Emission Line Galaxies in the SHARDS Hubble Frontier Fields. II. Limits on Lyman-continuum Escape Fractions of Lensed Emission Line Galaxies at Redshifts 2 < z < 3.5

Alex Griffiths1, Christopher J. Conselice2, Leonardo Ferreira1, Daniel Ceverino3,4, Pablo G. Pérez-González5,6, Olga Vega6, Daniel Rosa-González6, Anton M. Koekemoer7, Danilo Marchesini8, José Miguel Rodríguez Espinosa6, Belén Alcalde Pampliega11,12, and Elena Terlevich6

1 School of Physics and Astronomy, The University of Nottingham, University Park, Nottingham NG7 2RD, UK
2 Jodrell Bank Centre for Astrophysics, University of Manchester, Oxford Road, Manchester UK; conselice@manchester.ac.uk
3 Departamento de Física Teórica, Facultad de Ciencias, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
4 Instituto de Astrofísica de Canarias, E-38205 La Laguna, Spain
5 Centro de Astrobiología (CAB, CSIC-INTA), Carretera de Ajalvir km 4, E-28850 Torrejón de Ardoz, Madrid, Spain
6 Instituto Nacional de Astrofísica, Óptica y Electrónica, AP 51 y 216, 72000, Puebla, Mexico
7 Space Telescope Science Institute, Baltimore, MD 21218, USA
8 Physics and Astronomy Department, Tufts University, 574 Boston Ave., Medford, MA 02155, USA
9 Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Spain
10 Dipartimento di Fisica e Astronomia, Università di Padova, vicolo dell'Osservatorio 3, I-35122 Padova, Italy
11 European Southern Observatory (ESO), Alonso de Córdova 3107, Vitacura, Casilla 19001, Santiago de Chile, Chile
12 Departamento de Física de la Tierra y Astrozfíscia, Facultad de CC Físicas, Universidad Complutense de Madrid E-2840 Madrid, Spain

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Abstract

We present an investigation of escape fractions of UV photons from a unique sample of lensed low-mass emission line–selected galaxies at z < 3.5 found in the SHARDS Hubble Frontier Fields medium-band survey. We have used this deep imaging survey to locate 42 relatively low-mass galaxies down to log(M∗/M⊙) = 7 in the redshift range 2.4 < z < 3.5 that are candidate line emitters. Using deep multiband Hubble UVIS imaging, we investigate the flux of escaping ionizing photons from these systems, obtaining 1σ upper limits of f_{esc} ∼ 7% for individual galaxies and <2% for stacked data. We measure potential escaping Lyman-continuum flux for two low-mass line emitters with values at f_{esc} = 0.032_{-0.006}^{+0.007} and 0.211_{-0.006}^{+0.010}, both detected at the ~3.2σ level. A detailed analysis of possible contamination reveals a <0.1% probability that these detections result from line-of-sight contamination. The relatively low Lyman-continuum escape fraction limit and the low fraction of systems detected are an indication that low-mass line-emitting galaxies may not be as important a source of reionization as hoped if these are analogs of reionization sources. We also investigate the structures of our galaxy sample, finding no evidence for a correlation of escape fraction with asymmetric structure.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594)

1. Introduction

The universe started off as a hot plasma consisting mostly of free electrons and protons. Roughly 350,000 yr after the Big Bang, the universe had cooled enough such that these electrons and protons combined together to form neutral hydrogen atomic gas which was opaque to electromagnetic radiation. Today, we know that the universe is once again, for the most part, ionized.

With the universe about 100-150 million years old, the hydrogen gas which was opaque to electromagnetic radiation condensed into a structure driven by the gravitational lensing of the early universe. This structure formed stars and galaxies, and the cosmic microwave background observations

(absorption in light emitted below the Lyman limit, the lower energy limit in which photons are able to ionize hydrogen (e.g., Fan et al. 2006; Flury et al. 2022)). This puts a lower limit on reionization as having occurred at z > 6. The upper limit of this epoch is determined by the Thompson scattering of electrons from cosmic microwave background observations.

The latest Planck results (Planck Collaboration et al. 2018) suggest that the reionization of the universe happened relatively fast and late, with a midpoint redshift of z = 7.7 ± 0.7. These results are consistent with theories whereby reionization is driven primarily by massive stars and possibly AGN in low-mass galaxies (e.g., Duncan & Conselice 2015; Robertson et al. 2015; Parsa et al. 2018; Naidu et al. 2020). However, we lack precise, direct measurements of the amount of ionizing photons escaping from galaxies of different masses, especially for those at lower masses, which are the most common.

These low-mass galaxies within the EoR are difficult to study due to their faintness and the opacity of the intergalactic medium (IGM) at high redshifts (e.g., Vanzella et al. 2018). Searches for these systems are often aided by the strong gravitational lensing powers of galaxy clusters (e.g., Bhatawdekar et al. 2019) and now JWST (e.g., Bradley et al. 2022; Trussler et al. 2022; Adams et al. 2023). High-redshift samples are, however, still often biased toward the most luminous sources whose light is able to permeate through the high column density of the IGM. This
includes bright quasars and galaxies with strong Ly\(\alpha\) emission. It therefore remains possible that the bulk of galaxies responsible for reionization have yet to be discovered or properly identified.

Recent works have suggested that star-forming galaxies alone may not be sufficient to drive reionization. With new optical depth estimates from Planck (Planck Collaboration et al. 2018), the need for a large ionizing background at high redshifts is reduced. Combined with the discovery of early \((z > 4)\) populations of faint AGN (Glikman et al. 2011; Giallongo et al. 2015), this has prompted a reassessment of the contribution of AGN to cosmic reionization. Observational evidence (Giallongo et al. 2015; Madau & Haardt 2015) and theoretical studies (Yoshiura et al. 2017; Torres-Alba et al. 2020) show that AGN are possibly able to provide a significant source of ionizing flux, while investigations of known Lyman-continuum (LyC) leakers indicate potential AGN components (e.g., Jia et al. 2011; Prestwich et al. 2015; Kaaret et al. 2017; Grazian et al. 2018). However, other studies, e.g., Parsa et al. (2018), show that AGN may in fact not be needed or an important aspect of reionization. There is, therefore, significant debate in this matter that further observations can help address.

As well as the internal feedback from AGN and star formation, external influences, such as the merger history, can play a crucial role in the production of escaping ionizing photons. This is particularly important in low-mass halos (e.g., Chen et al. 2014), in which a merger event can readily expel large fractions of gas from the interstellar medium (ISM), resulting in lower column densities in which ionizing radiation can propagate more freely. For more massive galaxies, it has even been shown that fast accretion shocks associated with gravitational infall of baryons due to events such as mergers can also contribute to reionization (e.g., Dopita et al. 2011; Wyithe et al. 2011).

In the last few decades, significant effort has gone into searching for sources of escaping LyC radiation over various redshifts; however, many studies report nondetections, yielding mostly upper limits for individual sources. At low redshifts \((0 < z < 3)\), Leitherer et al. (2016) and Puschneg et al. (2017) reported detections in local starbursts, while a number of compact star-forming galaxies selected by their high nebular oxygen ratios have been shown to exhibit nonnegligible escape fractions (e.g., Izotov et al. 2016; Verhamme et al. 2017). At intermediate redshifts, Bian et al. (2017) detected LyC emission from a gravitationally lensed compact dwarf galaxy at \(z \approx 2.5\). It is still, however, largely the case that galaxies with unambiguous escaping LyC emission are relatively rare.

