Exploring $\text{He}^\text{II} \lambda 1640$ emission line properties at $z = 2 - 4$

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Abstract. He$^\text{II}$ is the most sought-after emission line to detect and characterize metal free stellar populations. However, current stellar population/photo-ionization models lack sufficient He$^+$ ionising photons to reproduce observed He$^\text{II}$ fluxes while being consistent with other emission lines. Using $\sim 10 - 30$ hour deep pointings from MUSE, we obtain $\sim 10$ $z \sim 2 - 4$ He$^\text{II}$ emitters to study their inter-stellar medium and stellar population properties. Emission line ratio diagnostics of our sample suggest that emission lines are driven by star-formation in solar to moderately sub-solar ($\sim 1/20$th) metallicity conditions. However, we find that even after considering effects from binary stars, we are unable to reproduce the He$^\text{II} \lambda 1640$ equivalent widths. Our analysis suggest that extremely sub-solar metallicities ($\sim 1/200$th) are required to reproduce observed He$^\text{II} \lambda 1640$ luminosities. Thus, current stellar populations may require alternative mechanisms such as sub-dominant active galactic nuclei or top heavy initial-mass-functions to compensate for the missing He$^+$ ionising photons.

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1. Introduction

The detection and characterization of the first generation of stellar populations in the Universe is of highest priority to the high redshift galaxy evolution community. Multiple observational attempts have been made to observationally confirm galaxies with evidence for population III (pop III; metal free) stars without any success (e.g., Cassata et al. 2013; Sobral et al. 2015), where Ly$\alpha$ and He$^\text{II}$ in the absence of other prominent emission lines are interpreted as existence of pristine metal-poor stellar populations (e.g., Inoue et al. 2011; Sobral et al. 2015). This interpretation is however challenging in the face of other processes that can produce He$^+$ ionising photons ($E > 54.4$ eV, $\lambda < 228$ Å). Additionally, the short life-time of pop-III systems and resulting inter-stellar medium (ISM)/inter-galactic-medium pollution by pair-instability supernovae (Heger & Woosley 2002), uncertainties in photometric calibrations, presence of active galactic nuclei (AGN), pristine cold mode gas accretion to galaxies, limited understanding of high-redshift stellar populations and the ISM contribute further to the complexity of detecting and identifying pop-III host systems (e.g., Matthee et al. 2017; Shibuya et al. 2017; Sobral et al. 2017). Thus, to make compelling constraints of stellar populations in the presence of strong He$^\text{II}$ emission and link with pop-III hosts, a comprehensive understanding of He$^\text{II}$ emission mechanisms is required.

Multiple mechanisms prominent in stellar populations in a variety of ages and physical/chemical conditions are expected to contribute to He$^\text{II}$ emission, i.e. young O/B type stars (e.g., Shirazi & Brinchmann 2012), hydrogen-stripped massive evolved Wolf-Rayet...
stars (e.g., Shirazi & Brinchmann 2012), post-asymptomatic giant branch stars (e.g., Binet et al. 1994), X-ray binary stars (e.g., Casares et al. 2017), radiative shocks (e.g., Izotov et al. 2012), AGN (e.g., Shirazi & Brinchmann 2012) have all been suggested as possible contributors. Additionally, mechanisms such as binary interactions and stellar rotation are expected to prolong the lifetime of young O/B stars extending the total amount of He\(^+\) photons present at a given star-formation history (e.g., Eldridge et al. 2017; Götberg et al. 2017). Even with a variety of such mechanisms, present stellar-population/photo-ionization models lack sufficient high-energy photons to produce observed He\(^{\text{II}}\)\(\lambda\)1640 line profiles consistently with other rest-UV emission lines in local and high-z galaxies (e.g., Shirazi & Brinchmann 2012; Senchyna et al. 2017; Berg et al. 2018).

2. Data & Analysis

The advancement of state-of-the-art sensitive multiplexed optical instruments in 8-10m class telescopes such as the The Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) has allowed us to obtain spatially-resolved spectroscopy of galaxies in this epoch in unprecedented numbers (e.g., Inami et al. 2017). Here, we present an analysis done using deep \(\sim 10 - 30\) hour pointings from MUSE obtained as a part of multiple MUSE guaranteed time observation programs (Bacon et al. 2015, 2017; Epinat et al. 2018; Marino et al. 2018). Our observations target He\(^{\text{II}}\)\(\lambda\)1640 emitters at \(z = 1.93 - 4.67\). The Universe at \(z \sim 2 - 4\) was reaching the peak of the cosmic star-formation rate density (Madau & Dickinson 2014), where systems were highly star-forming and evolving rapidly giving rise to a diverse range of physical and chemical properties (e.g., Kacprzak et al. 2016; Kewley et al. 2016; Steidel et al. 2016; Nanayakkara et al. 2017; Strom et al. 2017). Thus, with MUSE we are able to obtain rest-UV spectroscopy of young, low-metallicity, highly star-forming systems which may give rise to a diverse range of exotic phenomena capable of producing high-energy ionizing photons.

