Massive Stars Near and Far
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Dissecting the very metal-poor galaxy SBS0335-052E with MUSE: massive stars vs. nebular HeII emission

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Abstract. Nebular HeII emission implies the presence of energetic photons (E⩾54 eV). Despite the great deal of effort dedicated to understanding HeII ionization, its origin has remained mysterious, particularly in metal-deficient star-forming galaxies. Unfolding HeII-emitting, metal-poor starbursts at z∼0 can yield insight into the powerful ionization processes occurring in the primordial universe. Here we present a study on the origin of the extended nebular HeII emission in SBS 0335-052E, one of the most metal-poor ($Z \sim 3\%\ Z_\odot$) HeII-emitter starbursts known locally. Based on optical VLT/MUSE spectroscopic and Chandra X-ray observations, and current stellar models we found that the HeII-ionization budget of SBS 0335-052E can only be produced by peculiar, nearly metal-free ionizing stars (called here "PopIII-like" stars) with a top-heavy initial mass function. This result is in line with recent simulations for PopIII star formation down to z=0.

Keywords. galaxies: individual: SBS 0335-052E, galaxies: starburst, galaxies: dwarf, galaxies: ISM, galaxies: stellar content

1. Motivation

The presence of nebular HeII emission points to the existence of a hard radiation field as photon energies ⩾ 54 eV are necessary to ionize He^+. Highly ionized systems, like HeII emitters, are observed to be more frequent at high-z than locally (e.g., Kehrig et al. 2011; Cassata et al. 2013; Mainali et al. 2018). At the same time, observations of local, HeII-emitting star-forming (SF) galaxies suggest that the lower the metallicity (Z), the larger the nebular HeII line intensities (e.g., Senchyna et al. 2017). This is in line with the harder ionizing stellar spectra predicted at the lower metallicities typical in the early universe (e.g., Tumlinson & Shull 2000); the hard spectra from the first, hot Population III (PopIII) and nearly Z=0 stars can produce strong nebular HeII lines (e.g., Yoon et al. 2012; Nakajima & Maiolino 2022). Still, despite much observational and theoretical effort, including relevant advances in stellar modeling, the source of HeII ionization remains puzzling, especially in metal-poor SF galaxies (e.g., Kehrig et al. 2015a; Götberg et al. 2018; Stanway & Eldridge 2019; Pérez-Montero et al. 2020; Telford et al. 2021; Kehrig et al. 2021). Ultimately our understanding of metal-poor, hot massive

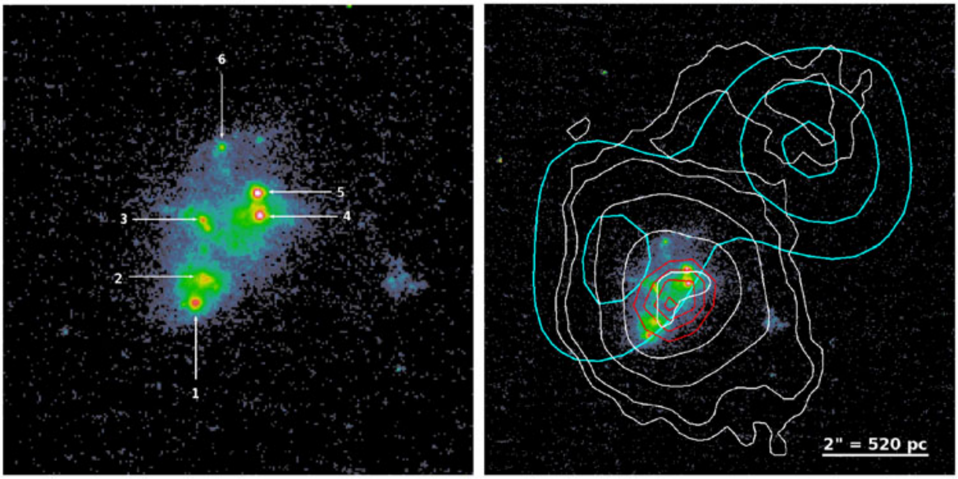

Figure 1. Left panel: HST ACS/F220W archival image of SBS 0335-052E (PI: G.Östlin). The brightest SSCs are labeled. The image is 6" × 6". Right panel: Soft (cyan lines) and hard (red lines) X-ray contours overlaid on the HST ACS/F220W image of SBS 0335-052E. The white curves represent the isocontours of the HeIIλ4686 emission line flux (see Fig. 2). In both panels, north is up and east is to the left (Figures taken from K18).

stars remains elusive which propagates to a lack of understanding of the formation of high-ionization lines as HeII.