Furthermore, this is a difficult measurement to make, as at higher redshifts, light from foreground galaxies along the line of sight can be a significant source of contamination (e.g., Bridge et al. 2010; Vanzella et al. 2012; Mostardi et al. 2015; Siana et al. 2015). A high IGM opacity also makes individual measurements challenging, which increases as we probe higher redshifts. However, it is possible to place constraints on reionization through the study of galaxy populations while making assumptions about the IGM clumping factor. Finkelstein et al. (2012) put limits on the escape fraction by investigating the luminosity density of a sample of 483 galaxies at \(z \approx 6–8\) selected from the CANDELS fields (Grogin et al. 2011; Koekemoer et al. 2011). Other studies, such as Grazian et al. (2012), use CANDELS data to examine the size–luminosity relation of 153 Lyman break galaxies (LBGs) at \(z \sim 7\) to infer limits on their contribution to reionization. These studies typically find that the luminosity function of star-forming galaxies must extend down to \(M_{\text{UV}} \sim -13\) in order to fully reionize the universe by \(z = 6\).

To circumvent some of these issues, in this paper, we examine lower-redshift analogs of the galaxies that might play a key role in the reionization of the universe: those of low-mass or dwarf systems. However, this does not come without its challenges. These dwarf galaxies, while being the most abundant type of galaxy in the universe, are difficult to detect due to their low mass and luminosity, which both contribute to their faintness and low surface brightness. Developments in data analysis techniques and deep survey strategies have helped to provide further insight into this population via group/cluster (e.g., Ferrarese et al. 2012; Kondapally et al. 2018) and field (e.g., Leisman et al. 2017) studies.

Galaxies at redshifts \(z \approx 3–4\) are within the ideal redshift range for the identification of LyC emission (e.g., Steidel et al. 2018). At \(z \gtrsim 3\), the Lyman limit is redshifted into the rest-frame \(U\) band, where the sky background is dark and the atmosphere is transparent, allowing for observations from ground-based telescopes. These sources also benefit from low IGM opacities. However, a limited number of LyC emitters have been identified at these redshifts to date (e.g., de Barros et al. 2016; Shapley et al. 2016; Vanzella et al. 2016; Marchi et al. 2018; Steidel et al. 2018; Fletcher et al. 2019; Naidu et al. 2020; Nakajima et al. 2020; Pahl et al. 2021), as searches are complicated by low-redshift interlopers that can result in false detections, requiring high-resolution imaging and spectroscopy for confirmation. To understand which galaxies might be analogs of the sources producing reionization, we explore different types of galaxies, including lower-mass ones such as those discussed in this paper.

In order to establish how important lower-mass sources could be as a driver for reionization, it is necessary to determine the net fraction of ionizing radiation that is able to escape the high column density H I gas surrounding these low-\(z\) counterparts. This is achieved by measuring the escape fraction, \(f_{\text{esc}}\) (Steidel et al. 2001), a parameterization of the fraction of LyC ionizing photons that are not absorbed by either the ISM surrounding young stars, the host galaxy’s circumgalactic medium (CGM), or the IGM.

As such, in this paper, we measure the escape fractions in a sample of lensed emission line galaxies identified via medium-band imaging observations, utilizing the strong lensing features of two Hubble Frontier Fields (HFF) clusters. Our data are unique in that our sources are discovered in very deep medium-band imaging from the SHARDS Frontier Fields (SHARDSFF) survey obtained with the Gran Telescopio de Canarias (GTC), with follow-up UV imaging from the Hubble Space Telescope (HST).

This paper is outlined as follows. In Section 2, we provide an overview of the observations and ancillary data, as well as details of the medium-band selection procedure. We calculate escape fraction upper limits for stacked and individual sources and detail our structural classification in Section 3. Finally, we discuss our main results and draw conclusions in Sections 4 and 5. Throughout this paper, we adopt a \(\Lambda\) cold dark matter cosmological model with \(\Omega_{\Lambda} = 0.7\), \(\Omega_M = 0.3\), and \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\). All magnitudes are given in the AB system (Oke 1974).
Figure 1. Transmission curves of the medium-band SHARDS filters (F517W17, F823W17, F883W35, F913W25, and F941W33) and broadband HST filters (F606W, F814W, and F105W) used for the selection of emission line galaxies. All curves have been individually normalized by their maximum transmission. We use the SHARDS medium-band filters to select our line emitter candidates in comparison to the broadband HST filters (F606W, F814W and F105W), whose filter transmission curves are also shown.

2. Observations and Data Reduction

The present analysis is based on new medium-band observations of two of the HFF galaxy clusters (Lotz et al. 2017), A370 and MACS J1149.5+2223, and their corresponding parallel fields. We couple these medium-band observations with the multwavelength photometric catalogs made available through the HFF-DeepSpace project (Shipley et al. 2018). We focus on candidate line emitters as a subsample of star-forming galaxies and those that are likely in their early stages. It is possible that these systems are analogs of the star-forming galaxies and those that are likely in their early stages. It is possible that these systems are analogs of the sources that reionize the universe, given their low mass and line-emitting nature. We describe these samples below in some detail.

2.1. HST and Medium-band Imaging

Medium-band imaging data of the A370 and MACS J1149.5+2223 clusters (hereafter A0370 and M1149) are obtained from the SHARDS-FF survey (PI: Pérez-González). Observations simultaneously cover the clusters and their respective parallel fields in a single pointing. At the time of this study, observations of A0370 had been carried out with four SHARDS filters (F517W17, F823W17, F913W25, and F941W33), while M1149 had been observed in three filters (F883W35, F913W25, and F941W33). The SHARDS-FF observations are performed with the Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy (OSIRIS) instrument at the 10.4 m GTC at the Observatorio del Roque de los Muchachos in La Palma. A total of 240 hr of time was granted to the SHARDS-FF program with observations beginning in 2015 December. The wavelength response of these filters in comparison to the HST comparison filters is shown in Figure 1.

Individual images are reduced using a dedicated OSIRIS pipeline (Pérez-González et al. 2013). The pipeline performs bias subtraction and flat-fielding, as well as illumination correction, background gradient subtraction, and fringing removal. Additionally, the pipeline implements World Coordinate System alignment, which includes field distortions, twodimensional calibration of the passband and zero-point, and the stacking of individual frames.

In order to select emission line galaxy candidates, we require well-calibrated multiwavelength broadband catalogs. For this reason, we utilize the data made available as part of the HFF-DeepSpace project (Shipley et al. 2018). These data combine up to 17 Advanced Camera for Surveys (ACS) WFC3 filters with ultradeep Ks-band imaging and Spitzer-IRAC, when available. We also include UVIS HST observations within the filters F225W, F275W, and F336W for the M1149 cluster, and F275W and F336W for the A0370 cluster. We also utilize the F160W observations within WFC3 for morphological measurements.

The catalogs we use also include photometric redshifts and lensing magnification factors, as well as original imaging data, models, and calibration information, providing an ideal ancillary data set for candidate selection. We note here that HFF-DeepSpace observations cover only a fraction of the area surveyed by SHARDS-FF. Considering the cluster and parallel field, this roughly constitutes ~35% and ~38% of the total SHARDS-FF coverage for A0370 and M1149, respectively.

2.2. Lensing Magnification

In order to provide accurate measurements of stellar mass and luminosity derived properties, the strong gravitational lensing effects induced by these massive galaxy clusters need to be accounted for. For this, reliable lensing models are required. Fortunately, for each of the six HFF clusters, seven independent teams have undertaken work to produce lens models, each employing various methods and initial assumptions. The magnification factors derived from these models are provided in the HFF-DeepSpace data set, and the full details of their derivation can be found in Section 5.5 of Shipley et al. (2018). For further information on the lensing models, we refer the reader to the MAST website.13 To demagnify stellar masses and exclude any outliers, we take the median magnification factor (μ, provided in later tables) from all of the lens models available in the HFF-DeepSpace data.

