X-ray emission from He $\lambda$1640 emitting galaxies in VANDELS

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ABSTRACT

We present X-ray measurements for 18 star-forming galaxies showing He $\lambda$1640 emission at $z \sim 2.2 - 5$ in the Chandra Deep Field South, to test whether they show any X-ray excess compared to galaxies with no He emission. Using aperture photometry on the 7 Ms Chandra image, we find that even though He $\lambda$1640 emitting galaxies in our sample (especially those with FWHM(He $\lambda$1640) < 1000 km s$^{-1}$) have marginally higher X-ray emission than galaxies with no He $\lambda$1640, the difference is not statistically significant. The X-ray luminosity per star formation rate ($L_X$/SFR) for He $\lambda$1640 emitters and non-emitters are comparable, which rules out any enhanced contribution from young X-ray sources. The $L_X$/SFR at $z \sim 3$ for both He $\lambda$1640 emitters and non-emitters is consistent with observations at lower redshifts, and in line with the redshift evolution predicted by models. We also find that our $L_X$/SFR measurements are consistent with the metallicity dependence predicted and observed in the literature. Therefore, we conclude that there is no significant difference between the X-ray emission from galaxies with and without He $\lambda$1640 emission, which rules out enhanced contribution from XRBs or weak or obscured AGN in galaxies with strong He $\lambda$1640 at $z \sim 3$. Given the other similarities in the physical properties of both He $\lambda$1640 emitters and non-emitters reported earlier, alternative sources of He $\lambda$1640 ionising photon production, such as localised low-metallicity stellar populations, Pop-III stars, etc. may need to be explored.

Key words: galaxies: high-redshift – X-rays: binaries – galaxies: evolution

1 INTRODUCTION

Low-mass star-forming galaxies are largely considered to be the key drivers of reionisation, a process through which the Universe made a phase transition from neutral to completely ionised by $z \sim 6$ (Robertson et al. 2010, 2015; Wise et al. 2014; Bouwens et al. 2015). With decreasing metallicities at higher redshifts (Henry et al. 2013; Steidel et al. 2014; Amorin et al. 2017; Sanders et al. 2018; Cullen et al. 2019), galaxies in the early Universe should be capable of producing a large number of ionising photons ($E > 13.6$ eV) and complete the process of reionisation by $z \sim 6$ (Stanway et al. 2016). The metal-free stars (the so-called Pop III stars) in these very early galaxies should have very high masses and temperatures (e.g. Bromm & Larson 2004; Bromm & Yoshida 2011), resulting in the production of hard UV ionising fields that are capable of exciting high-ionisation emission lines, such as He $\lambda$1640, whose ionisation potential is $\sim 54.4$ eV or $\lambda < 228$ (Tumlinson et al. 2001; Schaerer 2003; Scannapieco et al. 2003).

The number of known galaxies that show the high ionisation He $\lambda$1640 emission line has been steadily growing across redshifts. In
the local Universe ($z \sim 0$), the He II $\lambda 4868$ line is often seen in the spectra of low-mass star-forming galaxies and almost all of these galaxies are metal-poor (Garnett et al. 1991; Guseva et al. 2000; Izotov & Thuan 2004; Shirazi & Brinchmann 2012; Kehrig et al. 2013, 2018; Berg et al. 2016; Senchyna et al. 2017). Rest-frame UV observations of some of these $z \sim 0$ metal-poor galaxies have revealed the presence of both He II $\lambda 1640$ as well as C IV $\lambda 1540$ emission lines (Berg et al. 2019; Senchyna et al. 2019), reinforcing the presence of hard ionising fields due to massive, metal-poor stars. The samples of He II emitting galaxies at high redshifts have increased too, primarily using lensing (Patricio et al. 2016; Berg et al. 2018) and large-area spectroscopic surveys (Cassata et al. 2013; Nanayakkara et al. 2019; Saxena et al. 2020), leading to detections of He II emitting galaxies out to $z \sim 4$.

Most of the broad He II emission seen across redshifts can be explained primarily through winds driven by Wolf-Rayet (WR) stars (Schaerer 1996). The WR origin in some broad He II emitters (FWHM > 1000 km s$^{-1}$) has indeed been confirmed through the detection of WR ‘bumps’ in the spectra of galaxies around the He II and C IV emission lines (Brinchmann et al. 2008; Kehrig et al. 2011; Shirazi & Brinchmann 2012). The inclusion of binary-star evolution in stellar population synthesis (Eldridge et al. 2017; Stanway & Eldridge 2018) results in stars spending longer periods of time in the WR phase, and fits the observed He II line better compared to single-star models (e.g. Steidel et al. 2016). However, not all broad He II emitters, particularly those with low metallicities, may be directly connected with the presence of WR stars (e.g. Shirazi & Brinchmann 2012; Kehrig et al. 2015).

The picture becomes even more complicated when trying to explain the origin of the narrow He II emission line (FWHM < 1000 km s$^{-1}$) (e.g. Stanway & Eldridge 2019). Some stellar synthesis models including binary stars can reproduce the UV emission line ratios of He II, O III and C III of galaxies that show He II $\lambda 1640$ line observed at high redshifts. However, these models still under-predict the observed equivalent widths (EW) of the He II line (Nanayakkara et al. 2019; Saxena et al. 2020). Other physical mechanisms, such as strong shocks (Dopita & Sutherland 1996; Thuan & Izotov 2005; Izotov et al. 2012), stellar rotation mixing leading to higher effective temperatures (Szécsi et al. 2015), ‘stellar stripping’ that results in the rejuvenation of old stars that provide extra He II ionising photons (Goïberg et al. 2018, 2019), presence of metal-free Pop III stars (Schaerer 2003; Cassata et al. 2013; Visbal et al. 2017), low-level AGN activity (e.g. Mignoli et al. 2019) and contribution from X-ray binaries (XRBs) (Garnett et al. 1991; Stasińska et al. 2015; Kehrig et al. 2015; Schaerer et al. 2019; Senchyna et al. 2019) have been proposed as possible explanations to account for the missing He II ionising photons seen in star-forming galaxies.

