The Lives and Death-Throes of Massive Stars
Proceedings IAU Symposium No. 329, 2016
J.J. Eldridge, J.C. Bray, L.A.S. McClelland & L. Xiao, eds.

doi:10.1017/S1743921317003489

II Zw 40 – 30 Doradus on Steroids

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Abstract. We obtained HST COS G140L spectra of the enigmatic nearby blue compact dwarf galaxy II Zw 40. The galaxy hosts a nuclear super star cluster embedded in a radio-bright nebula, similar to those observed in the related blue compact dwarfs NGC 5253 and Henize 2-10. The ultraviolet spectrum of II Zw 40 is exceptional in terms of the strength of He II 1640, O III] 1666 and C III] 1909. We determined reddening, age, and the cluster mass from the ultraviolet data. The super nebula and the ionizing cluster exceed the ionizing luminosity and stellar mass of the local benchmark 30 Doradus by an order of magnitude. Comparison with stellar evolution models accounting for rotation reveals serious short-comings: these models do not account for the presence of Wolf-Rayet-like stars at young ages observed in II Zw 40. Photoionization modeling is used to probe the origin of the nebular lines and determine gas phase abundances. C/O is solar, in agreement with the result of the stellar-wind modeling.

Keywords. galaxies: dwarf, galaxies: starburst, galaxies: stellar content

1. Introduction

II Zw 40 (= UGCA 116), together with I Zw 18, is the founding member of the class of blue compact dwarf (BCD) galaxies. This class was originally defined by Sargent (1970) and Sargent & Searle (1970) who demonstrated that the optical spectra of these galaxies are indistinguishable from those of extragalactic H II regions. BCDs and related dwarf starbursts have since been recognized as objects that are characterized by their blue optical colors, small sizes (< 1 kpc), and low luminosities of $M_{\rm B} > -18$ (Gil de Paz & Madore 2005). These galaxies do not typically show signs of AGN activity but have strongly enhanced star formation in a relatively pristine chemical environment. Owing to these properties, BCDs have been proposed as nearby analogs of star formation in young galaxies at high redshift (Thuan 2008). Among BCDs are some of the most metal-poor star-forming galaxies detected in the universe (Kunth & Östlin 2000). These properties make BCDs preferred targets for observations in the ultraviolet (UV) where they are generally bright due to their blue colors. II Zw 40 is one of the few exceptions, which lacked UV spectra despite its remarkable properties due to its high Galactic foreground reddening (see below).

Super star clusters are an important mode of star formation in starbursts (Meurer *et al.* 1995). II Zw 40's morphology is dominated by a central super star cluster, which is the powering source of a radio-infrared super nebula (Beck *et al.* 2013, Kepley *et al.* 2014). The radio super nebula requires a powering ionizing photon output of $\sim 10^{52.7}$ s^{-1}, which makes this region 10 times as luminous as 30 Doradus, the most luminous giant H II region in the Local Group. Radio super nebulae have also been detected in the BCDs

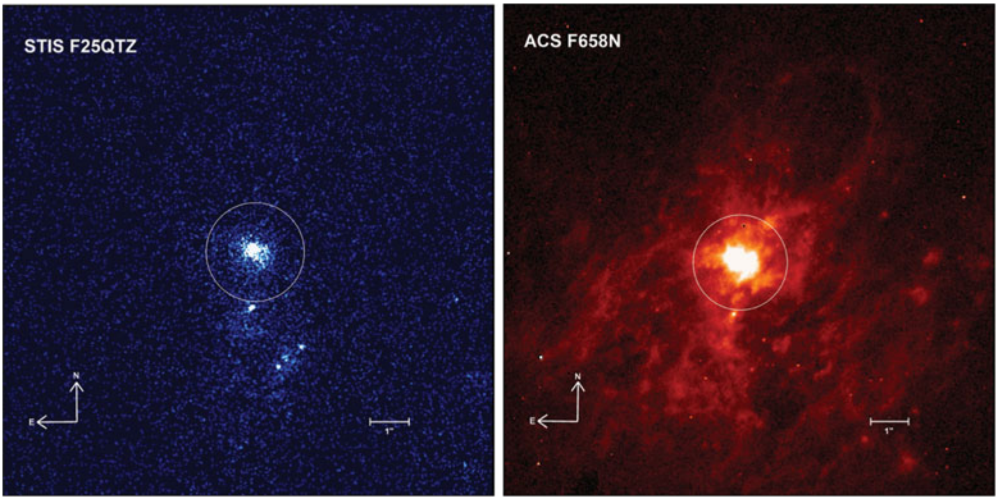

Figure 1. STIS F25QTZ (left) and ACS F658N (right) images of the super nebula. F25QTZ is centered on $\lambda \approx 1600$ Å, and F658N encompasses Hα. The circle indicates the location of the COS aperture, which covers a physical area of 135 pc diameter.

NGC 5253 and Henize 2-10 (Beck 2015). They are thought to be the earliest phases in the evolution of super star clusters, suggesting a very young age for the cluster.