We find an average lensing magnification for the sample of μ = (2.98) across all galaxies in our sample. The distribution is, however, very skewed, with the mode = 1, where many galaxies are not magnified at all, and the maximum value is 19.48. The mean absolute deviation of the magnification values is 2.22. We use the individual magnification factors to demagnify the fluxes for each galaxy in our sample from

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13 https://archive.stsci.edu/prepds/frontier/lensmodels/
which we calculate the stellar mass and UV magnitudes for our systems, which we use later in this paper. All of these values, which we use throughout, have been demagnified by each galaxy’s magnification factor unless otherwise stated.

2.3. Selection of Line Emitters

We focus this paper on candidate line emitters at $z > 2$, as we can with some confidence conclude that they are at these redshifts. However, we will need spectroscopy to confirm that these single lines are within our redshift of interest. We examine these systems in detail, as line emitters might also be more likely to contain a high escape fraction and/or higher levels of ionizing photons (Stark et al. 2015; Naidu et al. 2022; Schaerer et al. 2022), as opposed to normal star-forming galaxies without line emission. Part of the reason is that it is not yet clear whether or not galaxies that are line emitters are always more likely to produce LyC emission that escapes. For example, Wang et al. (2021) found fewer LyC leakers as a function of measured [S II] line equivalent width (EW), implying that galaxies with escaping LyC flux are more likely to be found at lower line fluxes. This is thus an important question that deserves more attention.

To select for emission line galaxy candidates, the medium-band data are flux calibrated to match the existing broadband catalogs. In this section, we provide a brief summary of the data calibration and candidate selection relevant for this paper. A full discussion and details for the entire set of SHARDS-FF data is provided in Griffiths et al. (2021).

First, we calculate the aperture photometry of all individual medium-band mosaics using SExtractor (Bertin & Arnouts 1996) in dual-image mode, using deep detection images from the HFF-DeepSpace data set. We do this carefully by matching point-spread functions (PSFs) and aligning the data between the bands. First, we match all observations to the PSF of the SHARDS F883W filter, which has a seeing of $\sim 1''0$. We do this by deriving convolution kernels for each band using the PSFs retrieved from the SHARDS and Hubble data sets (see Griffiths et al. 2021 for more detail). Once this is done, we then use $2''$ apertures to recalculate the photometry in SExtractor’s dual-image mode, utilizing the deep detection images from the HFF-DeepSpace data (see Shipley et al. 2018, their Section 3.3). We correct for any flux falling outside of the $2''$ apertures by deriving total flux values. Aperture photometry is adjusted by applying a correction factor calculated for each galaxy, although in practice, this is small.

After converting aperture fluxes to total flux, we correct for galactic extinction and standardize all zero-points to 25, as our photometry is adjusted for empirically determined zero-point errors (see Skelton et al. 2014, for further details).

To perform candidate selection, we first calculate photometric redshifts using our new medium-band data with the HST data using EAZY14 (Brammer et al. 2008). We run EAZY on an object-to-object basis due to the spatially varying central wavelengths of the SHARDS-FF filters. The geometric effects of the SHARDS-FF observations are due to the incidence angles of the GTC/OSIRIS light beam, which causes the effective central wavelength of the filter to vary as a function of location within the image. The central wavelength is calculated for each object in order to provide more accurate photometric redshift estimates. We further use the stellar population synthesis code FAST15 (Kriek et al. 2009) to estimate stellar masses, star formation rates, ages, and dust extinctions based on the photometric redshifts from the EAZY output.

For the selection of emission line candidates among galaxies in our redshift range of interest, we employ a two-parameter selection method that has been well established in previous studies (e.g., Matthee et al. 2015; Santos et al. 2016; Sobral et al. 2017). These criteria ensure that the objects selected show real color excesses due to an emission line, not from random scatter or measurement uncertainties. The first of these criteria is to set a lower limit on the observed emission line EW. We follow the methods used in previous searches and set an observed EW cut of 25 Å (e.g., Ouchi et al. 2008) to remove sources with little or no excess in the medium band. The EW is calculated via the equation

$$EW = \frac{\Delta \lambda_{MB}}{f_{MB} - f_{BB}} \frac{f_{BB} - f_{MB}}{\Delta \lambda_{BB}}$$

(1)

where MB stands for medium band, and BB stands for broadband, such that $\Delta \lambda_{MB}$ and $\Delta \lambda_{BB}$ are the widths of the medium- and broadband filters, respectively, and $f_i$ are the flux densities. The second criterion we use for the line emitter selection is the excess significance ($\Sigma$; e.g., Bunker et al. 1995). This is used to quantify whether the flux excess is real or due to random scatter. The excess significance is calculated as (Sobral et al. 2013)

$$\Sigma = \frac{1 - 10^{-0.4(ZP - MB)}}{10^{-0.4(ZP - MB)}(\frac{\sigma_{\text{BB}}^2}{\sigma_{\text{MB}}^2})^{0.5} \sqrt{\pi r_{\text{ap}}^2 (\sigma_{\text{BB}}^2 - \sigma_{\text{MB}}^2)}}$$

(2)

where MB and BB are the medium- and broadband magnitudes, respectively; ZP represents the normalized zero-point (25); and $r_{\text{ap}}$ is the aperture radius in pixels. The rms of the background pixel values, $\sigma_{\text{px}}$, is estimated by randomly placing empty apertures across the respective images. A selection criterion of $\Sigma > 3$ is used to classify sources as potential line emitters (Sobral et al. 2013). We show the visual representation of this selection process for the A0370 cluster and the F913W medium-band filter in Figure 2.

To select potential LyC emitters from our overall sample of emission line galaxies, we utilize HST/UVIS observations; this includes filters: F225W, F275W, and F336W for the M1149 cluster, but is limited to only F275W and F336W for the A0370 cluster (note that these data are not available for the parallel fields). From the total sample of emission line candidates, these filters permit a search for potential LyC emitters over the redshift range $z \approx 2 - 3.5$, yielding a total subsample of 62 candidate objects that were originally in our first cut sample. Ultimately, we narrow this down to 42 objects, and in Table 1, we provide a full breakdown of the filter-dependent redshift ranges and final emission line number counts.

The redshifts of our final objects were selected so as to include LyC radiation within a filter of observations. We also are careful to remove objects with redshifts that might be affected by red leaks. We select these redshift ranges to ensure as much as possible that nonionizing continuum radiation at $>912$ Å is $<1\%$ of the light we detect in the UVIS filters. From our calculations, which mirror those of Smith et al. (2020), we

14 https://github.com/gbrammer/eazy-photoz/

15 http://www.astro.berkeley.edu/~mariska/FAST.html
determine that at most only a single object we observe will have more flux contamination than this due to the red leak. Neither of our individual detections, however, would be affected by this.

The redshift and stellar mass distributions of the final subsample we use in our detailed analyses for LyC escaping light are shown in Figures 3 and 4, respectively. As mentioned early, these values have been demagnified as outlined in Section 2.2.