XRBs are binary star systems where the production of X-rays is powered by mass transfer from the ‘donor’ star to a very compact companion, such as a neutron star or black hole, which is called the ‘accretor’. The donor star can have a range of masses – when the mass of the donor star is lower than the accretor, the system is referred to as a low-mass XRB. In cases where the donor star is massive, typically a O- or B-type star, the system is referred to as a high-mass XRB. The dominant sources of X-rays from young, star-forming galaxies at high redshifts are generally high-mass XRB systems (e.g. Lehmer et al. 2016). Observations of X-ray emission from star-forming galaxies (at fixed star formation rates) have revealed a strong metallicity dependence of their X-ray luminosities. This means that the contribution from XRBs increases with decreasing metallicities (Basu-Zych et al. 2013b; Dona et al. 2015; Brophy et al. 2016; Lehmer et al. 2016; Fornasini et al. 2019). This metallicity dependence of XRBs has also been explored from a theoretical point of view (Fragos et al. 2013a,b; Madau & Fragos 2017). Especially in the early Universe, when the overall ages and metallicities of galaxies were lower and star formation rates (SFRs) were higher, X-ray luminosities are also found to correlate strongly with the galaxy SFRs (Basu-Zych et al. 2013a; Lehmer et al. 2016; Aird et al. 2017). This suggests that high-mass XRBs formed in star-forming regions within galaxies are the driving forces behind the observed X-ray luminosities of these galaxies. Since low metallicities and high-mass star formation are also required to power nebular He II emission, enhanced contribution from XRBs may offer an explanation to the missing He II ionising photons problem (e.g. Schaerer et al. 2019).

Building upon the new sample of He II emitting galaxies at $z \sim 2.5$ that was presented in Saxena et al. (2020, hereafter S20), in this paper we explore the X-ray emission from these He II emitters. The layout of this paper is as follows: in Section 2 we briefly outline the original sample of He II emitting galaxies and their physical properties. In Section 3 we introduce the X-ray data used in this study and present our methodology for X-ray photometry. In Section 4 we discuss the results of our X-ray analysis, and compare the X-ray properties of He II emitters with a comparison sample of non-He II emitters. In Section 5 we present a discussion of our results, and comment on whether X-ray sources play a dominant role in galaxies with He II emission. Finally, we conclude the findings of this paper in Section 6.

Throughout this paper, we assume a ΛCDM cosmology with $\Omega_m = 0.3$ and $H_0 = 67.7$ km s$^{-1}$ Mpc$^{-1}$ taken from Planck Collaboration et al. (2016), and use the AB magnitude system (Oke & Gunn 1983).

2 SAMPLE OF HE II EMITTERS FROM VANDELS

The sample of He II emitting galaxies considered in this study was first presented in S20, and we refer the readers to this paper for the full description of sample selection, derived physical properties and analysis of both individual and stacked UV spectra. In this section we briefly summarise the key findings of S20. The galaxies were selected from VANDELS (Pentericci et al. 2018; McLure et al. 2018), which is a recently completed deep VIMOS survey of the CANDELS CDFS and UDS fields (Grogin et al. 2011; Koekemoer et al. 2011) carried out using the Very Large Telescope. We shortlisted a total of 50 star-forming galaxies over a redshift range $z = 2.2 - 4.8$ that showed He II emission in their spectra. Of these, 33 were classified as Bright He II emitters where the signal-to-noise ratio (S/N) of the He II emission line was greater than 2.5, and 17 were classified as Faint emitters with S/N(He II) < 2.5. Out of the total of 50 shortlisted He II emitters, 26 lie in the Chandra Deep Field South (CDFS) and 24 lie in UKIDSS Ultra Deep Survey (UDS) field.

Overall, galaxies that show He II emission have very similar physical properties, such as stellar mass, star formation rates and UV magnitudes, to similarly selected VANDELS galaxies with no He II emission over the same redshift range. We find that the stellar mass range of our He II emitters is $M_\star = 10^{8.8 - 10.7}$ M$_\odot$ (where M$_\odot$ represents solar mass), the UV-corrected star formation rate (SFR) range is SFR = $10^{0.7 - 2.3}$ M$_\odot$ yr$^{-1}$ and the absolute UV magnitude range is $M_{UV} = -21.9$ to $-19.2$. Two sample Kolmogorov-Smirnov (KS) tests showed that the physical properties of He II emitters are not significantly different from those that do not show He II emission in their spectra at the same redshifts.

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Using UV emission line ratio diagnostics (He \( \eta \lambda 1640, \) O \( \eta \lambda 1666, \) C \( \eta \lambda 1909), \) we found that He \( \eta \) emitters that have not been classified as potential AGN in S20 favour models with sub-solar stellar metallicities and low stellar ages, based on both single-star and binary-star models. The comparison with models was performed using line ratios from both individual galaxy spectra as well as stacks. Stacked spectra were produced for Faint He \( \eta \) emitters (S/N(He \( \eta \) < 2.5), galaxies that show narrow He \( \eta \) (FWHM < 1000 km s\(^{-1}\)) and those that show broad He \( \eta \) (FWHM > 1000 km s\(^{-1}\)). We found that line ratios from the stack of narrow He \( \eta \) emitters favour lower metallicities than the broad emitters. This is in line with predictions based on He \( \eta \) ionising photons being produced in Wolf-Rayet (WR) stars (see Shirazi \& Brinchmann 2012, for example) – higher metallicity stellar populations have more stars in the WR phase, which give rise to broad He \( \eta \) emission lines due to strong stellar winds.

For individual galaxies with bright He \( \eta \) emission as well as the stack of faint and narrow He \( \eta \) emitters, we found that although binary-star models do a reasonably good job at reproducing the line ratios, they under-predict the He \( \eta \) EWs. This means that these models are unable to produce the number of He \( \eta \) ionising photons required to power the observed emission line strengths, and additional sources of ionising photons may be required. We argued that there are several mechanisms that could be producing these missing photons, including sub-dominant AGN, stripped stars and/or X-ray binaries (XRBs), particularly the high-mass XRBs, as previously mentioned. An effective way to investigate the impact of sub-dominant AGN or enhanced contribution from XRBs is to study the X-ray emission from He \( \eta \) emitting galaxies and in the following sections we describe the available X-ray data and our X-ray photometry methodology.