The HeII line is also in comfortable reach of new and next generation telescopes (e.g., *JWST, ELT*) which will detect the rest-frame UV of many of galaxies during the epoch of reionization (e.g., Puech et al. 2018). Therefore detailed studies on the origin of nebular HeII at low redshifts are required to better interpret far-away high-ionizing emitters. Low metallicity, HeII-emitters at z ∼ 0 provide useful constraints on the little-known SEDs of metal-poor, hot massive stars, and are unique systems in which to test stellar population synthesis models at sub-SMC metallicities and gain a deeper understanding of the reionization era (see e.g., Kehrig et al. 2008, 2013, 2015a, 2015b; Senchyna et al. 2020; Telford et al. 2021).

In Kehrig et al. 2018 (hereafter K18) we combine *Multi-Unit Spectroscopic Explorer* (MUSE)/VLT optical integral field spectroscopy data (spectral resolving power is R = $\lambda/\delta\lambda = 2988$) with X-ray Chandra observations of SBS 0335-052E to obtain a new view on the origin of the nebular HeII excitation in this galaxy. SBS 0335-052E is among the most metal-poor (12+log(O/H)= 7.11 ∼ 3% $Z_\odot$; e.g., Papaderos et al. 2006) HeII-emitting SF galaxies known at z ∼ 0. It thus represents a nearby analog of distant metal-poor HeII emitters, providing a unique laboratory to study the high-ionization phenomenon expected to be common at z > 6. The left-panel of Fig. 1 shows the *HST/ACS* UV image of SBS 0335-052E where we can see its six brightest super-star clusters (SSCs) distributed over a region of ∼ 2 arcsec (∼ 520 pc at the distance of 54 Mpc). Below we summarize the main results from K18.

2. What is ionizing nebular HeIIλ4686 in SBS 0335-052E ?

Based on the MUSE data we find a highly extended HeIIλ4686-emitting region which consists of a roundish oval shape component with a diameter of ∼ 5 arcsec (∼ 1.3 kpc at the distance of 54 Mpc) over the galaxy core, and a shell-like structure (called here "HeII shell") which are connected to each other. The HeII-emitting zone extends out

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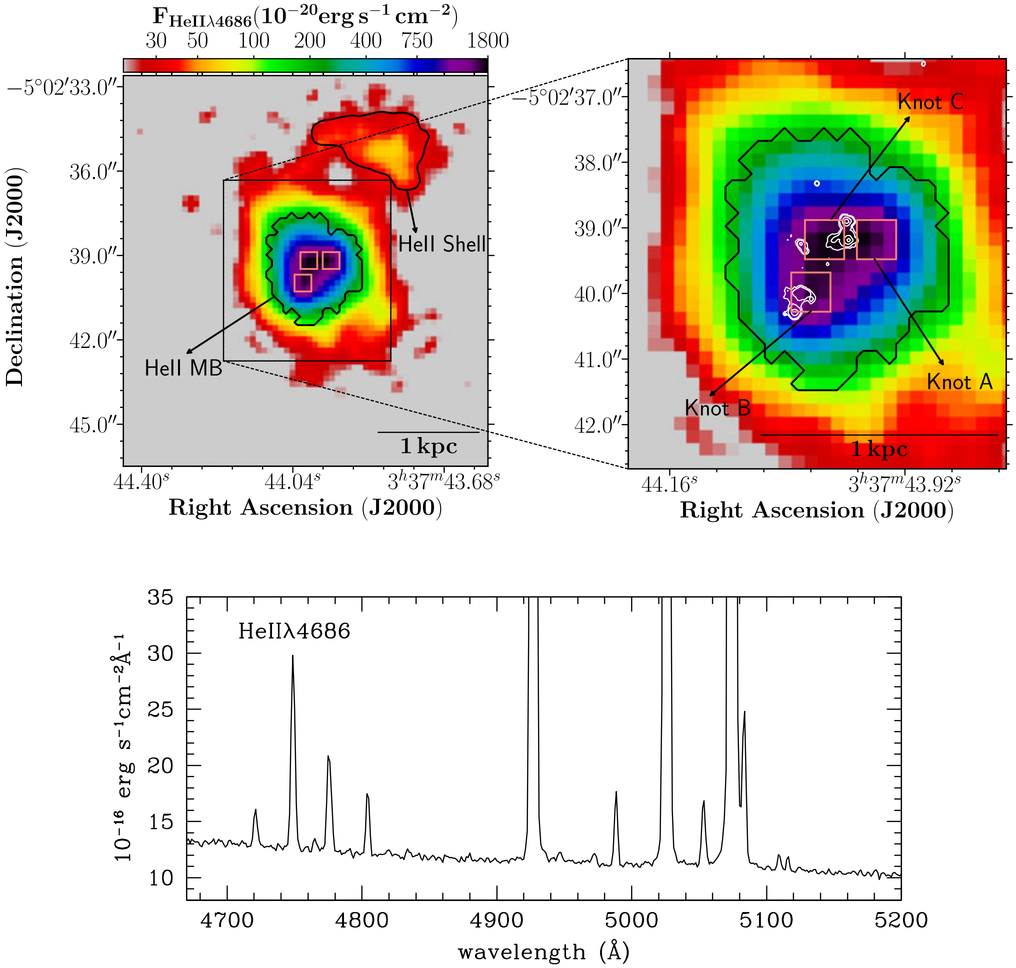

