stars; some are only minimally chemically evolved, with oxygen abundances as low as $1/40^{\rm th}$ that of the sun (Thuan 2008). Their blue, compact appearance arises from prominent star-forming regions containing massive stars. BCD's are starting to receive due attention as they are the closest analogues to the $z \geq 7$ galaxies being discovered by the Hubble Space Telescope (e.g. Finkelstein, Papovich, Giavalisco, et al. 2010). The proximity of BCD's allows us to observe them over a wide spectral band, from X-rays to radio wavelengths, and at high spatial resolution; some have even been resolved into individual stars.

One of the most primitive and best studied BCD is I Zw 18. The ionized gas in I Zw 18 has a low oxygen abundance ($O \sim 1/30\ O_{\odot}$) and nitrogen abundance ($N \sim 1/100\ N_{\odot}$) (Pequignot 2008). Metal abundances in the surrounding H I envelope are even lower (Aloisi et al. 2003; Lecavelier des Etangs et al. 2004). HST optical imagery indicates that the two massive star clusters making up the main body of I Zw 18 contain young, massive but apparently normal stars (Hunter & Thronson 1995). Optical spectra of both northwest and southeast clusters revealed the presence of WC stars (Legrand et al. 1997; Izotov et al. 1997), and two WC star-like objects were identified on STIS low-resolution, long-slit UV spectrograms (Brown et al. 2002).

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2 Observations

In April 2010, we obtained a far-UV spectrum of the northwest massive star cluster of I Zw 18 using Hubble's Cosmic Origins Spectrograph (COS). The spectrum covers the wavelength region, $\lambda \sim 1130 - 1760$ Å. As the northwest cluster more or less fills the COS 2.5-arc second aperture, the effective resolving power, $R \sim 3500$, is lower than the nominal (point-source) resolving power of COS. The signal-to-noise ratio of the observed spectrum, S/N=15-30 per 7-pixel resolution element, is on the low side for analysis of weak lines. We plan to obtain longer-exposure spectra later this year. Nevertheless, this S/N and resolution (0.4 Å) of the spectrum in hand are sufficient to identify and measure the major stellar features in the UV spectrum.

Not surprising for a low-metallicity galaxy, the stellar features are weak. To help gain an appreciation of how weak, Figure 1 compares the far-UV spectrum of I Zw 18-NW to that of a single star in the Small Magellanic Cloud, NGC 346-113 (OC6 Vz), a metal-deficient star near the zero-age main