### 3 X-RAY ANALYSIS

#### 3.1 Data

We use X-ray images from the Chandra X-ray Observatory in the CDFS, which has a total of 7 Ms of exposure time collected over a period of more than a decade, covering an area of \( 485 \text{ arcmin}^2 \) (Luo et al. 2017), making it the deepest X-ray data set in any extragalactic field. Additional data products in the CDFS include the effective exposure map and the PSF map, which are used for aperture photometry. More details about the data reduction and products from CDFS used in this study can be found in Giallongo et al. (2019). Although Chandra data is also available in the UDS field\(^2\), the effective exposure time of the Chandra image available in UDS is \( \approx 600 \) ks. This is quite shallow compared to the 7 Ms of exposure time available in the CDFS field. Since the goal of this study is to perform aperture photometry for star-forming galaxies at high-redshifts that are likely to be very faint at X-ray wavelengths, the depths reached by 600 ks of exposure time will not be sufficient. Therefore, we restrict the X-ray analysis to only the He \( \eta \) emitters that lie in the CDFS field.

Out of 26 He \( \eta \) emitters (both Bright and Faint sources) from S20 in the CDFS field, 21 lie within the X-ray image footprint with high exposure time in CDFS. Of these, 3 were classified as potential AGN in S20 owing to the presence of strong C IV emission in their spectra. Interestingly, these 3 possible AGN are not detected in X-rays in the CDFS 7Ms catalogue from Luo et al. (2017). Further, S20 showed that BPASS models are able to explain the C IV/He \( \eta \) line ratios observed in these sources through ionisation by star formation alone. However, we take a conservative approach for the purposes of this paper and eliminate these three C IV emitting sources from our sample. The final sample, therefore, consists of 18 He \( \eta \) emitters, out of which 13 have narrow (FWHM < 1000 km s\(^{-1}\)) and 5 have broad (FWHM > 1000 km s\(^{-1}\)) He \( \eta \) emission lines. The rest-frame UV spectra of He \( \eta \) emitting galaxies can be found in S20.

#### 3.2 X-ray photometry of He \( \eta \) emitters

To estimate X-ray fluxes, we use the 0.8 – 3 keV band image because of two reasons. First, as Giallongo et al. (2019) showed, using the 0.8 – 3 keV image instead of the standard soft X-ray band of 0.5 – 2 keV results in higher number of counts recovered due to the higher transmissivity of the 0.8 – 3 keV band. Second, the redshift distribution of the sources in this study is such that the 0.8 – 3 keV band comes closest to rest-frame energy range of 2 – 10 keV, upon which the analysis of this paper as well as several other observational studies that will be used for comparison are based. Therefore, the uncertainties arising from the application of \( k \)-corrections are minimised.

We measure the X-ray flux of He \( \eta \) emitters by performing aperture photometry using Photutils (Bradley et al. 2019). We place a circular aperture at the RA and Dec of each source (taken from the VANDELS catalogue), encompassing the effective Chandra PSF (median diameter of 3.0″) to measure the total number of counts from the source. To measure the local background, we place a circular annulus with inner radius of 10″ and outer radius of 20″, centred on the same position as the circular aperture. Within the annulus, we mask pixels that are brighter than 4σ for accurate background estimation. For each source we measure the total number of counts from the source and the background, \( C_{\text{gal}} \) and \( C_{\text{bkg}} \), the area encompassed, \( A_{\text{gal}} \) and \( A_{\text{bkg}} \) (pixel\(^2\)), and the effective exposure times, \( t_{\text{gal}} \) and \( t_{\text{bkg}} \) (seconds), respectively. We follow Fornasini et al. (2019) and calculate the background subtracted counts, \( C_{\text{bkgsub}} \), as

\[
C_{\text{bkgsub}} = C_{\text{gal}} - C_{\text{bkg}} \times \left( \frac{A_{\text{gal}} 	imes t_{\text{gal}}}{A_{\text{bkg}} 	imes t_{\text{bkg}}} \right)
\]

(1)

To convert from background subtracted counts in the 0.8 – 3 keV band to X-ray flux in the standard 2 – 10 keV band, which was selected to facilitate comparison with other similar studies, we must assume a spectral model to calculate the effective photon energy (\( E_{\text{eff}} \)) in the band and the appropriate \( k \)-correction (\( k_{\text{corr}} \)). In line with similar studies in the literature (e.g. Brodrick et al. 2016), we assume a model with an unobscured power-law spectrum with photon index \( \Gamma = 2.0 \) and a galactic extinction value of \( 5 \times 10^{20} \) cm\(^{-2}\) (van de Voort et al. 2012), which is the average value observed for star-forming galaxies at high redshifts inferred from cosmological simulations. We then use pimms\(^3\) to calculate \( E_{\text{eff}} \) required to convert counts in the 0.8 – 3 keV band to fluxes in the 2 – 10 keV energy range. We calculate X-ray fluxes in the 2 – 10 keV range, \( F_{2-10 \text{ keV}} \), by dividing background subtracted counts by the effective exposure

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1 The images and catalogues are publicly available at http://personal.psuedu/wmb/cdfs/cdfs-chandra.html
2 http://www.mpe.mpg.de/XraySurveys/XUDS/
3 https://heasarc.gsfc.nasa.gov/docs/software/tools/pimms.html

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time ($t_{\text{gal}}$) and multiplying with $E_{\text{eff}}$, giving

$$F_{2-10 \text{ keV}} = \frac{C_{\text{bksub}}}{t_{\text{gal}}} \times E_{\text{eff}} \quad (2)$$

To finally calculate X-ray luminosities, we use luminosity distances, $D_L$, determined from the systemic redshift of sources given in S20 and apply the $k$-correction, $k_{\text{corr}} = (1 + z)^{2.0}$. Therefore, the X-ray luminosities in the 2 – 10 keV band, $L_{2-10 \text{ keV}}$, are calculated as

$$L_{2-10 \text{ keV}} = F_{2-10 \text{ keV}} \times 4\pi D_L^2 k_{\text{corr}} \quad (3)$$

### 3.3 Stacking

Since the S/N of X-ray emission from individual star-forming galaxies at these redshifts is likely to be low, we also stack the X-ray luminosities of our sources. The stacked X-ray luminosity of $N$ sources is calculated as

$$L_X^{\text{stack}} = \frac{1}{N} \sum_i^{N} F_{X,i} \times 4\pi D_L^2 k_{\text{corr}} \quad (4)$$

As shown by Fornasini et al. (2019), the above mentioned approximation for stacking works for galaxies that have comparable $L_X$ values. Since in this study we are probing galaxies with similar physical properties such as redshifts, star formation rates and masses, and the luminosities that go into the stack are weighted by the effective exposure time, we do not expect large inaccuracies in the stacked luminosity measured in this way. To achieve the highest S/N, we first stack X-ray counts from all 18 He $\text{n}$ emitters. Additionally, we also stack the counts from only the 13 sources classified as Narrow He $\text{n}$ emitters, because as mentioned earlier, explaining the origin of the narrow He $\text{n}$ emission line is of particular interest. We return to the results of X-ray measurements for He $\text{n}$ emitting sources in Section 4.1.