Figure 2. Top panel: The HeIIλ4686 flux map in two different scales showing the boundaries of the areas that we use to create the 1D spectra of several HeII-emitting regions, and the integrated spectrum of SBS 0335-052E (see K18 for details); the pink boxes are centered on the three HeII-emitting peaks; in the top-right panel the white lines mark the location of the brightest SSCs of SBS 0335-052E. Bottom panel: A zoom-in of the integrated spectrum of SBS 0335-052E over $\sim$ 4670-5200 Å(Figures taken from K18)

to distances $\gtrsim$ 6 arcsec ($\sim$ 1.5 kpc) from the youngest SSCs, and presents three peaks spatially displaced from the brightest stellar clusters (see top panels in Fig. 2)

We checked that the FWHM of the HeIIλ4686 line is comparable to that of the other nebular emission lines (e.g., Hβ, [OIII]λ5007). The values of the mean (μ) and standard deviation (σ) for the FWHM(HeII)/FWHM(Hβ) and FWHM(HeII)/ FWHM([OIII]λ5007) ratios are $\mu = 1.13$ ($\sigma = 0.09$) and $\mu = 1.10$ ($\sigma = 0.10$), respectively. The narrow line profile for the HeIIλ4686 emission and its spatial extent are evidence of its nebular nature.

We took benefit of our IFU data to create for the first time the integrated spectrum of SBS 0335-052E by adding the nebular emission across our MUSE FOV ($\sim$ 340 arcsec^2 $\sim$ 23 kpc^2; see bottom-panel in Fig. 2). Using this spectrum we recovered the entire nebular HeII emission and compute the corresponding total HeII-ionization budget, Q(HeII)$_{int}$ $\approx$ 3.17×10^{51} photon s^{-1}. As we showed in e.g., Kehrig et al. 2015a, 2020, this observational

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quantity is essential to perform a free-aperture investigation on the formation of the narrow HeII line.

In the righ-panel of Fig. 1 we show the Chandra X-ray emission from the different sources found in SBS 0335-052E. From our analysis of the combined MUSE and Chandra data, we infer that the Q(HeII) provided by the X-ray (soft and hard) emission from SBS 0335-052E is well below the needed value to ionize He^+ at the level measured in this galaxy.

Although we cannot discard some contribution to the HeII excitation from shocks, our MUSE IFU data favors hot massive stars as the main agent of the HeII ionization in SBS 0335-052E. The optical diagnostic diagrams shown in Fig. 3 indicate that for all positions in SBS 0335-052E our emission-line ratios fall in the general locus of SF objects according to the spectral classification scheme from Kewley et al. 2001. Accordingly, photoionization from hot massive stars seems to be the dominant excitation mechanism within SBS 0335-052E, regardless of the locus in the galaxy. Also, we find no sign of significant [SII]/Hα and/or [OI]λ6300/Hα enhancement (a frequent indication of shock-excited gas; e.g., Allen et al. 2008) associated with the HeII-emitting region (see top panels in Fig. 3). In particular, there is no [OI]λ6300 emission with S/N $\geq$ 5 at the location of the HeII shell whose filamentary structure could suggest an important shock excitation; the HeII shell also shows low values of [SII]/Hα associated with (see Fig. 3). These observational facts reinforce that the nebular HeII in SBS 0335-052E is mainly due to stellar sources. Next, we explore the hot massive star scenario.