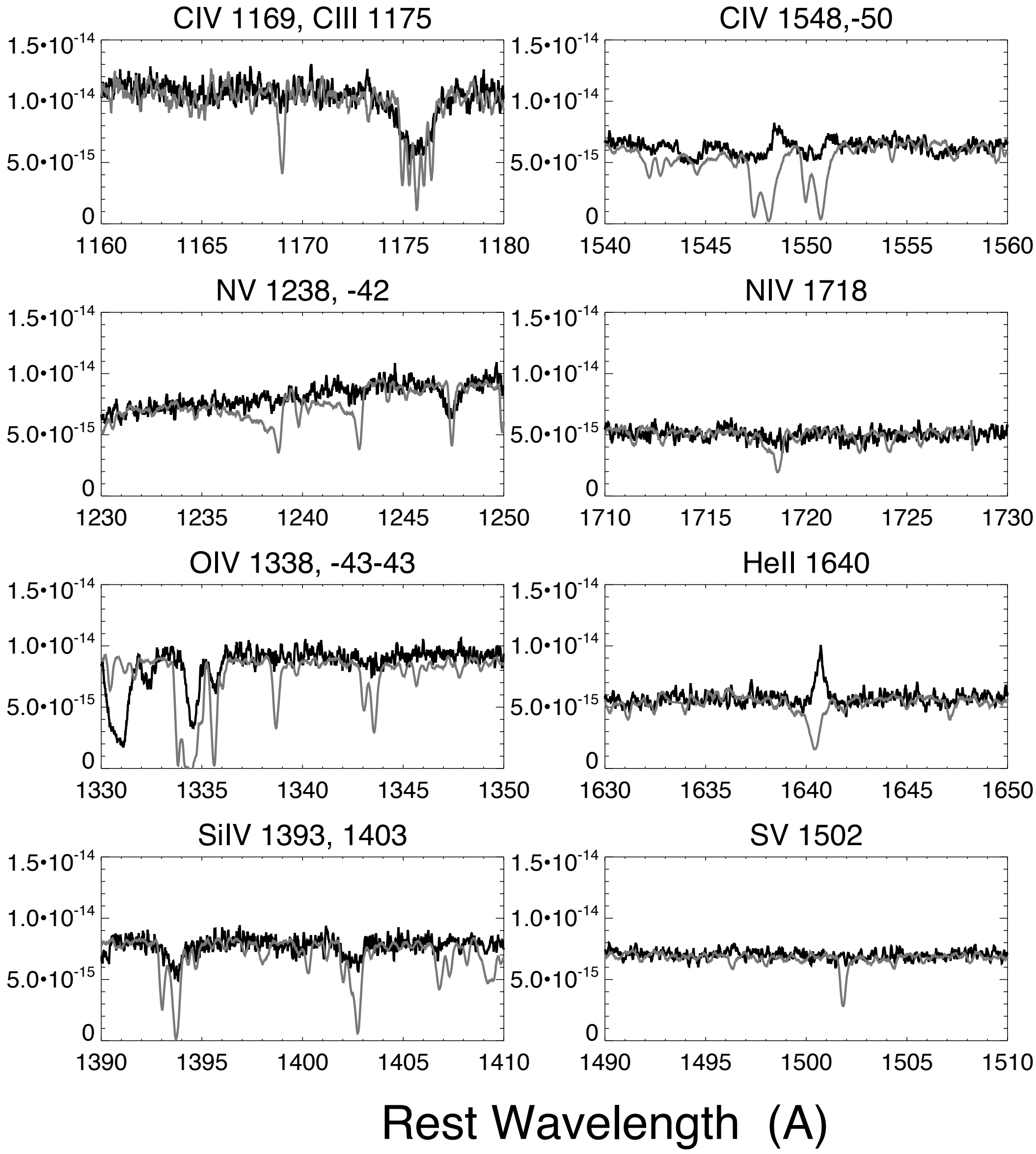

Figure 1: Comparison of the COS spectrum of I Zw 18 (black) with the STIS spectrum of NGC 346-113 (gray) scaled to the flux of I Zw 18 and smoothed to match the resolution of COS.

sequence (Heap, Lanz & Hubeny 2006). In the spectrum of I Zw 18, C III 1175 is moderately strong, the C IV 1549 resonance doublet has a weak P Cygni profile, O IV 1342-3 is present (although too difficult to measure because of the low S/N), and He II 1640 is a strong emission line – all features consistent with a stellar population containing WC stars. Since many of the brighter stars must be O-type stars, it was expected that the N V 1240 doublet and N IV 1718 would also be present, but they are only marginally detected if at all. The Si IV 1400 doublet appears to be purely photospheric rather than having P Cygni profiles, no doubt a consequence of very low metallicity.

3 Observed Properties of the Stellar Population

Figure 2 shows an ultraviolet color-magnitude diagram of stars in the COS aperture derived from HST/STIS images obtained by Brown et al. (2002). Geneva isochrones for $\log Z/Z_{\odot} = -1.7$ (Lejeune & Schaerer 2002) scaled to a distance of 14.1 Mpc are superposed. The CMD indicates a spread in ages, compatible with continuing star formation. The very blue stars brighter than $m_{FUV} = 20$ have masses of 150 $M_{\odot}$ or more. They are likely unresolved binaries or multiple systems. The brightest star-like object has a WC spectrum according to Brown and colleagues. The spectra of the other bright blue stars in I Zw 18 vary widely, especially in the strength of Ly-α absorption; some show unidentified emission lines. One caution: the distance to I Zw 18 is not a settled matter; e.g. Izotov & Thuan (2004) obtain D=14.1 Mpc, while Aloisi et al. (2007) estimate D=18 Mpc. If the longer distance is adopted, the luminosities and masses will be even higher than inferred from Fig. 2.