### 3.4 Comparison sample of non-He $\text{n}$ emitters

To isolate the possible effect of X-ray sources in He $\text{n}$ emitting galaxies, it is essential to compare the X-ray properties of He $\text{n}$ emitters with those of non-He $\text{n}$ emitters with similar properties such as redshifts and UV magnitudes. Therefore, to build a comparison sample of non-He $\text{n}$ emitters we select galaxies with VANDELS spectra that do not show any He $\text{n}$ emission in the redshift range $2.2 < z < 4.8$ with absolute UV magnitudes between $-22 < M_{I,500} < -19$, which is the redshift and UV magnitude range seen in our sample of He $\text{n}$ emitters (see S20). We then identify any bright X-ray AGN from the sample of non-He $\text{n}$ emitters by matching the coordinates with the CDFS 7 Ms source catalogue from Luo et al. (2017), using a radius of 2 arcseconds. All sources that have a match are removed from the comparison sample. Finally, we only consider those sources that lie in a high effective exposure time region in the CDFS 7 Ms image. This results in a total of 225 galaxies with similar physical properties compared to the He $\text{n}$ emitters that lie in the coverage area of the CDFS 7 Ms image.

To ensure comparable effective exposure times to accurately compare the X-ray properties of He $\text{n}$ emitters and non emitters, we randomly draw 18 galaxies from the sample of non-He $\text{n}$ emitters and perform X-ray photometry and stacking as mentioned above. To take into account the statistical variations introduced by randomly sampling galaxies from the non-emitter sample, we bootstrap this process and draw 500 independent samples of 18 galaxies for which stacked X-ray counts and fluxes are calculated. For each stack, we calculate the X-ray luminosity in the 2 – 10 keV band by taking the average redshift of the galaxies that go into the stack. The final stacked X-ray luminosity and the associated error of non-He $\text{n}$ emitters is measured from the median and standard deviation of the 500 independent bootstrap iterations.

### 3.5 Star formation rates and $L_X$/$SFR$

An important quantity that is often used to parametrise the effect of XRBs in star-forming galaxies is the ratio of X-ray luminosity to the star formation rate ($L_X$/SFR). Therefore, we also calculate and compare this quantity for both He $\text{n}$ emitters and non emitters. The dust-corrected SFRs for VANDELS sources are derived from multi-band spectral energy distribution (SED) fitting, as described in McLure et al. (2018). The SFRs for He $\text{n}$ emitters along with more details are given in S20.

For He $\text{n}$ emitters, the stacked $L_X$/SFR is calculated by dividing the $L_X$ by the SFR for each galaxy. For non emitters, $L_X$/SFR for each stack in the 500 bootstrap repetitions is calculated by using the average star formation rate of the galaxies that go into the stack ([SFR]), and dividing the stacked ($L_X$) value with [SFR] for each bootstrap repetition. We find that when bootstrapping, there are no major differences between dividing each $L_X$ by the corresponding SFR, or by dividing the stacked $L_X$ by the median SFR for each iteration and adopt the latter approach for non-He $\text{n}$ emitters to ease computation. The final ($L_X$/SFR) and associated dispersion of non emitters is calculated by measuring the median and standard deviation of the distribution of $L_X$/SFR from bootstrapping. For the purposes of this study, we do not take into account errors on the derived SFR.

### 4 RESULTS

#### 4.1 X-ray counts and luminosities

Performing X-ray photometry, we find that 4 out of 18 individual He $\text{n}$ emitters have counts with high S/N (> 2.5$r$), enabling reliable measurements of X-ray fluxes and luminosities. The background subtracted counts for these sources in the 0.8 – 3 keV band range from 7.9 – 14.4, translating into luminosities in the 2 – 10 keV band of $L_X = 3.1 - 5.6 \times 10^{34}$ erg s$^{-1}$ (where $X = 2 – 10$ keV). These luminosities are below the $L_X = 10^{32}$ erg s$^{-1}$ limit, where luminosities brighter than this are generally associated with dominant contribution from AGN. This provides additional confirmation that most of our He $\text{n}$ emitters are unlikely to have a dominant contribution from AGN, in line with what the rest-frame UV line ratio analysis suggested in S20. We also note that of the 4 sources that are detected with high-enough S/N in X-rays, 3 were classified as Bright and one as Faint by S20, and all four have narrow He $\text{n}$ emission lines (FWHM < 1000 km s$^{-1}$). The X-ray properties of these individually detected sources are given in Table 1.

For the stack of all 18 He $\text{n}$ emitters, the average background subtracted counts measured are $6.3 \pm 2.4$, and for only the 13 narrow He $\text{n}$ emitters, the measured counts are $7.2 \pm 2.6$. The average background subtracted counts measured for non-He $\text{n}$ emitters using bootstrapping are $4.7 \pm 0.9$ per source, which are lower, but not significantly different than those measured for He $\text{n}$ emitters. We then compare the measured X-ray luminosities in the 2 – 10 keV band from stacks of He $\text{n}$ emitters. We point out that the average redshifts of the two stacks are slightly different, which affects the
Table 1. X-ray properties of individually detected He ii emitting sources.

| ID       | z         | $C_{\text{bkgsub}}$ | $F_X$ | $L_X$ | SFR | $\log L_X$ |
|----------|-----------|---------------------|-------|-------|-----|------------|
|          |           |                     | (10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2}) | (10^{43} \text{ erg s}^{-1}) | (M_\odot \text{ yr}^{-1}) |          |
| CDFS23215 | 3.47      | 9.1 ± 3.0           | 10.8 ± 3.6 | 5.6 ± 1.9 | 20.2 | 40.44±0.12 |
| CDFS113062 | 2.69      | 11.2 ± 3.3          | 13.6 ± 4.1 | 3.1 ± 0.9 | 47.4 | 39.82±0.11 |
| CDFS122687 | 2.64      | 14.4 ± 3.8          | 17.0 ± 4.5 | 3.7 ± 1.0 | 92.0 | 39.60±0.10 |
| CDFS10094† | 3.56      | 7.9 ± 2.9           | 8.2 ± 2.9 | 4.6 ± 1.6 | 46.4 | 39.99±0.13 |

1: classified as Faint He ii emitter (S/N(He ii) < 2.5) in S20.