### 2.4. Spectroscopic Redshifts and Selected Emission Lines

When available, we utilize spectroscopic redshifts obtained from the HFF-DeepSpace catalogs, as well as from VLT/MUSE observations via the work of Lagattuta et al. (2019). Spectroscopic redshifts in the HFF-DeepSpace catalogs are compiled from the literature (see Section 5.1 of Shipley et al. 2018), while Lagattuta et al. (2019) investigated the MUSE observations obtained as part of program 096.A-0710(A) (PI: Bauer) with a combination of targeted extractions based on HST imaging and a “blind” emission line search. Spectroscopic redshifts are available for nine of our candidates; comparing these values to our photometric redshift estimates, we find that our photo-zs are robust with an average $\Delta z/(1 + z) = 0.04$, with the exception of object ID 2330, which is found to be contaminated by a nearby bright source ($z_{\text{phot}} = 2.06, z_{\text{spec}} = 3.81$). This is a higher-redshift accuracy than what was found in the overview paper of Griffiths et al. (2021). This is due to the fact that we are studying a sample of galaxies at a well-defined redshift range, whereby the photometric redshifts are more straightforward to measure than at lower or higher redshifts. Given that Griffiths et al. (2021) spanned the entire redshift range of possible line emitters, it is natural for the accuracy of photometric redshifts to be lower for this larger range.

The combination of available HST/UVIS data and our medium-band selection method provides a unique opportunity to probe a rarely studied population of lower-mass galaxies in the range $2 < z < 3.5$ that have emission lines. With the exception of a few systems, such as galaxy ID 1629, which is...
selected by the Ly$\alpha$ 1216 Å line, our sample is identified via lines typically present in the galaxies thought to be analogs of those that contribute significantly to reionization at $z > 6$. These lines possibly include rest-frame UV emission lines such as C IV, N V 1240 Å, C iii] 1909 Å, Mg ii 2798 Å, various Fe lines, and the 2175 Å bump. These lines are present in AGN and low-metallicity star-forming regions, where hard spectra from low-metallicity stars can excite the higher-ionization lines. However, without spectroscopy, we cannot confirm the exact line identification for our candidates. Our sample is ultimately a photometric redshift selection of galaxies detected with line emission with a redshift that places them within the range where they can have their LyC light examined in the range $2 < z < 3.5$.

We remove from our sample any systems where there are no possible corresponding emission lines near the measured photometric redshift. We can better understand our photometric redshift distribution if we consider our photo-$z$ accuracy of $\delta z/ (1 + z) \sim 0.04$, resulting in a $\delta z \sim 0.16$–0.18 uncertainty, within our redshift range. This can account for some of the blurred distribution seen in Figure 3, where we would normally expect to find discrete redshifts based on where known lines would be located in our filters.

Thus, our sample provides a method for identifying candidate faint and low-mass galaxies at these redshifts. Figures 3 and 4 show the distribution of stellar masses and photometric redshifts for our line emitter sample that we study throughout this paper. It is important to note that without further spectroscopic follow-up, it is difficult to exactly identify the appropriate emission line(s) responsible for the observed flux excess at these redshifts. This is beyond the scope of this paper, and as such, we make no inferences about the properties of our sample galaxies based on this selection, although it is possible that a fraction are AGN. Follow-up spectroscopy of our sources will be required to confirm their exact redshifts, determine the observed emission line identity, and confirm any AGN nature.

### 3. Results

For the remainder of this paper, we discuss the LyC limits for our sample and examine two tentative detections of LyC emitters from our photo-$z$/line emission sample. We first give a description of our formalism and then discuss the individual LyC-detected objects. We then analyze the stacked limits for the sample itself based on this formalism.

#### 3.1. LyC Escape Fraction Formalism

The UV escape fraction of high-redshift galaxies can be derived from differential measurements of the ionizing flux (LyC, $\lambda_{\text{rest}} \lesssim 912$ Å) compared to nonionizing (UV, $\lambda_{\text{rest}} \gtrsim 1500$ Å) emission. However, as the intrinsic spectral energy distribution (SED) of galaxies is not typically known, and the LyC from young stars is readily attenuated through the ISM and IGM, relative escape fractions are usually derived from observations while making assumptions on the intrinsic flux ratio based on models.

The relative escape fraction, $f_{\text{esc}}$, was first introduced by Steidel et al. (2001) and is defined as the fraction of escaping LyC photons divided by the fraction of escaping nonionizing (UV) photons. Following Shapley et al. (2006) and Siana et al. (2007), the relative escape fraction is derived from the observed flux density ratio ($f_{\text{UV}}/f_{\text{LyC}}$) via the equation

$$f_{\text{esc}} = \frac{(f_{\text{UV}}/f_{\text{LyC}})_{\text{int}}}{(f_{\text{UV}}/f_{\text{LyC}})_{\text{obs}}} \exp(\tau_{\text{IGM}}),$$

where $(f_{\text{UV}}/f_{\text{LyC}})_{\text{int}}$ is the intrinsic flux ratio, and $\exp(\tau_{\text{IGM}})$ is the inverse of the redshift-dependent IGM attenuation of LyC by neutral H I.

#### 3.2. Individual Limits

Using the methods outlined in Section 3.1, we measure relative escape fractions for our emission line–selected galaxies in two of the frontier fields clusters at $2 < z < 3.5$. We successfully measure rest-frame ionizing flux densities of more than 2σ significance in just two galaxies from our sample (as we will discuss below), suggesting the detection of leaking LyC emission within at least these two systems. We describe our measurement, tests for contamination, and, ultimately, the escape fraction limits below.

#### 3.2.1. Measurements

We measure the escape fractions of individual galaxies utilizing calibrated HST images. These images are cleaned of cosmic rays, background-subtracted, and PSF-matched, and the brightest cluster galaxies are modeled and subtracted out. We utilize all available HST/UVIS bands (filters F225W, F275W, and F336W with 1σ depths of ~29 mag) and select complementary imaging in the F435W and F606W bands in order to sample the nonionizing emission at a rest-frame UV wavelength of $\lambda \sim 1500$ Å. We define redshift ranges and filter matches such that the Lyman limit falls outside of the filter bandpass. This is necessary in order to avoid contamination by nonionizing emission in the LyC measurements. For the full details of the filter combinations and redshift ranges, see Table 1.

To measure the fluxes from our sample, we initially take total flux values from the HFF-DeepSpace catalogs for the corresponding bands, in which the well-calibrated multi-wavelength photometry provides an estimate for the LyC-to-UV flux ratios. The HFF-DeepSpace photometry is performed in SExtractor dual-image mode using a deep, stacked detection image created from the F814W, F105W, F125W, F140W, and F160W bands (see Shipley et al. 2018, for more details). However, in the majority of cases, we find no detections of LyC flux within the catalog. Instead, we utilize the segmentation maps from these deep detection images to mask objects.
and obtain reliable background estimates from which 1σ upper flux limits are estimated.

We do this because the LyC photons may be emitted from subregions of a galaxy. That is, the LyC flux may not be coplanar with the nonionizing emission or rest-frame UV flux within a galaxy (e.g., Nestor et al. 2011). Because of this, the LyC emission may not always be associated with nonionizing emission, as described in Vanzella et al. (2012). Thus, in order to obtain accurate flux ratio estimates, we conduct careful photometric measurements within the same spatial region of the ionizing and nonionizing images. As all images are matched in pixel scale and PSF, and we map isophotes from the deep detection images to the measurement images in order to obtain spatially correlated isophotal fluxes over both the LyC and UV bands.

3.2.2. Contamination Tests

Contamination of foreground galaxies near candidate UV continuum emitters is an important aspect that must be considered, as this can easily mimic actual LyC detections (e.g., Nestor et al. 2011; Vanzella et al. 2012; Mostardi et al. 2015). The reason is, if there are other galaxies apparently close in projection but at different redshifts, we could easily mistake the light from those systems as part of the object itself.

We deal with this issue in a few ways, which we explain in detail in this section. We first analyze by eye and investigate all galaxy images closely in order to check for sample contamination. All of our final LyC-detected systems are isolated with a well-defined structure and thus do not show any evidence for peculiar structures that could be due to intervening galaxies. In fact, we find and remove from our sample a total of 20 false-positive interlopers, including sources that fall outside of the HST/UVIS pointings and those with a bright object nearby, which we do not further consider.