To investigate the stellar source scenario we compare observations with stellar models applying two approaches. A more simple one which makes use of models of single massive stars on a star-by-star basis gives us the following. The star-by-star study points out that Wolf-Rayet stars (WRs) solely cannot explain the HeII-ionizing energy budget derived for SBS 0335-052E. From models for fast-rotating Z=0 stars (Yoon et al. 2012), used here as an approximation for the HeII ionizing output of nearly metal-free stars, we found that $\sim$ 230 stars with mass M_{ini} = 150 $M_{\odot}$ (with Q(HeII) $\approx 1.42 \times 10^{49}$ photon s^{-1} each) would be sufficient to account for the observed $Q(HeII)_{Int}$. Additionally, the ionizing spectra produced by these star models are hard enough to explain the highest He IIλ4686/Hβ values observed, assuming that ionization-bounded conditions are met.

Our second approach is based on the stellar population synthesis BPASSv2.1 (Eldridge et al. 2017). The outcomes from the BPASSv2.1 code indicate that while calling upon very massive stars (M >100 $M_{\odot}$) is not essential, a binary population with a 'top-heavy' IMF seem to be required to clear up the observed HeII flux budget. More interestingly, according to BPASSv2.1 models, stars with metallicity (Z = 0.05 % solar) much lower than that of the ionized gas (Z $\sim$ 3 % solar) of SBS 0335-052E are to be invoked to explain the HeII ionization in this galaxy. In this hypothetical scenario, such nearly metal-free stars could not belong to the same SSCs which host more chemically evolved objects. Also, caution should be exercised when evaluating the Z = 10^{-5} and 10^{-4} models; empirical data for stellar atmospheres at these low Z are not available.

Despite its nature as an entirely hypothetical scenario, both approaches suggest that (nearly) Z=0 stars (PopIII-like) are required to produce the total HeII ionizing photon flux. We highlight that similar results have been found to explain the HeII ionization in other nearby, metal-poor SF galaxies (see Kehrig et al. 2015a; Kehrig et al. 2015b; Kehrig et al. 2016; Senchyna et al. 2017).

3. Conclusions

Cosmic dawn marks a phase transition of the universe during which PoIII stars and their hosts put an end to the dark ages. The nature of these first sources is highly unconstrained (e.g., Schneider et al. 2002; Liu & Bromm 2020). The hard spectra of