Table 2. X-ray properties of stacks.

| Stack       | N | Total exp. (Ms) | $\langle z \rangle$ | $\langle C_{\text{bkgsub}} \rangle$ | $\langle F_X \rangle$ | $\langle L_X \rangle$ | $\langle SFR \rangle$ | $\log L_X$ |
|-------------|---|-----------------|---------------------|---------------------|---------------------|---------------------|---------------------|------------|
| All He ii   | 18 | 126             | 3.04                | 6.3 ± 2.4           | 7.5 ± 3.8           | 2.6 ± 1.1           | 48.9     | 40.03±0.15 |
| Narrow He ii | 13 | 91              | 3.33                | 7.2 ± 2.6           | 8.4 ± 3.8           | 3.2 ± 1.2           | 46.4     | 40.11±0.14 |
| No He ii *  | 18 | 126             | 3.17                | 4.7 ± 0.9           | 6.4 ± 1.3           | 2.5 ± 0.5           | 28.1     | 39.93±0.14 |

*: errors measured on the stack of non-He ii emitters are from 500 bootstrap replications.

Figure 1. The distribution of stacked X-ray luminosities in the 2 – 10 keV band for galaxies with no He ii emission, using bootstrapping (grey). The dot-dashed red line marks the median values from non-He ii emitting galaxies, the solid orange line marks the average X-ray luminosity of all He ii emitters and the dashed green line marks the luminosity of only narrow He ii emitters. Although narrow He ii emitters show higher X-ray luminosities in comparison, the Z-score and P-value derived from comparing with the distribution of non-He ii emitters shows that the difference between the two is not statistically significant at 3σ.

We find that the stacked X-ray luminosity of all He ii emitters, with an average redshift of $\langle z \rangle = 3.04$, is $\langle L_X \rangle = 2.6 \times 10^{41}$ erg s$^{-1}$, and the stacked luminosity of narrow He ii emitters, with a higher average redshift of $\langle z \rangle = 3.33$, is $\langle L_X \rangle = 3.2 \times 10^{41}$ erg s$^{-1}$. For non-He ii emitters, the average redshift across 500 bootstrapped stacks is $\langle z \rangle = 3.17$ and the stacked luminosity (using bootstrapping) is $\langle L_X \rangle = 2.5 \times 10^{41}$ erg s$^{-1}$. Figure 1 shows the distribution of X-ray luminosities measured from bootstrapping for non-He ii emitters (with the red dot-dashed line indicating the median), the solid orange line marks the value derived for all He ii emitters and the dashed green line marks the value for narrow He ii emitters. The X-ray properties of the stacks are given in Table 2.

Our results show that the X-ray luminosities of He ii emitting galaxies are marginally higher than that of non-He ii emitters. In particular, we find that the stack of narrow He ii emitters has the highest X-ray luminosity. However, we note that all measurements are within 1σ error bars of each other. To determine whether the difference in X-ray luminosities measured is statistically significant, we calculate their Z-scores and P-values, which roughly give the probability of a measurement being a statistical fluctuation from a given distribution. Using the distribution obtained from bootstrapping for non-He ii emitters for comparison, we find a Z-score of 0.40, giving a P-value of 0.355 for the luminosity of all He ii emitters, indicating that there is a 35.5% chance that this measurement is a statistical fluctuation. Therefore the stacked luminosity of all He ii emitters cannot be deemed to be significantly different from the distribution of X-ray luminosities of non-He ii emitters. For the narrow He ii emitters, we find a Z-score of 1.45 and a P-value of 0.073, indicating a statistical fluctuation probability of 7.3%. Although the probability of this measurement being a statistical fluctuation is lower, the inferred P-value still indicates that the difference cannot be deemed to be statistically significant even at 2σ.

We point out here that the number of galaxies stacked in each bootstrapped iteration of non-He ii emitters is 18, whereas the number of sources with narrow He ii emission is 13. However, reducing the number of stacked galaxies to 13 in the bootstrapped measurements does not alter the median value, and results in an increase in the standard deviation of the distribution. The increased standard deviation would cause the inferred P-value of narrow He ii emitters to be higher, thereby reducing the statistical significance even further.

Therefore from our X-ray measurements, we conclude that although He ii emitters, and narrow He ii emitters in particular, show marginally higher X-ray luminosities when compared to non-He ii emitting galaxies, the difference between the stacked X-ray luminosities of He ii emitting and non-emitting galaxy populations...
is not statistically significant. Hence, we find no evidence of enhanced contribution from X-ray sources, presumably X-ray binaries or AGN, in galaxies that show the He II emission line presented in S20. We discuss this implication further in Section 5.

4.2 L_X/SFR

Since the X-ray luminosities of high-mass XRBs in star-forming galaxies are correlated with their star formation rates (SFRs), comparing the L_X/SFR for He II emitters and non emitters may shed some light on the differences in the contribution of XRBs. High-mass XRBs are the driving forces behind the correlation between L_X and SFR, as they begin to form only few tens of Myrs after a starburst event and therefore, closely trace the star formation rates (see Antoniou & Zezas 2016, for example).

Before calculating L_X/SFR, we note that the median SFRs of the He II emitting galaxies and non-emitting galaxies considered in this study are slightly different. For the stack of all He II emitters, the median SFR is \( \langle SFR \rangle = 48.9 \, M_\odot \, yr^{-1} \) and for the stack of narrow He II emitters, \( \langle SFR \rangle = 46.4 \, M_\odot \, yr^{-1} \). These values are higher than the median SFR of galaxies that do not show He II with \( \langle SFR \rangle = 28.1 \, M_\odot \, yr^{-1} \). We note once again that the SFRs for all galaxies considered in this study are derived using multi-band SED fitting from rest-frame UV to infrared wavelengths. For the stack of all He II emitting galaxies, we calculate \( \log({L_X}/\langle SFR \rangle) = 40.03 \, erg \, s^{-1} / (M_\odot \, yr^{-1}) \), for narrow He II emitters we calculate \( \log({L_X}/\langle SFR \rangle) = 40.11 \, erg \, s^{-1} / (M_\odot \, yr^{-1}) \), and for galaxies with no He II emission, we calculate \( \log({L_X}/\langle SFR \rangle) = 39.93 \, erg \, s^{-1} / (M_\odot \, yr^{-1}) \). Similar to X-ray luminosities, we once again find that the L_X/SFR values of He II emitters are marginally higher than non-emitters, but these measurements are not significantly different from each other. Therefore, we conclude that there is no clear excess of L_X/SFR in galaxies that show (narrow) He II emission and those that do not.