We also investigate the likelihood of contamination in the LyC filters by investigating the number density of faint sources detected in the UV filters across our field that, in principle, could result in contamination from an overlap with our sources. To do this, we calculate the average magnitude in both UV bands for our sample of line emitters from which we investigate the LyC properties through both the direct detections and the nondetections, which we stack (Table 2).

We find that the average magnitude for detected systems in the F275W and F336W bands is ~27.5. We make the very reasonable assumption that a contaminating galaxy would have to be at about this magnitude or fainter to be considered as an interloper or contamination; otherwise, we would be able to visually remove these systems. In the F275W band, we find that the number density of these sources and fainter is 14–20 galaxies arcmin⁻², with a similar number density in the F336W band. This results in a surface density of effectively ~14.1 ± 3.6 sources arcmin⁻². Our two galaxies have LyC fluxes isolated to within around 0''2 radius aperture in size. Using this fact, we calculate the likelihood of a chance superposition based on the aperture in which these detections are made.

There are, on average, four of these 0''2 radius regions within the larger search for LyC emission centered on each galaxy. We thus calculate the likelihood that the detected flux arises from an alternative unrelated source, given the number density of background galaxies calculated in the previous paragraph. Based on this, we calculate a probability of 1 in 1400 (<0.1%) that a single LyC detection is a chance superposition with a foreground or background source. This is certainly smaller than our total number of sources and is not high enough to account for our two detections. Thus, we conclude that due to the small physical sizes of our system, and the relative paucity of sources in the field at these magnitudes, chance superposition is unlikely to be the cause of our two candidate detected LyC fluxes.

3.2.3. Escape Fraction Calculation and IGM Absorption

Ideally, intrinsic flux ratios (f_{UV}/f_{LyC})_{int} need to be modeled for each galaxy individually, where values typically range between 2 and 10. However, as the intrinsic ratio is sensitive to a host of unknown features within a galaxy’s physical properties, such as metallicities, stellar ages, and star formation histories, we assume a value of (f_{UV}/f_{LyC})_{int} = 3. This is a reasonable average and allows us to carry out a direct comparison of our results to previous work in the literature where this same assumption is made. This estimate has been shown to be appropriate for a young (\sim 10⁷ yr) stellar population of solar metallicity (Rutkowski et al. 2016). We note that low-mass galaxies are expected to be extremely metal-poor (<0.1 Z_☉) such that (f_{UV}/f_{LyC})_{int} < 3 (e.g., Bouwens et al. 2016; Ceverino et al. 2019). However, it has been shown that the amplitude of the Lyman break does not change considerably down to these metallicities, with intrinsic flux ratios dropping only as low as ~2 (e.g., Leitherer et al. 1999; Inoue et al. 2005). Thus, this assumption does not produce a large uncertainty in our results.

Neutral hydrogen clouds along the line of sight toward high-redshift galaxies can significantly affect the measured UV fluxes through both continuum and Lyman line absorption. To correct for IGM absorption, denoted by 𝜈_{IGM}, we adopt the Inoue et al. (2014) model, constructed using simulations based on observational statistics of the column density and redshift distribution of the Lyα forest, Lyman limit systems, and damped Lyα systems.

To account for this, we carry out a series of Monte Carlo simulations of IGM absorption, simulating 1000 lines of sight at the redshift of each candidate as shown in Figure 5. The mean IGM transmission can then be estimated from the resulting probability distribution convolved with the corresponding LyC filter bandpass. We also include uncertainties in our photometric redshifts for our galaxies as part of the uncertainty in the IGM optical depth, which we propagate throughout our analysis.

As explained in Steidel et al. (2018), there may also be some excess line-of-sight absorption due to traversing the CGM in the galaxy hosting the LyC emission. For samples such as ours, at low stellar mass, there has not been a detailed consideration of this effect, and for comparison to other works, we do not attempt to correct for it in this paper. The effect of this would be to only slightly increase our upper limits and detection values, especially given that lower-mass systems are likely to contain a smaller CGM. There are also no galaxies close to the line of sight for our two sources. Therefore, absorption from the CGM of the host or another foreground galaxy is also unlikely to be a major effect.

We thus use these values of IGM transmission along with the observed flux ratio, (f_{UV}/f_{LyC})_{obs}, in order to estimate the escape fraction via Equation (3).

In summary, we find that there are two galaxies in our sample with escaping LyC above 1σ when measuring isophotal
fluxes as described above. The properties of these sources are listed in Table 2, along with the other galaxies in our sample at the same redshifts that are not individually detected. The two galaxies with tentative LyC detections are numbered 809 and 803 in this table. For these two galaxies, we measure fluxes inside a 0.2°2 radius aperture centered on the peak of the flux in
the LyC band. Following a careful quantification of local background levels, we find the significance of both of these sources to be $\sim 3.2\sigma$. We calculate these galaxies’ relative escape fractions as $f_{\text{esc}}^{\text{rel}} = 0.032^{+0.003}_{-0.004}$ and $0.021^{+0.011}_{-0.006}$, respectively. Both galaxies are low-luminosity systems with $M_{\text{UV}} = -18.3$ and $-18.86$, respectively. They both also have relatively low stellar masses with $M_*=10^9 M_\odot$. These two systems are also among those at the higher end of our redshift range at $z = 3.46$ and 3.28, respectively.

For nondetections ($<1\sigma$ within the first examination), we provide upper flux limits ($1\sigma$) based on the background measurements considering only the pixels associated with the isophotes for each galaxy. The properties of these galaxies are summarized in Table 2, for which we find an average upper limit for each galaxy’s escape fraction within our sample. We find a wide range of upper limits on the escape fraction, depending on the properties of each system, but most have limits at $<0.07$.

### 3.3. Stacked Limits

In this section, we discuss in more detail how we calculate our stacked limits for the LyC escape fraction for our sample. To do this, we create stacked images in both the rest-frame ionizing and nonionizing bands for all nondetections in our sample within the same HST/UVIS filter mosaics. We do not include the two galaxies for which have individual detections when carrying out this stacking. This means that our limits do not include these two systems, and the results must be understood in this context as a limit of detections for systems within our observational setup.

As we are investigating galaxies over the redshifts range of $2 < z < 3.5$, simply stacking all objects in our emission line sample would not provide robust estimates, mainly due to variations in the IGM transmission and galaxy properties at varying redshifts. Thus, we stack candidates based on the rest-frame LyC filter, limiting the redshift range and minimizing variations in $\tau_{\text{IGM}}$. By limiting the redshift range of objects included in the stacks, we also reduce contributions from nonionizing flux in the LyC measurements, as well as the red leak in the F275W filter. We stack the rest-frame ionizing flux in the HST/UVIS F275W and F336W filters, utilizing the HST/ACS F606W filter for the corresponding rest-frame UV stacks. We do these stacks in several different ways, altering our methodology to test any variation in our results. We also apply this procedure independently for each cluster field.