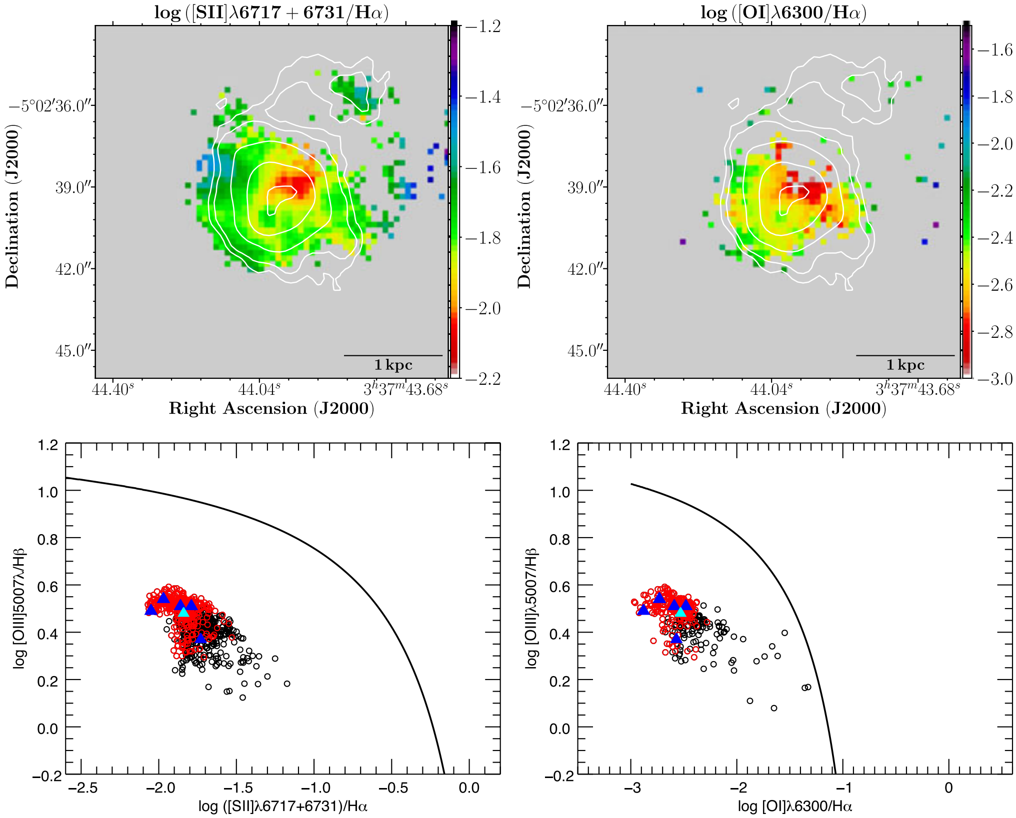

Figure 3. Top row: maps of the line ratios [SII]/Hα and [OI]/Hα. Only line fluxes with S/N (per pixel) > 5 are plotted. All maps are presented in logarithmic scale. Isocontours of the HeIIλ4686 emission line flux are shown overplotted for reference. East is left and North is up. Bottom row: diagnostic diagrams: log ([OIII]/Hβ) vs. log ([SII]/Hα) and log ([OIII]/Hβ) vs. log ([OI]/Hα). Open circles correspond to individual spaxels from MUSE; red circles mark the individual HeII-emitting spaxels. Overlaid as triangles are the line ratios measured from the 1D spectra of selected galaxy regions; the solid curve is the maximum starburst model from Kewley et al. 2001 that isolate purely SF objects (below and to the left of the curve) from those where some other source of ionization rather than hot massive stars is required.

PopIII and nearly Z=0 stars can produce intense HeII emission. However, the origin of nebular HeII emission in metal-poor star-forming galaxies, near and far, is still unclear (e.g., Kehrig et al. 2015a; Saxena et al. 2017).

Metal-deficient HeII-emitting systems nearby are ideal to constrain the physics of hot, metal-poor ($Z < Z_{SMC}$) massive stars and so the sources responsible for the Universe reionization, a major scientific objective of most of future facilities (e.g., ELT-MOSAIC, SKA). We have shown that IFU observations of such metal-poor HeII-emitters at z∼0 provide extended empirical insight into the gas conditions and stars which support high-ionization emission (see Kehrig et al. 2008, 2013, 2015a, 2016, 2018, 2021)

In K18 we used MUSE IFU and Chandra observations to investigate the nebular HeII emission in the extremely metal-poor galaxy SBS 0335-052E found at ∼ 54 Mpc. We demonstrated that conventional HeII-ionizing sources (WRs, shocks, X-ray photons) are not sufficient to explain the observed HeII emission in this galaxy. From present models we found that nearly metal-free ($Z{\sim}10^{-5}$) hot stars ("PopIII-like" stars) and a top-heavy

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IMF are required to reproduce the HeII-ionizing energy budget derived for SBS 0335-052E; Z$\sim10^{-5}$ is slightly larger than the predicted critical metallicity (Z$\sim10^{-4}$ solar) for IMF (and PopIII/PopII) transition (e.g., Schneider et al. 2002). We also want to note that recent theoretical studies predict that pockets of pristine gas may survive in weakly enriched ISM (Z$\sim10^{-5}$ - 10^{-4}) allowing PopIII star formation down to z=0 (see Liu & Bromm 2020).

The possibility remains that narrow HeII in metal-deficient galaxies is indeed powered by "PopIII-like stars", although HeII ionization keeps challenging current stellar models at the low Z regime (e.g., Kehrig et al. 2015a, 2015b, 2018).

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Discussion

DE MINK: Do you think that X-ray binaries can play a role ?

KEHRIG: No, not really. For SBS 0335-052E we extracted its X-ray spectrum based on the spatial distribution of the hard X-ray emission and then we convolved the best fitting model with the energy dependent cross-section of He^{+} to obtain the effective number of He^{+}-ionizing photons, and we got a number which is much lower than the observed one.

DE MINK: Is it possible that X-ray binaries deeply embedded from which we do not see the X-rays directly contribute to the HeII ionization?

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KEHRIG: I do not think this is a possibility if you consider the large area over which nebular HeII emission is observed.

CROWTHER: We have a clear metallicity from oxygen from the HII regions, but how about iron ? Of course it is difficult to measure iron abundance but is there any contrain on the stellar metallicity based on iron abundance ?

KEHRIG: I am not sure about Fe abundance measurements for SBS 0335-052E but what I can tell you is that the metallicity measurements for the gas and stars are similar in this galaxy.