4.2.1 Redshift evolution

To place our measurements of L_X/SFR for both He II emitters and non-emitters in the context of the general star-forming galaxy population at high redshifts, we compare our measurements to those in the literature. We begin by looking at the redshift evolution of L_X/SFR inferred from samples of star-forming galaxies at \( z \approx 2 \) from Fornasini et al. (2019). In Figure 2 we show our measurements of L_X/SFR both for individually detected sources and stacks along with observational points of view (Basu-Zych et al. 2013a,b; Brorby et al. 2016; Fornasini et al. 2019). The shaded region marks the redshift range probed in this study. Also shown are models predicting the redshift evolution of L_X/SFR from Lehmer et al. (2016) and Aird et al. (2017). We note that the redshift evolution models shown essentially capture the ’X-ray main sequence’ of star formation, and have been calibrated using measurements at lower redshifts. The model predictions shown are normalised for star formation rates of 20 M_\odot yr^{-1}.

We find that our measurement of L_X/SFR for both He II emitters and non emitters is consistent with what has been measured for star-forming galaxies at \( z \approx 1.5 - 2.5 \), and in line with model predictions. Overall, we find little to no evolution in L_X/SFR between redshifts of 2 to 3. However, a proper study that captures the X-ray flux from the entire star-forming population in a systematic fashion is required to more accurately determine whether or not there is any redshift evolution out to \( z \approx 3 \). We note here that a key difference between the L_X/SFR determined for our sample and that of Fornasini et al. (2019) is how the SFRs are measured. For our sources, we rely on SED derived SFRs, whereas the SFRs for a majority of sources in the Fornasini et al. (2019) sample are derived using direct measurements of the He II emission line. Therefore, the time scales of star formation activity captured by rates derived from the SED and the He II line would be different.

4.2.2 Dependence on metallicity

Several studies have explored the dependence of L_X/SFR in star-forming galaxies on stellar metallicity, both from theoretical (Fragos et al. 2013a,b; Madau & Fragos 2017) and observational points of view (Basu-Zych et al. 2013a,b; Brorby et al. 2016; Fornasini et al. 2019). Almost all evidence points towards a negative correlation between L_X/SFR and metallicity, both in the local and high-redshift Universe. This anti-correlation is driven primarily by the presence of higher mass black hole binaries at lower metallicities, that increases the contribution of high-mass XRBs to the overall L_X/SFR measured.

For our He II and non-He II emitting galaxies, we presented stellar metallicity measurements in S20, which were performed by fitting spectral features in the UV spectrum following the method of Cullen et al. (2019). To achieve high enough S/N to enable metallicity measurement, we only used stacks of all He II emitters. Although such methods may not be as accurate as direct metallicity measurements from rest-frame optical emission lines, the stellar metallicities inferred can still provide valuable insights. In the context of predictions from models and previous observational evidence, we now compare whether our L_X/SFR measurements are in line with its dependence on metallicity that has been previously seen.

We once again compare our measurements with those of For-
nasini et al. (2019). Note here that Fornasini et al. (2019) use the gas-phase (O/H) ratios derived from spectroscopy as a proxy for stellar metallicity for their sample of star-forming galaxies. To facilitate comparison, we convert these (O/H) ratios to metal mass stellar metallicity for their sample of star-forming galaxies. To facilitate comparison, we convert these (O/H) ratios to metal mass.

Figure 3. Dependence of \( L_X/\text{SFR} \) on stellar metallicity. The orange square shows the measurement for all He \( \text{II} \) emitters, and red circle represents the non-He \( \text{II} \) emitters. Also shown for comparison are observations from Fornasini et al. (2019) for their samples of star-forming galaxies at \( z \sim 2 \). Overlaid on top of the observations are predictions of XRB models from Fragos et al. (2013a), in addition to the local relation between \( L_X/\text{SFR} \) and metallicity observed by Brorby et al. (2016). The metallicities measured for both He \( \text{II} \) emitters and non-emitters are taken from S20. Our measurements for both classes of galaxies at \( z \sim 3 \) are comparable with observations at lower redshifts, and also in line with both model predictions and the \( z \sim 0 \) relation. The assumed solar metallicity here is \( \log Z = -1.7 \).

Figure 4. \( L_X/\text{SFR} \) as a function of He \( \text{II} \) EW for both Bright (blue) and Faint (orange) He \( \text{II} \) emitters from the sample of S20. The individual galaxies with S/N > 2 in the X-ray image are marked with stars and \( 2\sigma \) limits are marked using downward pointing arrows. The average errors on \( L_X/\text{SFR} \) and He \( \text{II} \) EWs are shown in the top-right. It is clear that for He \( \text{II} \) emission with comparable EWs, the measured \( L_X/\text{SFR} \) spans more than an order of magnitude. This suggests that there is no clear correlation between \( L_X/\text{SFR} \) and He \( \text{II} \) EW, leading to the conclusion that XRBs are not universally dominant in He \( \text{II} \) emitting galaxies.

5 DISCUSSION

5.1 No evidence of XRB excess in He \( \text{II} \) emitters

We find that the differences between \( L_X \) and \( L_X/\text{SFR} \) of He \( \text{II} \) emitters and non-emitters are not statistically significant. These results suggest that there is no excess X-ray emission, of whatever origin, in galaxies that show strong He \( \text{II} \) emission in their spectra. As shown in S20, the metallicities measured for both He \( \text{II} \) emitters and non-emitters are comparable too, in addition to physical properties such as stellar masses and star formation rates. Since the \( L_X/\text{SFR} \) we measure for both classes of galaxies are also consistent with models and predictions for the general star-forming galaxy populations, we find that there is no discernible difference in either the X-ray emission or other physical properties of galaxies that show He \( \text{II} \) emission in their spectra. 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Since the \( L_X/\text{SFR} \) we measure for both classes of galaxies are also consistent with models and predictions for the general star-forming galaxy populations, we find that there is no discernible difference in either the X-ray emission or other physical properties of galaxies that show H

Our findings are in line with what was reported by Senchyna...
et al. (2019), who found no strong correlation between $L_X$/SFR and He II/Hα ratios for a small sample of nearby galaxies, leading them to conclude that high-mass XRBs are not dominant contributors to the He II ionising photon budget. However, our results appear to be inconsistent with the findings of Lebouteiller et al. (2017), Schaerer et al. (2019) and Heap et al. (2019), who reported that contribution from XRBs in the well-studied metal-poor galaxy in the local Universe, I Zw 18, can account for the nebular He II (4468 Å) seen in its spectrum. These studies also showed that the X-ray luminosities observed in this galaxy are in line with the metallicity dependence of XRBs.