We initially followed a simple stacking procedure, summing all pixels in $4^\prime \times 4^\prime$ postage stamps for both the rest-frame LyC and UV filters. However, no significant detections are seen through this basic stacking method. As described in Siana et al. (2010), variations in the sizes and morphologies of the sample galaxies can produce unreliable measurements within stacked data. For example, a strong flux measured in a pixel of one postage stamp may be compromised by noise within others where the spatial extent of the stacked galaxies can vary significantly. To account for these issues, we perform an optimized stacking procedure. As detailed in Siana et al. (2010), we sum only over the pixels in the LyC and UV stamps that are associated with the isophotes defined by the UV-band images. This stacking procedure also provides no statistically significant detection in the LyC. Furthermore, we carry out a series of stacking procedures whereby we slightly change the positions of the centers of the stacks and stack the directly observed, as well as demagnified, images. We show visual examples of one of our stacking procedures in Figures 6 and 7 for the two A0370 cluster stacks, whereas Figure 8 shows the two individual detections. As can be seen, there may be some off-center residuals after the stacking has been carried out, depending on how the alignment of the galaxies in question is done. To avoid this issue, investigated stacking procedures using slightly different centers to uncover the importance of these offsets in detecting a signal. We ultimately find that the stacking limits do not depend on this, and essentially the same limits are found through all iterations. When combining the data, we also investigate several methods, including inverse variance weighting and uniform weighting, finding essentially no difference.

We also carefully mask out neighboring objects before any stacking is carried out to ensure as much as possible that contamination from other galaxies is not entering the signal when the stack is carried out. However, this process is not foolproof, as it is possible that not all of this light is identified correctly. In general, however, any contamination from other galaxies would only raise our escape fraction limit. Since we already find very low limits, this ensures that the value of the typical escape fraction for our sample is lower than this.

As mentioned in Section 3.1, the nature of the IGM and the uncertain intrinsic flux ratios of these galaxies make the accurate measurement of average or limits of escape fractions difficult. For this reason, we also implement stacking procedures for measuring the limits of detections, enabling the study of properties of the galaxy sample in a more statistically significant manner. Due to the wide redshift range of our sample, we stack objects from each cluster into bins based on the available filters, providing four stacks in total. We do, however, note that due to the small sample size, particularly for the candidates identified in the MACS 1149 imaging, stacked results may not be representative of the galaxy population as a whole.
Note, however, that the galaxies in our stacks have a range of lensing magnification factors. This fact slightly complicates how stacking can be done and how to interpret our values. We stacked our samples both with and without demagnifying each galaxy’s light by its magnification factor. This simply means dividing the observed pixel counts in the area of the galaxy we stack by this magnification factor. We do not find any significant detections both before and after demagnifying fluxes by the magnification factor. However, to obtain our quantified escape fraction limits, we demagnify the pixel values before stacking. This ensures that the values we stack are true limits and not biased by any possible boosting by magnification. We present our stacked values in Table 3.

We also carry out our analysis after extra “cleaning” of the images to ensure our results are reliable. Using the segmentation maps to isolate neighboring sources within the postage stamps, we use a modified version of the python package galclean.\(^6\) As described in Ferreira et al. (2018), galclean makes use of Astropy’s photutils package (Astropy Collaboration et al.
2013) to replace contaminating pixels with random values sampled from the noise, such that the background distribution of each image remains unchanged. The images are then stacked as previously described. When we carry out our measurements again on these cleaned images, we also find no flux above background levels in the LyC stacks.

In Figure 9, we show the relative escape fraction \(f_{\text{esc}}^{\text{rel}}\) as a function of redshift for our sample. These relative escape fractions are corrected for IGM transmission, estimated via our Monte Carlo simulations of 1000 sight lines per object. Our tentative detected sources and the upper limits from Table 2 are displayed as the solid dark blue triangles for galaxies classified as asymmetric (mergers) and with orange solid triangles for the non-asymmetric (non-mergers), respectively. Stacked limits (Table 3) are shown as the four solid lighter blue triangles with lower escape fraction limits. Additionally, we include various results from the literature, spanning the entire redshift range of our sample.

In summary, we place stacked limits using selections for our sample on the escape fraction to be <0.01 and <0.02 in the A0370 field and slightly higher for the MACS field. Our stacked limits are thus between 1% and 4% for the escape fractions for our systems. This implies that, outside of our two direct detections, the escape fractions for these low-mass galaxies with line emission is not very high and on average these galaxies do not emit a large LyC flux. We discuss the implications of this in Section 4.1.

### 3.4. Galaxy Structure

One of our goals is understanding whether galaxy structure correlates with the escape of ionizing radiation. This is a reasonable hypothesis, as merging or other dynamically unstable events will disrupt the structure of a galaxy and potentially allow LyC photons to escape. We use the asymmetry parameter (Conselice et al. 2000) \(A\) from the CAS system (Conselice 2003) to quantify the structures of our sources. This is one of the most robust nonparametric morphology measurement methods and is often used as a way to estimate merger fractions based on a galaxy’s morphology (Conselice et al. 2003, 2008; Bluck et al. 2012). Note that all of our morphological measurements are carried out on the reddest HST filters.

We focus on structure quantification using the asymmetry \((A)\) index, as it captures the most important structural features at this resolution and signal-to-noise ratio level. The asymmetry of a galaxy image is defined as

\[
A = \frac{\Sigma|I - I_{180}|}{\Sigma|I|} - A_{BG},
\]

where \(I\) is the source flux, \(I_{180}\) is the source flux rotated by 180° around its center, and \(A_{BG}\) accounts for the asymmetry of the background. The background term, \(A_{BG}\), is measured in the same way as the asymmetry but with a patch of the sky that does not overlap with the source’s segmentation map.

Additionally, we measure the concentration index \((C)\) as the ratio of two radii, each containing a fraction of light from the light from the source, as

\[
C = 5 \log_{10} \left( \frac{R_{80}}{R_{20}} \right),
\]

where \(R_{80}\) and \(R_{20}\) are radii containing 80% and 20% of the flux of the galaxy, respectively. The concentration measurement is a robust indicator of how steep the light profile of the source is, and it is known to correlate with morphological type

\(^6\) https://github.com/astroferreira/galclean
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(Conselice 2003). The space of parameters formed by the asymmetry \(A\) and concentration \(C\) can then be used to identify if a galaxy is potentially a merging system, a late-type galaxy, or an early-type galaxy.

In the context of mergers, the asymmetry measurement is combined with the smoothness (Conselice 2003), \(S\), to define a region of the parameter space dominated by galaxy major mergers using the following criteria:

\[(A > 0.35), \quad (A > S).\]  

(6)

The value of \(A\) captures how asymmetric the morphology of a galaxy is, and \(S\) measures the contribution from high spatial frequency structures to the galaxy’s flux, such as star-forming regions. The \(A > S\) limit ensures that galaxies with pockets of clumpy star formation are not responsible for the bulk asymmetric structures.

To measure the asymmetry, we first select the band with the highest signal-to-noise ratio for each source. This means that most measurements are done in the F606W or F814W bands, but the values are consistent with F160W. We generate a segmentation map with the code galclean and replace neighboring sources with a sampling of the background to ensure that our \(A\) measurements are not affected by it. From this, we measure the Petrosian radius (Petrosian 1976), \(R_p\), and axis ratio, \(q\), using the code Morphotteryka (Ferrari et al. 2015) and proceed to estimate the asymmetry of the source by measuring it within an elliptical aperture of 1.5\(R_p\) and axis ratio \(q\). Our results are presented in Table 2, and a visualization of the morphologies is shown in Figure 10, where the \(A\) value is given in the top left corner of each image, while the source identification and band used for the measurement are shown in the bottom left corner.

Accurate segmentation maps and Petrosian regions for the unstacked images of sources 3266 and 4213 are impossible to create accurately due to their low signal-to-noise ratio. Additionally, sources 2997 and 5226 contain lensed morphologies that give possibly artificially high \(A\) values. Finally, due to the proximity to bright sources, the source masking process for source 2330 is not ideal and can introduce biases in the \(A\) measurement. As such, we have accurate measurements and merger classifications for most of our sources.

