Challenges in Panchromatic Modelling with Next Generation Facilities
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Probing the ISM of He II λ1640 emitters at $z = 2 - 4$ via MUSE

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Abstract. He II λ1640 emission in the absence of other metal lines is the most sought-after emission line to detect and characterize metal free stellar populations. However, even recent stellar population models with sophisticated treatment of stellar evolution also lack sufficient He^+ ionising photons to reproduce observed He II fluxes. We use VLT/MUSE GTO observations to compile a catalogue of 15 $z \sim 2 - 4$ He II λ1640 emitters from $\sim 10 - 30$ hour pointings. We show that both He II λ1640 detections and non-detections occupy similar distribution in UV absolute magnitudes. Rest-UV emission line analysis of our sample shows that the emission lines of our He II λ1640 emitters are driven by star-formation in solar to moderately sub-solar (∼1/20th) metallicity conditions. However, we find that even after considering effects from binary stars, we are unable to reproduce the He II λ1640 equivalent widths. Alternative mechanisms are necessary to compensate for the missing He^+ ionising photons.

Keywords. galaxies: high-redshift, galaxies: ISM, ultraviolet: ISM

1. Introduction

Several works have tried to obtain observational signatures for the existence of metal-free (pop-III) stars in the early Universe via current ground and space based telescopes (e.g., Cassata *et al.* 2013; Sobral *et al.* 2015). The failure to obtain observational evidence for these first generation of stars has been attributed to reasons such as the short life-time (∼ 1Myr) of pop-III systems, photometric calibration, presence of active galactic nuclei (AGN), pristine cold mode gas accretion to galaxies, and limited understanding of high-redshift stellar populations and the inter-stellar-medium (ISM). All these effects have contributed in varying degrees to the complexity of detecting and identifying pop-III host systems (Fardal *et al.* 2001; Yang *et al.* 2006; Sobral *et al.* 2015; Agarwal *et al.* 2016; Bowler *et al.* 2017; Matthee *et al.* 2017; Shibuya *et al.* 2017; Sobral *et al.* 2018).

With large samples of high-z galaxies, candidates for galaxies containing a significant population of pop-III stars can be selected due to the presence of strong Lyα and He II emission lines in the absence of other prominent emission features. These lines can be interpreted as existence of pristine metal poor stellar populations (Tumlinson *et al.* 2003; Raiter *et al.* 2010; 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). Therefore, to make compelling constraints of stellar populations in the presence of strong He II emission and link with pop-III hosts, a comprehensive understanding of He II emission mechanisms is required.

Stellar populations in a variety of ages and physical/chemical conditions undergo various mechanisms that may contribute to He II emission, such as young O/B type stars (e.g., Shirazi & Brinchmann 2012), hydrogen-stripped massive evolved Wolf-Rayet stars (e.g., Shirazi & Brinchmann 2012), very massive low-Z WNh stars (hydrogen rich WN stars; Gräfener & Vink 2015), post-asymptomatic giant branch stars (e.g., Binette *et al.* 1994), X-ray binary stars (e.g., Casares *et al.* 2017), radiative shocks (e.g., Izotov *et al.* 2012), and AGN (e.g., Shirazi & Brinchmann 2012). Binary interactions and stellar rotation 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, we still lack E> 54.4 eV photons in stellar population models to produce observed He II λ1640 line profiles consistently with other rest-UV emission lines (e.g., Shirazi & Brinchmann 2012; Senchyna *et al.* 2017; Berg *et al.* 2018).

2. Data & Analysis

The new generation of sensitive multiplexed optical instruments in 8-10m class telescopes such as the The Multi Unit Spectroscopic Explorer (MUSE; Bacon *et al.* 2010) has enabled astronomers to obtain spatially-resolved spectroscopy of galaxies throughout cosmic time in unprecedented numbers (e.g., Inami *et al.* 2017). Here, we present a sample of 15 He II λ1640 detections (including 3 AGN) obtained from deep $\sim 10-30$ hour pointings as a part of multiple MUSE guaranteed time observation programs (Bacon *et al.* 2015, 2017; Epinat *et al.* 2018; Marino *et al.* 2018) between $z = 1.93 - 4.67$. The Universe at $z \sim 2-4$ was reaching the peak of the cosmic star-formation rate density (Madau & Dickinson 2014), with galaxies in 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.* 2016, 2017; Strom *et al.* 2017). 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.

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 II λ1640 emission in the non-active galaxy sample. Additional details on sample selection are given in Nanayakkara *et al.*, (submitted). In Figure 1 (left panel), we show the C III]/He II λ1640 vs O III]/He II λ1640 line ratio diagrams for single-star stellar population models from Gutkin *et al.* (2016). 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). In this line ratio diagram, our galaxies occupy a region, that can be described by star-forming galaxies with solar to $\sim 1/20$th solar metallicities. We note that, when effects of binary stellar evolution are considered, the line-ratio diagnostics become more degenerate (also see Xiao *et al.* 2018). However, the line-ratios of our He II λ1640 emitters fall within the range powered by star-formation.