The fact that we find no clear excess of X-ray emission in galaxies that show He II emission compared to those that do not suggests that within the scope of this analysis, we do not find evidence of high-mass XRBs being the dominant sources of He II ionising photon production in $z \sim 3$ galaxies. Although the narrow He II emitting galaxies do show a marginal excess in X-ray emission, with the current data (and limits on errors) available we can not definitively conclude whether this excess is statistically significant. Since the CDFS 7 Ms X-ray data is the deepest available in any extragalactic field, the step forward might be to reduce error bars on X-ray measurements from He II emitters through the identification of much larger samples of He II emitting galaxies.

5.2 Presence of obscured AGN?

The photon energies required to ionise He II ($E > 54$ eV) are easily produced in the accretion disks of active galactic nuclei (AGN) across redshifts. However, the presence of AGN in high-redshift galaxies leads to the excitation of other emission lines that also require extremely high energy photons, in addition to brightness at radio and X-ray wavelengths. S20 used radio or X-ray detections, as well as detection of C IV in emission to identify possible AGN in the sample, and these sources were removed from the analysis presented in this study (even though the presence of both He II and C IV can be explained using some stellar models without the need for AGN). With the addition of deeper X-ray photometry, we can explore whether weaker or obscured AGN could still be present in the sample of He II emitters.

Thanks to the choice of observing band (0.8 – 3 keV) and the redshift of our sources, the strong Fe Kα emission line at a rest-frame energy of 6.4 keV, often associated with reflection of X-ray emission from the accretion disk of the AGN (e.g. Lightman & White 1988), is in principle observable for our sample. Ricci et al. (2014) showed that the Fe Kα line is observed both in obscured and unobscured AGN. Therefore, if the He II emission in some sources is indeed originating from the AGN, we can expect to see some contribution of the bright Fe Kα line at the X-ray wavelengths probed. Comparing the X-ray counts and luminosities of He II emitting and non-emitting galaxies, we already showed that there is no statistically significant difference between the two. Therefore, in the context of emission from AGN, this means that there is no clear contribution from the Fe Kα line to the X-ray luminosity of He II emitters. In combination with the lack of other clear AGN signatures in the spectra of He II galaxies presented in S20, we may conclude that the scenario where faint or obscured AGN are powering the He II emission seen is unlikely.

Further, we can use the stacked X-ray luminosities determined for various classes of He II emitters to estimate the likelihood of the presence of obscured AGN, based on luminosity functions from the literature (e.g. Aird et al. 2015; Buchner et al. 2015). Vito et al. (2018) extended such studies to fainter X-ray luminosities and calculated the fraction of obscured AGN both as a function of X-ray luminosity as well as redshift using the Chandra 7Ms image. Vito et al. (2018) showed that this fraction drops rapidly at luminosities below $L_{2-10\text{ keV}} = 10^{42}$ erg s$^{-1}$ in the redshift range $z = 3 – 6$ (however, their sample is incomplete below this luminosity limit too). The stacked X-ray luminosities measured for our He II emitting sample are in the range $L_{2-10\text{ keV}} = 10^{41.4-41.5}$ erg s$^{-1}$, and the observed drop in the fraction of obscured AGNs at low X-ray luminosities suggests that the presence of obscured AGNs in the He II emitting sample is highly unlikely. Further, Circosta et al. (2019) showed that even obscured AGN at $z > 2.5$ can have X-ray luminosities in excess of $L_X > 10^{42}$ erg s$^{-1}$, which is much larger than the luminosities we find for He II emitting sources in this study.

5.3 Other possible explanations for He II

Apart from XRBs and AGN, there may be localised high-mass star formation occurring in certain regions of the galaxy that could be powering the He II emission that is observed in the UV spectra. For high-redshift galaxies, the SED inferred physical properties (with limited resolution and sensitivity) tend to get averaged over the entire galaxy. Therefore, comparable metallicities and X-ray luminosities of galaxies that show He II emission and those that do not suggest that the physical properties of both these classes of objects are largely similar. However, some differences in stellar populations are needed to explain the He II emission seen in some galaxies. Since $L_X$/SFR of star-forming galaxies is dependent on metallicity (although with some scatter), it may be possible that there are localised regions of high-mass, low-metallicity star formation, possibly also hosting more XRBs, within He II emitting galaxies. S20 showed that the stacked rest-frame UV spectrum of all He II emitting galaxies has stronger nebular emission lines when compared to the stack of non-He II emitters, suggesting recent star formation. A scenario where star forming clumps at low metallicity, which ultimately power the He II (and other nebular) emission, are present in a galaxy with an overall evolved stellar population cannot be ruled out. Since the X-ray luminosities measured from the CDFS image also encapsulate emission from the entire galaxy, it is impossible to study any spatial effect in the X-rays for the He II emitting galaxies.

In the local Universe where galaxies are spatially resolved, it is possible to study the spatial overlap between He II emission, regions of intense star formation and/or X-ray point sources. Kehrig et al. (2018) studied X-ray emission from the metal-poor starburst galaxy SBS 0335-052E showing He II 4686 Å emission in the local Universe, and reported that the low X-ray luminosities of point sources detected within the galaxy effectively rule out significant contribution from XRBs to the He II ionising budget, even though X-ray sources are spatially coincident with the He II emitting regions. Kehrig et al. (2018) concluded that ionisation by single metal-free stars or binary stars with $Z < 10^{-5}$ with a top-heavy initial-mass function in current stellar population models is the most likely explanation for the He II emission observed in this particular galaxy. However, Schaerer et al. (2019) suggested that beaming effects on X-ray emission, which result in relatively low observed X-ray fluxes but do not rule out contribution from XRBs towards the He II ionising budget, may offer an explanation.