Distortions due to magnification by the clusters can, in principle, create higher asymmetries, even if they are not readily visible, as mentioned as an obvious effect for sources 2997 and 5226. We investigate this and determine that there is no correlation between asymmetry and magnification overall. Thus, it is very likely that the galaxies with a high asymmetry are due to the intrinsic structure and not magnification issues. Furthermore, we do not find a trend between magnification and escape fraction limit. This would be expected, in any case, if galaxies are randomly magnified behind the cluster.

We consider all galaxies above the asymmetry threshold of Equation (6) to be highly distorted. We thus find a high asymmetry fraction of \(45\% \pm 11\%\) for our sample. This is significantly higher than for larger-mass galaxies at similar redshifts from previous studies (e.g., Conselice & Arnold 2009; Conselice 2014). This is potentially due to our probing lower-mass galaxies that are likely more asymmetric than the higher-mass systems at the same redshifts. In general, lower-mass galaxies in the nearby universe have a high asymmetry, but this light is clumpy due to star-forming regions and thus not due to a dynamical process that alters the bulk structure of the system, e.g., Conselice (2003). We discuss the implications of these measurements in Section 4.2.

4. Discussion

4.1. Comparison to Previous Work

Here we investigate our sample escape fraction properties and compare them with other studies. First, we note that Xu et al. (2016), Anderson et al. (2017), and Atek et al. (2022) found that low-mass galaxies are potentially the dominant contributors to reionization with escape fractions that are anticorrelated with mass and \(M_{UV}\). Xu et al. (2016) predicted escape fractions that increase from \(~5\)% in the mass range of \(10^8–10^9 M_{\odot}\) up to \(40\%–60\%\) for fainter, even lower-mass galaxies, while Anderson et al. (2017) found a power-law dependence of \(f_{esc}\) on UV magnitude. Individually, Vanzella et al. (2016) found that a single star-forming galaxy at \(z = 3.2\) has an escape fraction that is likely \(~50\%) (see also Shapley et al. 2016 for a similar object). A multiply lensed galaxy, dubbed “the Sunburst Arc,” is found to have an escape fraction that varies between 14\% and 64\% among the lensed images at \(z = 2.37\) (Rivera-Thorsen et al. 2019). These objects overlap with our sample and show that some star-forming galaxies can have a high escape fraction.

We show our limits and measurements of the escape fraction with galaxy mass and UV magnitude in the bottom two panels of Figure 9 and the results in Table 2. Although we have
limited data and only upper limits, these results tend to agree to some degree with the simulations of Hassan et al. (2016) and Yoshiura et al. (2017), who found that the escape fractions have relatively low values \( f_{\text{esc}} < 15\% \), independent of galaxy mass or magnitude.

While the methods for estimating the escape fraction of a galaxy are fairly consistent throughout the literature, the selection of galaxy types is varied. Searches for escaping LyC, such as those of Shapley et al. (2016), Grazian et al. (2017), and Saxena et al. (2022), examine selected star-forming galaxies typically discovered in HST observations combined with ground-based data. Similarly, Steidel et al. (2001), Iwata et al. (2009), and Boutsia et al. (2011) searched for combinations of LBGs and Ly\(\alpha\) emitters (LAEs) over various field and protocluster environments. Finally, studies such as Rutkowski et al. (2017) and Smith et al. (2020) used preselection of candidates via emission line and spectroscopic redshift catalogs.

Care needs to be taken when comparing our results to previous work, as very little research has been done on measurements of escape fractions for these types of purely emission line–selected galaxies at these redshifts that have low masses. Typically, the relatively small fields covered by lensing clusters, where these galaxies are found, have not provided the sample numbers required for these types of studies. Furthermore, obtaining samples of emission line galaxies with low masses is complicated by the lack of spectroscopy for such faint systems.

Individual limits are not as robust as they could be due to uncertainties in the IGM opacity along an individual galaxy’s sight lines, and without spectroscopic follow-up, intrinsic flux

Table 3

| Cluster | Filter | \( N_{\text{obj}} \) | \( z \) | \( M_{\text{UV}} \) (mag) | \( \log(M_*/M_\odot) \) | \( \mu \) | \( \tau_{\text{IGM}} \) | \( f_{\text{esc}} \) |
|--------|--------|-----------------|------|-----------------|-----------------|------|---------------|----------|
| M1149  | F275W  | 4               | 2.76 | −18.97          | 9.40            | 4.62 | 0.19          | <0.04    |
| M1149  | F336W  | 2               | 3.36 | −18.34          | 8.18            | 1.37 | 0.13          | <0.02    |
| A0370  | F275W  | 18              | 2.75 | −18.01          | 8.44            | 2.67 | 0.22          | <0.02    |
| A0370  | F336W  | 15              | 3.14 | −18.45          | 8.76            | 3.26 | 0.21          | <0.01    |

Note. The columns are as follows. (1) Cluster field from which objects have been identified. (2) Filter used for stacking. (3) Number of galaxies in the stack. (4)–(8) Same as Table 2; values are calculated as the mean of all corresponding stacked objects. (9) The 1\(\sigma\) upper limit on relative stacked LyC escape fraction.

Figure 8. The LyC (left), UV (middle), and F814W (right) postage stamps for the two galaxies in our sample with flux measurements of >2\(\sigma\) in LyC. Postage stamps are \( \sim 1''5 \times 1''5 \) in size. Object ID 803 is located in the MACS 1149 cluster and detected in the F336W band at redshift \( z = 3.28 \). Source ID 809 is also detected in the F336W band and is located in the A0370 cluster field at \( z = 3.28 \).
ratios are difficult to estimate. By implementing an intrinsic flux ratio of 3, we are able to compare our results to previous work, but note that galaxies of lower mass are expected to be extremely metal-poor (<0.1 \( Z_\odot \)), such that 2 < (\( f_{\text{UV}}/f_{\text{LyC}} \))_{\text{int}} < 3.

Our tentative detection of a measurable escape fraction for two of our low-mass systems (\( M_\ast = 10^{7.81} \) and \( 10^{8.91} \) \( M_\odot \)) allows us to investigate the likelihood that low-mass emission line-selected galaxies are able to significantly contribute to the reionization of the universe. One way to make this measurement

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**Figure 9.** Relative escape fractions as a function of redshift (top), \( M_{\text{UV}} \) (bottom left), and demagnified stellar mass (bottom right). The orange points with error bars represent individual galaxies in which we have obtained flux measurements of more than 1σ significance in the LyC images (tentative detections), while 1σ upper limits for the remainder of the sample are shown by solid blue and orange triangles (which are nondetections) for high-asymmetry (\( A > 0.35 \); mergers) and low-asymmetry (\( A < 0.35 \); non-merger) systems. The properties of these individual measurements are detailed in Table 2. Lighter blue triangles show the results of the stacking procedures as detailed in Table 3. Empty arrows show stacked results from the literature spanning the entire redshift range of our sample (Steidel et al. 2001; Shapley et al. 2006; Iwata et al. 2009; Boutsia et al. 2011; Grazian et al. 2017; Rutkowski et al. 2017; Marchi et al. 2018; Steidel et al. 2018; Fletcher et al. 2019; Smith et al. 2020).
from our data is to consider the amount of LyC emission coming from these systems and using standard assumptions about the structure of the high-redshift IGM (e.g., Duncan & Conselice 2015). An average escape fraction of $\sim 0.03$ would allow reionization to occur (Finkelstein et al. 2019) if a relatively high number of low-mass galaxies are present at high redshift, which indeed seems likely to be the case (e.g., Conselice et al. 2016; Bhatawdekar et al. 2019; Duncan et al. 2019). However, an average escape fraction of $\sim 0.03$ can be ruled out for the line emitters we study here, where our stacked limit is lower than this value. This implies that perhaps low-mass, relatively dust-free, star-forming galaxies may not be the dominant source of reionization, and more detailed study of other low-mass galaxies and their escape fractions is desperately needed to expand on our results.