2. New Data

We obtained UV spectra of the super nebula and its ionizing cluster with HST's COS using the G140L grating. The spectra cover the wavelength range 1150 - 2000 Å and have a spectral resolution of about 0.5 Å. The ionizing stars are concentrated in one super star cluster, which is essentially a single point source in the UV (see Fig. 1, left). In contrast, the optical Hα image (Fig. 1, right) shows nebular emission which is more extended inside the COS aperture, as well as diffuse emission over hundreds of parsecs. The super nebula is at the core of the galaxy whose extended (several kpc) tidal tails indicate previous interaction and merging of two dwarf galaxies (Kepley *et al.* 2014).

The processed spectrum is reproduced in Fig. 2. No reddening or redshift correction has been applied. Owing to its location close to the Galactic plane ($b = 10.8°$), II Zw 40 has a high foreground reddening of $E(B-V) = 0.73$. Despite the high dust attenuation the COS spectrum permits useful constraints on the ionizing cluster and the super nebula. Apart from the geocoronal Lyman-α 1216 and O I 1300 emission lines, the spectrum shows, among others, stellar N V 1240, C IV 1550, He II 1640 as well as nebular O III] 1666 and C III] 1909.

3. Results

We compared the observed UV spectrum of the super nebula and its ionizing cluster to synthetic spectra generated with the population synthesis code Starburst99 (Leitherer *et al.* 2014). We adopted metal-poor ($Z = 1/7^{th}$ $Z_\odot$) stellar evolution models with rotation (Ekström *et al.* 2012, Georgy *et al.* 2013), a Kroupa (Kroupa 2008) initial mass function (IMF), a single stellar cluster, and a distance of 11.1 Mpc (Marlowe *et al.* 1997). Comparison of the spectral slope, luminosity and stellar spectral lines provides the intrinsic reddening, cluster mass, and age, respectively. The best-fit model (see Fig. 3)

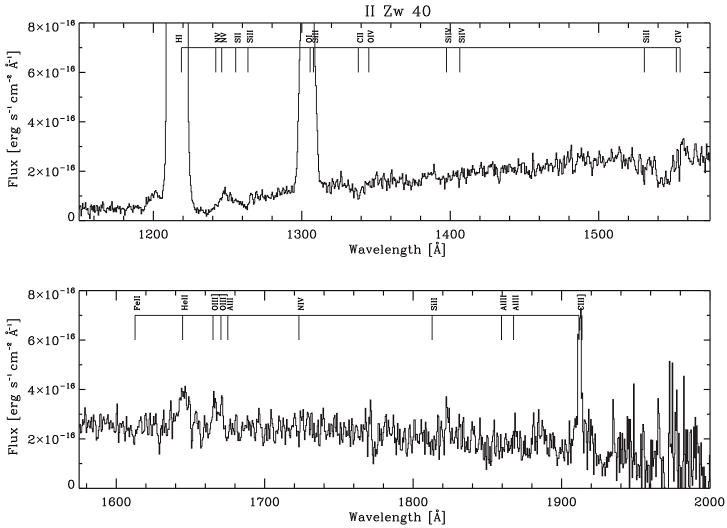

Figure 2. COS G140L spectrum of the super nebula and its ionizing star cluster with line identifications given at the top.

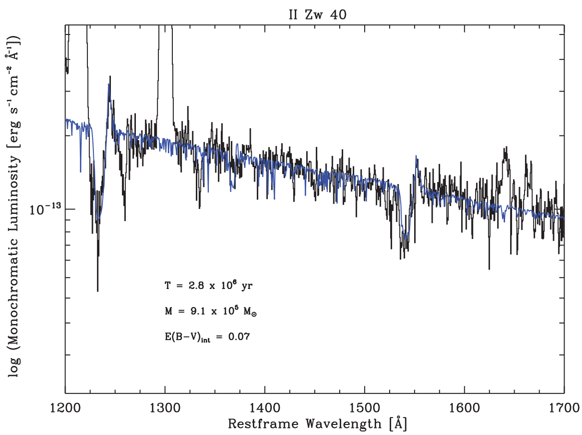

Figure 3. Restframe UV spectrum of the super nebula corrected for foreground and intrinsic reddening (black) compared to a model spectrum of a star cluster with parameters listed (blue).

corresponds to a stellar cluster with intrinsic reddening $E(B-V) = 0.07$, a mass of 9.1×10^5 $M_\odot$, and an age of 2.8×10^6 yr. The young age is constrained mainly by the strength of N V 1240 and the absence of Si IV 1400. This age is consistent with the upper limit derived in the radio from the strength of the free-free and the weakness of the synchrotron emission, suggesting few core-collapse supernovae (Kepley *et al.* 2014).