We have estimated the age and metallicity of I Zw 18-NW from the COS spectrum itself. Fig-

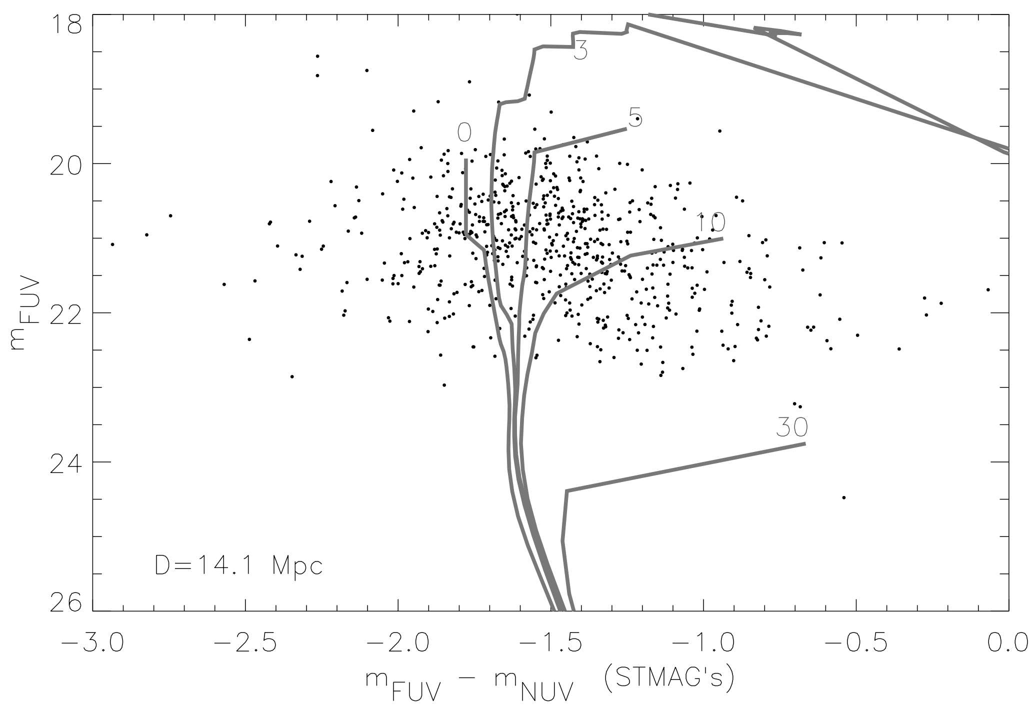

Figure 2: UV color-magnitude diagram of I Zw 18-NW stars in the COS aperture (black dots) and Geneva isochrones for $\log Z/Z_{\odot} = -1.7$, mass range, $M = 0.8 - 150\,M_{\odot}$, and age of continuing star-formation = 0, 3, 5, 10, and 30 Myr, as labeled. The magnitudes and colors were measured by Malumuth et al. (in preparation) via PSF-fitting photometry. Corrections for Galactic extinction, E(B-V)=0.032, have been applied.

ure 3 compares the observed spectrum of I Zw 18-NW to a spectral population synthesis model of stars having formed over the past 15 Myr (CSFR=0.055 $M_{\odot}$/yr) and with a scaled-solar metallicity, $\log Z/Z_{\odot} = -1.7$. The stellar population synthesis models are based on NLTE photospheric spectral models of Lanz & Hubeny (2003, 2007) and Geneva evolutionary tracks (Lejeune & Schaerer 2002). The main age/metallicity diagnostics are C IV 1169 and C III 1175. (The nitrogen lines are too weak to be measurable and clearly have a very low abundance, the Si IV 1400 doublet does not vary significantly in the age/metallicity range of interest, and the C IV 1549 doublet, and He II 1640 emission are formed at least partially in the wind, where the photospheric models are invalid.) The closest agreement (least disagreement) between model and observation is at an age∼15 Myr, and a metallicity, $\log Z/Z_{\odot} = -1.7$ (the lowest metallicity in the Geneva grid of evolutionary tracks). At a younger age, e.g. 3 Myr, C IV 1169 and O IV 1342-43 are too strong, while C III 1175 is too weak. At an older age, e.g. 30 Myr, the C IV and O IV lines are too weak. At a higher metallicity, e.g.