Our sample comprise of 15 He\(^{\text{II}}\)\(\lambda\)1640 detections (including 3 AGN) and is the largest sample of \(z \geq 2\) He\(^{\text{II}}\)\(\lambda\)1640 emitters with multiple emission line detections. Additional details on sample selection process is described in Nanayakkara et al., (in prep). We remove AGN from our sample and use multiple emission line diagnostics from Gutkin et al. (2016) and Xiao et al. (2018) to explore the ISM conditions of the He\(^{\text{II}}\)\(\lambda\)1640 sample. We find that in C\(\text{III}\)/[O\(\text{III}\)] vs Si\(\text{III}/\text{CIV}\), C\(\text{III}/\text{HeII}\)\(\lambda\)1640 vs [O\(\text{III}/\text{HeII}\)]\(\lambda\)1640, and [O\(\text{II}/\text{HeII}\)]\(\lambda\)1640 vs C\(\text{III}/\text{SiII}\) line ratio diagrams our galaxies occupy a region, that can be described by star-forming galaxies with solar to \(\sim 1/20\)th solar metallicities. In Figure 1, we show the C\(\text{III}/\text{HeII}\)\(\lambda\)1640 vs [O\(\text{III}/\text{HeII}\)]\(\lambda\)1640 line ratio diagrams for single-star stellar population models from Gutkin et al. (2016) and binary-star models from BPASS Xiao et al. (2018). Our values agree with literature data of high-z sources (Patrício et al. 2016; Berg et al. 2018) and have considerably lower metallicities compared to \(z = 0\) sources from Senchyna et al. (2017). When effects of binary stellar models are added, the line-ratio diagnostics become more degenerate (also see Xiao et al. 2018), however, line-ratios are still within the range powered by star-formation.

The main discrepancy between model and data arise only once line EWs are compared. As shown by Figure 2, Xiao et al. (2018) binary models are able to reproduce observed C\(\text{III}\) EWs but lacks sufficient mechanisms to reproduce the observed He\(^{\text{II}}\)\(\lambda\)1640 EWs. We expect this to be primarily driven by the lack of photons below \(\lambda < 228\) Å in BPASS models (e.g., Berg et al. 2018). We further develop a simple prescription to investigate the difference in He\(^{\text{II}}\)\(\lambda\)1640 ionising photons between observed data and Xiao et al. (2018) model predictions by normalizing observed C\(\text{III}\) luminosities with the models. In Figure
Figure 1. Rest-frame C/II/Heii λ1640 vs [OIII]/Heii λ1640 emission line ratios of the MUSE Heii λ1640 sample. Individual galaxies with SNR $>3$ for all four emission lines are shown as stars. **Left:** The tracks are from Gutkin et al. (2016) models. Each set of tracks with similar colour resemble three C/O ratios and the region between the minimum and maximum C/O tracks are shaded by the same colour. From top to bottom the ionization parameter increases. Line ratios from Patricio et al. (2016), Senchyna et al. (2017), and Berg et al. (2018) are shown for comparison. MUSE line ratios of the Lyman continuum emitter from Naidu et al. (2017) is shown by the filled star. **Centre:** Model line ratios computed by Xiao et al. (2018) using BPASS binary stellar population models. Symbol size of each track increase as a function of time and ranges from $t = 1$ Myr to $t = 50$ Myr from the onset of the star-burst. Models are computed with $\log_{10}(n_H) = 1.0$ with varying $U_s$ between $-2.5$ and $-1.5$.

3 we show the fraction of observed He$^+$ ionising photons compared to the predictions from the models. Only extreme sub-solar metallicities ($\sim 1/200$th) are able to accurately predict the observed He$^+$ ionising photons, which is strongly in contrast with predictions from line-ratio diagnostics.

3. Conclusions & Future directions

Here, we have used deep optical spectroscopy from MUSE to obtain a sample of Heii λ1640 detections at $z \sim 2 - 4$ to study their ISM conditions using state-of-the-art stellar-population/photo-ionization models. Using rest-UV emission-line ratio diagnostics we show that our galaxies could mostly be explained by $Z/\zodot \sim 0.05 - 1.0$ photo-ionisation models, but, we show that even BPASS binary models lack sufficient ionising photons to re-produce observed Heii λ1640 EWs. Using a simple prescription, we show that our observed Heii λ1640 luminosities can only be explained using extreme sub-solar metallicities ($\sim 1/200$th). Such low metallicities are in contradiction with our line-ratio diagnostics and stellar populations models can suffer large uncertainties due to lack of empirical calibrations in this regime. It is possible that extra contribution from X-Ray binaries, sub-dominant AGN, or effects related to stellar rotations at high metallicities can supply the missing ionising photons. Alternatively, if star-forming galaxies at $z \sim 2 - 4$ have a top-heavy initial-mass-function (see Nanayakkara et al. 2017), the extra O/B type stars will contribute to higher levels of ionising photons, which could increase the He$^+$ photon budget.

Future deep surveys such as the MUSE extreme deep field survey, a single 160 hour
Figure 2. $\text{C} \text{ iii}\lambda 1908$ vs $\text{He} \text{ ii}\lambda 1640$ equivalent widths of Xiao et al. (2018) models for a star-burst stellar population. Model parameters are similar to Figure 1 right panel.

Figure 3. The fraction of observed He$^+$ ionising photons compared to Xiao et al. (2018) model expectations as a function of observed $\text{He} \text{ ii}\lambda 1640$ luminosity of the MUSE $\text{He} \text{ ii}\lambda 1640$ sample. From left to right, we show the He$^+$ model predictions computed for three metallicities, $Z = 0.01, 0.0001$ with $\log_{10}(n_H) = 1.0$ and $U_s = -1.5$ for different times between 1−20 Myr from the onset of the star-burst. The dashed horizontal line indicates $y=0$, where there is no difference between observations and model predictions.

pointing by MUSE, will provide extremely high signal-to-noise rest-UV spectra at $z = 2 − 4$ to perform spectro-photometric analysis by simultaneous combination of nebular emission features with weaker ISM and photospheric emission and absorption features. Thus, we will be able to constrain stellar population properties to finer detail within this epoch and make predictions for future surveys by the James Webb Space Telescope. Given that individual detections of pop-III stars will be unlikely until proposed future space telescopes such as LUVOIR, we should push the current instruments to their maximum
potential to constrain the stellar population properties of galaxies leading to the buildup of the peak of the cosmic star-formation rate density.

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