The Starburst99 models can be used to predict the ionizing luminosity from an extrapolation of the best-fit UV spectrum to below 912 Å. This leads to log $N_{\rm L} = 52.8$ s^{-1}, in excellent agreement with the reddening-independent value derived from the radio free-free luminosity by Kepley *et al.* (2014). The ionizing luminosity and the stellar mass of the super star cluster exceed the values determined for the proto-typical local giant H II region 30 Doradus and its ionizing cluster NGC 2070 by an order of magnitude. The mass is similar to the masses of the most massive Galactic globular clusters (Gnedin & Ostriker 1997) and the super star clusters in the Antennae galaxies (Whitmore *et al.* 2010).

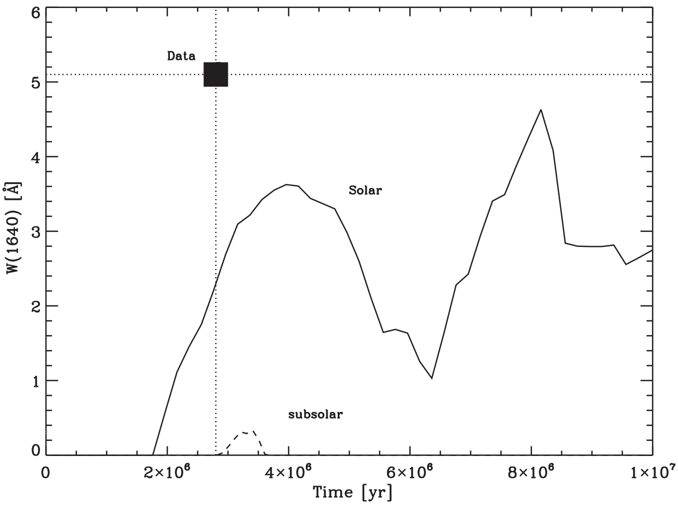

Figure 4. Stellar He II 1640 equivalent width for solar (solid) and $1/7^{th}$ solar (dashed) chemical composition predicted by evolution models with rotation. The filled square is the measured value.

It also approaches the masses of the most massive molecular clouds in the prototypical starburst galaxy M82 (Keto *et al.* 2005).

The synthetic and the observed stellar lines agree rather well in Fig. 3, with the notable exception of the broad He II 1640. This line has traditionally been associated with Wolf-Rayet (W-R) stars (Conti 1991), the late stages of massive-star evolution. Our models do not predict significant numbers of W-R stars due to the young age of the cluster so that the line is absent in the models. This is further illustrated in Fig. 4 where we compare the measured equivalent width to model predictions of rotating evolution models at solar and sub-solar chemical composition. Metal-rich populations barely reach the observed value, but only at older ages. Metal-poor populations do not produce significant He II 1640 at any age. The stars responsible for the observed He II 1640 are not accounted for in these models.

The strongest nebular line in the UV spectrum of II Zw 40 is C III] 1909 with an equivalent width of 9.5 Å. This is among the highest values observed in local star-forming galaxies and comparable to observations at high redshift (Rigby *et al.* 2015). The O III] 1666 has an equivalent width of about 3 Å, corrected for the underlying interstellar Al II 1670 absorption. Lyman-α is not observable in II Zw 40 due to its low velocity of 789 km s^{-1} and the corresponding geocoronal and Galactic contamination. Comparison of the observed C III] 1909 and O III] 1666 line strengths with photo-ionization models of Gutkin *et al.* (2016) suggests a very high ionization parameter and a near-solar C/O ratio of 0.4. This is consistent with the result of the stellar-wind modeling, where we obtained an excellent fit to C IV 1550 with solar C/O. II Zw 40's location in the C/O versus O/H diagram (Esteban *et al.* 2014) agrees with that of other dwarf galaxies, in which carbon is a primary element.

4. Implications

Our UV data nicely complement existing studies in the optical, infrared, and radio. The derived mass of the stellar cluster is of order 10^6 $M_\odot$, which approaches the maximum masses observed in young and old stellar clusters. It is also comparable to the mass of the most massive individual molecular clouds in starburst galaxies like M82, where dynamical shear is believed to set the upper mass limit. The spectrum of the super star cluster in II Zw 40 can be reproduced by a standard Kroupa-type IMF, which is essentially a Salpeter IMF in the mass range sampled. Our models include stellar masses up to 120 $M_\odot$. From analyses of individual stars, Crowther *et al.* 2016 find evidence of the initial mass function in NGC 2070 extending up to 300 $M_\odot$. Similarly, Smith *et al.* (2016) suggest the presence of massive stars with masses well above 100 $M_\odot$ in the nearby dwarf galaxy NGC 5253. In the absence of tracks for extremely massive stars in the evolution models available to us, we cannot test this suggestion in II Zw 40. However, we do find shortcomings in the existing evolution models. The UV spectrum of the super star cluster in II Zw 40 shows strong broad He II 1640 in emission. This line is most likely produced by hot, He-rich stars with strong mass loss. Such stars are commonly interpreted as "classical" W-R stars, yet they are not expected in large numbers at the young age of the cluster. Most likely, the emission is generated in the winds of very massive, mass losing core-hydrogen burning stars close to the main sequence. This stellar phase is not (yet) accounted for in the evolution models.

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