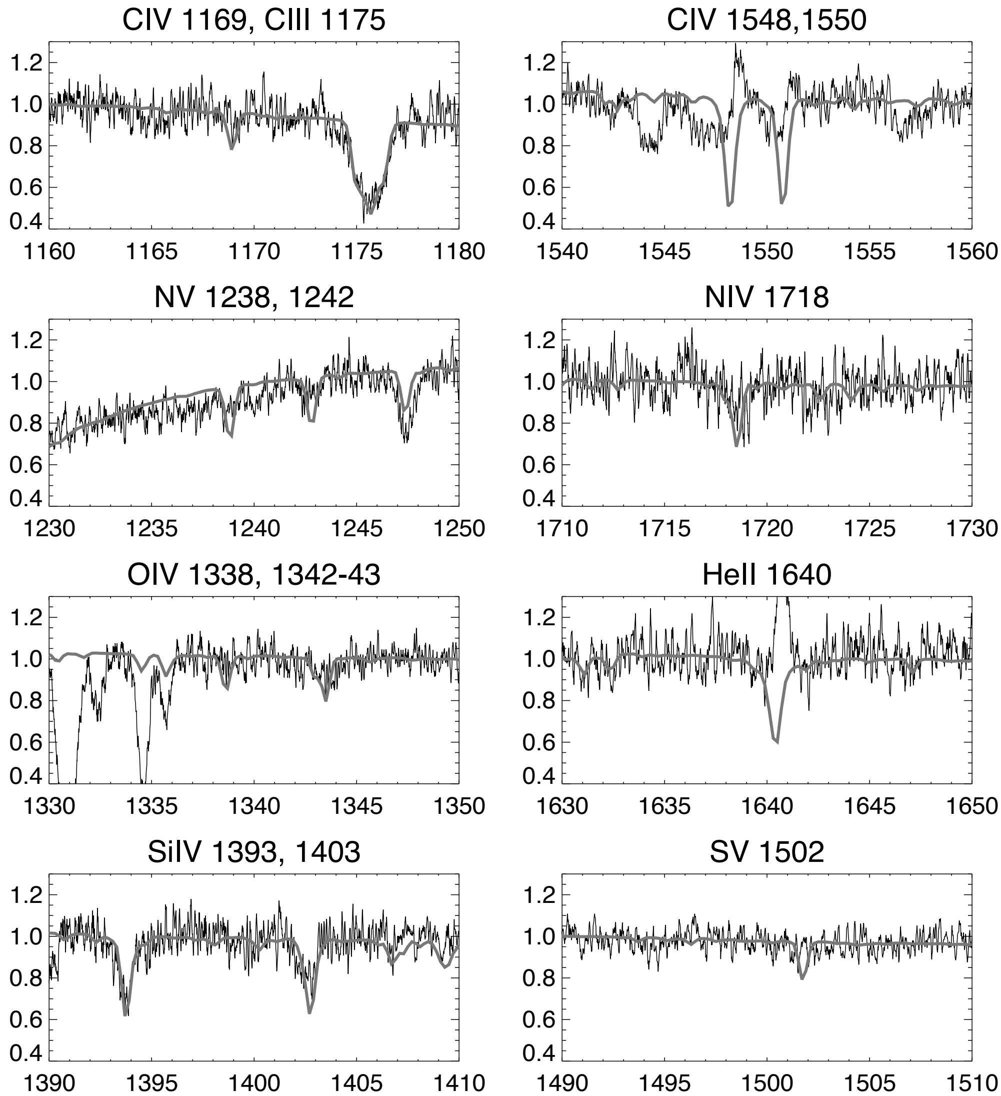

Figure 3: Comparison of the COS spectrum of I Zw 18 (black) with NLTE model photospheric spectrum (gray) of a stellar population with a continuing star-formation age=15 Myr and a scaled-solar metallicity, $\log Z/Z_{\odot} = -1.7$.

$\log Z/Z_{\odot} = -1.3$ of the evolutionary model, all the diagnostic C and O lines in the model are too strong. For comparison, a CSF age, $\sim 15-27$ Myr, was derived by Martin (1996) from dynamical considerations.

4 Star Formation and Evolution at Very Low Metallicity

Perhaps the massive stars in I Zw 18-NW are not as normal as originally thought –"normal" being stars like massive stars in the Galaxy except in having a lower metal content than galactic stars and thus, weaker winds. Symptoms of abnormality – more probably, symptoms of our lack of understanding of star formation and evolution at very low metallicity – include the following issues.