The main discrepancy between model and data arise only once line EWs are compared. As shown in the right panel of Figure 1, Xiao *et al.* (2018) binary models are able to reproduce the observed C III] EWs but lacks sufficient He^+ ionising photons to reproduce the observed He II λ1640 EWs, which is expected to be driven by the lack of photons below $\lambda < 228$ Å in BPASS models (e.g., Berg *et al.* 2018). By matching observed C III] luminosities to model C III] luminosities, we find that only extreme sub-solar metallicities ($\sim 1/200$th) are able to accurately predict the observed He^+ ionising photons in BPASS models, which is strongly in contrast with predictions from line-ratio diagnostics.

3. Conclusions & Future directions

We used deep optical spectroscopy from MUSE to obtain a sample of He II λ1640 detections at $z \sim 2-4$ to study their ISM conditions using state-of-the-art stellar-population/

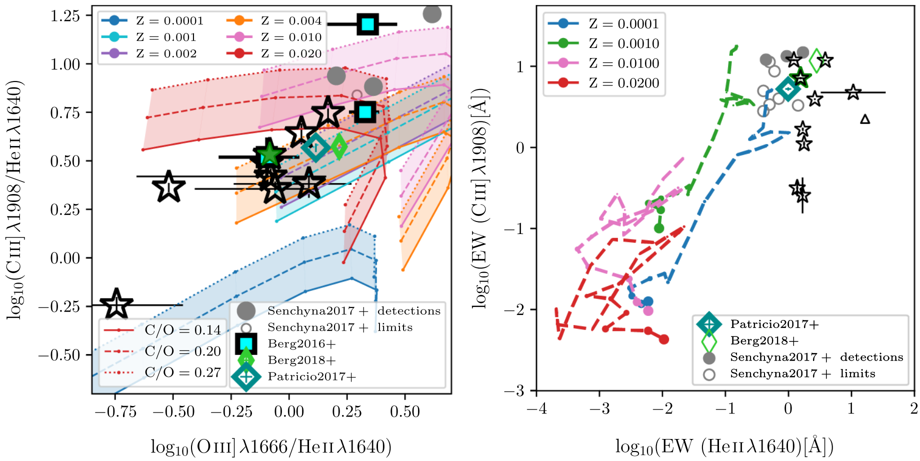

Figure 1. Left: Rest-frame C III]/He II λ1640vs O III]/He II λ1640 emission line ratios of the MUSE He II λ1640 sample. Only galaxies with SNR> 3 for all four emission lines are shown here. The tracks are from Gutkin *et al.* (2016) models. Each set of tracks with similar colour resemble three C/O ratios 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 Patrício *et al.* (2016), Senchyna *et al.* (2017), and Berg *et al.* (2016, 2018) are shown for comparison. MUSE line ratios of the Lyman continuum emitter from Naidu *et al.* (2017) is shown by the filled star. **Right:** C III] vs He II λ1640 equivalent widths of Xiao *et al.* (2018) models for a star-burst stellar population. Model parameters are similar to the left panel.

photo-ionization models. Emission line ratios of our He II λ1640 emitters could mostly be explained by Z∼ 0.05 − 1.0 $Z_{\odot}$ photo-ionisation models, but, even the BPASS binary models lack sufficient ionising photons to re-produce observed He II λ1640 EWs. In order to reproduce the observed He II λ1640 luminosities, BPASS stellar population models with extreme sub-solar metallicities (∼ 1/200th) are required. 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. Extra contribution to the number of ionizing photons from X-Ray binaries, sub-dominant AGN, or effects related to stellar rotations at high metallicities might be necessary to alleviate the tension between models and observations. In addition, top-heavy initial-mass-functions in star-forming galaxies (e.g., see Nanayakkara *et al.* 2017), will contribute to higher levels of ionising photons, which could increase the He^{+} ionising photon budget.

Future deep surveys such as the MUSE extreme deep field survey (PI R. Bacon), a single 160 hour pointing by MUSE, along with several deep pointings in *Hubble* frontier field parallels (PI L. Wisotzki) 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. By constraining the stellar population properties to finer detail within this epoch, we will be able to make accurate predictions for future surveys in the era of *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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Discussion

Yuichi Harikane: Do you think the strong He II λ1640 emission in Berg *et al.* (2018) can be explained if you assume ISM metallicity to be different to that of the stars?

Themiya Nanayakkara: He II λ1640 emission strength does show a dependence on stellar metallicity with BPASS models predicting a higher amount of He^+ ionising photons at low metallicities (also see Figure 3 of Nanayakkara *et al.* 2018). So if the stellar metallicity is low compared to the interstellar medium (as also argued by Steidel *et al.* 2016) it is possible that we might be under-predicting the amount of He^+ ionising photons produced by the stars in our systems. However, as I showed during my talk a $\sim 1/200\ Z_\odot$ metallicities are required to alleviate the tensions between the models and data, which

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might be somewhat unrealistic for UV bright systems at $z \simeq 1.6$. So additional changes in stellar populations might also be necessary.

Tomo Goto: How do you explain the existence of the galaxy at the extreme lower left in the line ratio plot (Figure 1 left panel)?

Nanayakkara: The models by Gutkin *et al.* (2016) have quite a few free parameters, which can be altered to reproduce this line ratio. Most ISM and stellar properties at high-z are not well constrained. Simultaneous analysis of rest-frame UV/optical emission and absorption is required to constrain these properties, thus data from very deep surveys such as the MUSE extreme deep field and future *James Webb Space Telescope* observations will be crucial to properly understand these systems.