As argued by S20, even though it remains unclear whether XRBs are the dominant producers of He II ionising photons or not, binary-star models (Eldridge et al. 2017) overall do a better job at producing more He II ionising photons compared to single star models (see also Steidel et al. 2016). Recent modelling of production of ionising radiation in star-forming galaxies by Plat et al. (2019)
showed that the highest He ii EWs are produced in low-metallicity stellar populations (both single and binary-star models) with high ionisation parameter values, log $U \gtrsim -2$. However, to explain the highest He ii EWs observed in the literature, the stellar populations must have very young ages ($\log \text{age}/\text{yr} < 7$). Plat et al. (2019) also showed that although contribution from XRBs could play a role, they may not be the dominant sources of He ii ionisation. Improvements in the predicted number of photons and inclusion of other physical phenomena associated with the evolution of massive (binary) stars, such as contribution from massive stars whose outer envelope has been stripped due to binary interactions exposing a helium core (Göteborg et al. 2018, 2019) may be needed to match the observed He ii EWs at high redshifts.

It may also be possible that small pockets of metal-free, Pop III-like stars exist within galaxies that show strong He ii emission (Tumlinson et al. 2001; Schaerer 2003; Scannapieco et al. 2003). Pop III stars, in combination with a more widespread population of Pop II (metal-enriched) stars, may be able to explain the bright He ii emission seen in high redshift galaxies (e.g. Vishal et al. 2017). We note, however, that not all strong He ii emitters in the S20 sample show a strong Lyα emission line, which is an important requirement for ionisation by Pop III-like stars. Additionally, a population of very massive stars (VMS) at low metallicities could be capable of producing the narrow He ii emission line, primarily due to strong but slower Wolf-Rayet type stellar winds (Gräfener & Vink 2015).

Finally, fast radiative shocks are known to be capable of powering high-ionisation emission lines in local, metal-poor galaxies (e.g. Thuan & Izotov 2005; Izotov et al. 2012) and such shocks may also play an important role in powering the narrow He ii emission seen in star-forming galaxies at high redshifts. However, isolating the impact of radiative shocks requires using the classical BPT diagnostics (Baldwin et al. 1981), and observations of rest-frame optical emission lines of He ii emitting galaxies at high redshifts using the James Webb Space Telescope may shed some light on the effects of shocks in these galaxies.

6 SUMMARY AND CONCLUSIONS

Building upon the sample of He ii J1640 emitting galaxies at $z \sim 2.2 - 5$ presented in S20, in this study we have presented their X-ray properties using the Chandra 7 Ms X-ray data in the CDFS field, the deepest X-ray data set available in a well studied extragalactic field. We have performed aperture photometry at the locations of He ii emitting galaxies to determine their X-ray fluxes and luminosities. To boost the effective exposure times and infer the average X-ray properties of the population of He ii emitting galaxies, we have also employed stacking analysis to calculate stacked X-ray luminosities. To put the X-ray properties of He ii emitting galaxies in context, we have performed a bootstrap analysis to measure X-ray luminosities of galaxies with no He ii emission in their UV spectra, but with comparable physical properties and redshifts. The main conclusions of this study are as follows:

- For individual galaxies with S/N > 2.5 in X-rays, we find luminosities in the range $L_{2-10 \text{ keV}} = 3.1 - 5.6 \times 10^{41} \text{ erg s}^{-1}$. Using stacking analysis, we find that the stacked X-ray luminosity of all He ii emitters is $L_{2-10 \text{ keV}} = 2.6 \times 10^{41} \text{ erg s}^{-1}$, and of only narrow (FWHM(He ii) < 1000 km s$^{-1}$) He ii emitters is $L_{2-10 \text{ keV}} = 3.2 \times 10^{41} \text{ erg s}^{-1}$.
- We then calculate the X-ray luminosities from randomly drawn samples non-He ii emitting galaxies using bootstrapping, finding $L_{2-10 \text{ keV}} = 2.5 \times 10^{41} \text{ erg s}^{-1}$ for non-He ii emitters. Although the stacked X-ray luminosity of He ii emitting galaxies is marginally higher than that of galaxies with no He ii, the difference is not statistically significant. Therefore, we conclude that there is no evidence of enhanced X-ray emission in galaxies that show He ii emission in their spectra at $z \sim 3$.
- To study what this result means for the impact of X-ray binaries (XRBs) in He ii emitting galaxies, we compare the $L_X$/SFR for galaxies with and without He ii. Once again we find that $L_X$/SFR measured for stacks of He ii emitters are marginally higher than that for galaxies with no He ii emission, but these values are again not significantly different and consistent within error bars.
- The redshift evolution and metallicity dependence of $L_X$/SFR measured in our stacks is consistent with what has been reported in the literature for galaxies at lower redshifts. Our measurements at $z \sim 3$ are compatible with models predicting the redshift evolution of $L_X$/SFR based on the ‘X-ray main sequence’ of star-forming galaxies, and we find little to no redshift evolution between $z \sim 2 - 3$. The metallicity dependence of $L_X$/SFR derived from our measurements is also consistent with little to no evolution at the lowest metallicity values.
- We find no clear correlation between $L_X$/SFR measured for individual X-ray detected He ii emitters and the equivalent width of their He ii emission. We also find that most of the bright He ii emitters do not show any X-ray detection. Therefore, we conclude that there is no direct link between contribution of XRBs to the strength of He ii in star-forming galaxies at $z \sim 3$.
- Given the low values of $L_X$ inferred from stacks of He ii emitters, we argue that even weak or obscured AGNs can be ruled out. Therefore, the He ii emission could either be powered by localised high-mass star formation, very high mass single or binary stars with low metallicities, viewing angle effects from XRBs or radiative shocks.

To discriminate between the various underlying mechanisms that are possibly powering galaxies showing He ii emission at high redshifts, a multi-wavelength approach is essential. For example, access to rest-frame optical spectra with high S/N can help determine the physical properties of the stellar populations and enable more accurate metallicity measurements for He ii emitting galaxies. Follow-up observations with high-spatial resolution, both through imaging and spectroscopy, may help isolate regions of enhanced star formation in these galaxies that could be powering the strong He ii emission lines observed. Improvements to modelling the origin of radiation from massive (binary) stars and including them in stellar population synthesis codes may also bring us closer to addressing the missing He ii ionising photons problem. Observations with upcoming facilities such as the James Webb Space Telescope and the Extremely Large Telescope may reveal answers to pressing questions surrounding the production of high energy photons from stars that ultimately escape from galaxies in the very early Universe and drive the process of reionisation.

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