Abundances. Studies of galactic halo stars (i.e. low mass, low metallicity) (Bonifacio et al. 2009, Fabbian et al. 2009) find that [C/O] first decreases with decreasing oxygen abundance but then rises when [O/H] ≤ -1. This upturn in [C/O] at very low metallicity is interpreted as due to the contribution of carbon in the winds of WR stars. The stellar [C/O] in I Zw 18-NW is consistent within the observational errors with this interpretation.

Nitrogen is synthesized in the CNO cycle operating in H-burning layers of the stellar interior. Nitrogen is said to be "primary" or "secondary" in origin depending on whether the seed C and O are synthesized in the star during helium burning, or were present in the material from which the star formed. Primary N is thought to be produced mainly by intermediate-mass stars ($M/M_{\odot} = 4-7$) on the asymptotic giant branch and is released back to the ISM only after about 250 Myr (Henry, Edmunds & Köppen 2000), well after O was ejected in Type II supernova explosions. But if massive stars are also major contributors of nitrogen, then there would be no time lag between the release of O and N. The low stellar N/O ratio in I Zw 18 favors intermediate-mass stars as the main source of N and a young age of the current star-formation episode.

Stellar Winds at Low Metallicity. The C IV 1549 wind feature has a surprisingly low edge velocity, $v_{edge} \sim 250$ km/sec, compared to predictions ($v_{\infty} \sim 1050$ km/sec) based on the relation, $v_{\infty} \propto Z^{0.13}$ (Leitherer, Robert & Drissen 1992; Vink, de Koter & Lamers 2001). Why is it so low? One possibility is that the density of C^{3+} ions is so low that the observed absorption comes from the denser base of the wind where the velocity is much lower than the terminal velocity. A second possibility is that the dependence of the terminal velocity on metallicity is much steeper than usually assumed,. A third possibility, the one we favor, is that the most massive stars producing the bulk of the C IV 1549 wind feature are close binaries, in which the wind of one star is affected by "radiative braking" by a close companion (Owocki 2007).

Crowther & Hadfield (2006) were the first to investigate the spectral properties of Wolf-Rayet stars at low metallicities, and they made specific predictions about the population of WC stars in I Zw 18. They pointed out that the luminosities of WR emission lines should be lower in low-metallicity stars, in qualitative agreement with the weak C IV 1548, 1550 and He II 1640 emission observed in I Zw 18. The lower line luminosities mean that it will take a higher number of WC stars (they estimate at least 30) to match the observed strengths of wind lines. Detailed modeling will be needed to reproduce the observed spectrum of I Zw 18-NW accounting for all contributors – O and B-type stars as well as WR stars.

Rotation-enhanced mass-loss vs. mass transfer in close binaries. Wolf-Rayet stars are the stellar cores of massive stars whose H-rich envelopes have been removed either by strong stellar winds or by mass transfer in close binaries. Not long ago, it was thought that single stars of low metallicity could not enter the WR phase of evolution, because radiatively-driven mass-loss in the lines would be too low to remove the H-rich outer layers characteristic of O-type stars. Then in 2005, Meynet & Maeder showed that when rotation is included in evolutionary models, massive, low-metallicity stars such as those in the SMC can indeed have a WR phase. Rotation favors the WR phenomenon by lowering the mass limit for entry into the WR phase and lengthening the WR phase. It appears, however, that rotation cannot explain the presence of only WC stars in I Zw 18-NW, because the computed lifetime in the WC phase is always shorter than in the WN phase, so I Zw 18-NW should show both WN and WC characteristics, in contradiction to the observations.

WR stars can also be formed via mass transfer through Roche Lobe Overflow in close binaries. To our knowledge, the binary hypothesis has not yet been developed and applied to very massive ($M/M_{\odot} > 60$), very low-metallicity stars such as those in I Zw 18 but is well deserving of future study. Not only could mass transfer in close binaries explain the presence of WC stars in I Zw 18, but it might also help to understand the low apparent terminal velocity inferred from the C IV 1549 resonance doublet through the mechanism of radiative inhibition.

Acknowledgements

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