This suggests that line-emitting low-mass galaxies at $z < 3.5$ would not emit enough LyC light to reionize the universe unless significant evolution in the escape fraction for these objects occurs (Finkelstein et al. 2019). There may also be examples of low-mass galaxies that are able to emit significant LyC radiation (e.g., Marques-Chaves et al. 2021; Flury et al. 2022; Vanzella et al. 2022), yet we are not able to find systems such as these in our higher-redshift low-mass sample, and overall average escape fractions are small (Ji et al. 2020).

The upper limits of LyC detections as derived from our stacking procedure suggest that our sample of low-mass galaxies may have overall similar escape fractions as samples of LBGs, LAEs, and star-forming galaxies (SFGs; Steidel et al. 2001; Shapley et al. 2006; Iwata et al. 2009; Boutsia et al. 2011; Grazian et al. 2017; Rutkowski et al. 2017; Marchi et al. 2018; Steidel et al. 2018; Fletcher et al. 2019; Smith et al. 2020; Atek et al. 2022), as displayed in Figure 9. We note, however, that our sample is small; for example, the largest stack contains only 19 objects. Thus, a significantly larger sample is required in order to provide more robust constraints on the possible contribution of this line-emitting galaxy population to the ionizing background. However, these systems do not emit copious LyC radiation. Overall, however, it does not appear that line-emitting systems are good locations for finding escaped LyC radiation. This agrees with the findings of Wang et al. (2021), who found that the fraction of low-redshift LyC leakers decreases at a higher level of $[S\text{II}]$ emission.

We can, however, make a comparison with the various detections we have already, although these depend strongly on the depth of the data. We find two out of 42 galaxies with escaping LyC, giving a galaxy population LyC-emitting fraction of $5\% \pm 3\%$. In comparison, Steidel et al. (2018) detected 15 galaxies out of 124 Lyman break–selected systems, for a fraction of $12\% \pm 3\%$, which is more than twice as high as our detection fraction. However, we find that the fraction of our sample detected is similar to the fraction of detected emitters for a general star-forming galaxy sample at similar
redshifts, which has a detection fraction of $6\% \pm 2\%$ (Saxena et al. 2022). It therefore appears that these systems are not copious emitters of LyC emissions compared to other galaxy selections. Our observations however place the best limits yet on the possible contribution of analog low-mass line emitter galaxies to the process of reionization.

### 4.2. Correlation with Galaxy Structure

The emerging theoretical picture of LyC escape is that feedback carves holes through the ISM (e.g., Ma et al. 2016; Trebitsch et al. 2017, and references therein). These chimneys of very low HI column densities are the channels through which LyC photons can escape from galaxies. Feedback from AGN may also form these holes by producing powerful outflows, as observed in more massive galaxies (Genzel et al. 2014). This feedback and changes in galaxy structure can perhaps be further enhanced by dynamical events that are creating asymmetries in galaxies.

As mergers are more common at higher redshifts, even back to the EoR (e.g., Duncan et al. 2019), this is potentially a major way in which LyC emission is facilitated to escape from distant galaxies. During the merger process, a galaxy’s internal HI reservoirs can be sufficiently disturbed such that photons that are usually attenuated by the IGM are able to stream freely outside of the galaxy through these low column density chimneys. Additionally, dynamical events, such as mergers, can lead to an increase of gas around the AGN and induce bursts of star formation, both of which can lead to an increased production of ionizing photons. While there is little observational work on this in the literature, our sample, which benefits from strong gravitational lensing from massive galaxy clusters, in principle provides a way to investigate these effects within fainter/lower-mass galaxies discovered behind these clusters due to lensing magnification.

To carry out this test, we separate sources into distorted and nondistorted subsamples using the asymmetries measured in Section 3.4 with the imposed limit from Equation (6). Figure 11 shows the asymmetry values for each of our sources as a function of signal-to-noise ratio and color coded by stellar mass. Figure 12 shows the distribution of our sample in the asymmetry–concentration plane (e.g., Conselice 2003). We find that 45% ± 11% of the candidates have high asymmetries, often interpreted as a sign of merging. As the CAS system for finding mergers has not been calibrated at such high redshifts and low masses, we do not claim that these are necessarily mergers and prefer to describe them as highly asymmetric. Thus, our sample is divided almost equally between asymmetric galaxies and those that are not asymmetric. As before, there is no strong evidence that lensing is systematically affecting these structures unequally between these two selected samples. Overall, we calculate that asymmetric galaxies have a stacked escape fraction limit of $<7\%$, while the more symmetric galaxies have a limit of $<4\%$. These limits are similar; thus, we cannot conclude that distorted structures are statistically more likely to have a higher LyC limit.

We cannot know for sure, but if these highly asymmetric galaxies are mergers, then this merger fraction is significantly higher than the merger fraction found at the same redshifts but for a higher stellar mass sample, giving $f_{\text{as}} \sim 0.2$, and measured at the same rest-frame wavelengths (e.g., Conselice & Arnold 2009; Duncan et al. 2019). Merger fractions for galaxies at similar masses and redshifts for typical nonlensed field galaxies do not yet exist, so we cannot make a direct comparison yet. Furthermore, we are probing the rest-frame UV for many of these systems, where galaxies have a more distorted structure, although the effects of this at high redshift are not as pronounced as at lower redshifts (e.g., Papovich et al. 2005). These higher asymmetries are, however, an indication that either mergers or intense star formation are more common for our line emitter systems than a general field sample selection at these redshifts.

### 5. Conclusions

In this paper, we investigate the escape fraction of line-emitting galaxies detected in the Hubble Frontier Fields (HFF)
using SHARDS medium-band imaging with the GTC. We use medium-band filters to find these emission line sources and ultraviolet HST imaging to measure or place limits on rest-frame LyC light. Overall, we discovered a set of 42 new line emitters at $z \sim 2$–3.5 in our SHARDS data that have corresponding coverage of rest-frame UV imaging from the HST at redshifts $z = 2$–3.5. Our major findings are as follows.

I. We find that two of our 42 systems have a measurable (3.2$\sigma$) escape fraction. These galaxies are relatively low-mass systems ($M_* < 10^9 M_\odot$) but not at the extreme low-mass end of our sample. As such, our results provide tentative evidence supporting the idea that low-mass galaxies might be an important reionization source. However, we would expect to have a higher LyC fraction, or more sources detected, if lower-mass line-emitting galaxies are indeed responsible for producing the energy driving reionization and if our sample is an analog of these (e.g., Duncan & Conselice 2015).

II. We stack the 40 galaxies in our sample that do not have $>2\sigma$ detections into bins based on cluster membership and the HST/UVIS band. We do not find leaking LyC in any of the stacks and calculate upper limits using the same methods we use for the individual galaxies.

III. The observed distribution of $f_{\text{esc}}^\text{ULV}$ with galaxy mass and UV magnitude can be accounted for through a combination of LyC detection threshold limits and uncertainties in the intrinsic UV flux ratio at lower masses. We are unable to find or rule out any trends with these properties.

IV. We find that almost half of our candidate emission line galaxies show signs of distorted structures based on an asymmetry index cut. This cut allows us to investigate the nature of galaxies with distorted light structures that can result from mergers or intense star formation. However, when we stack these systems, we find no statistical difference in escape fraction limits for the asymmetric versus nonasymmetric galaxies.

Ultimately, our goal is to examine more distant low-mass galaxies at $z > 7$ to determine if they have properties similar to the ones we study in this paper. With JWST, we will study the analogs of these systems in the Epoch of Reionization (EoR). Further examination of similar low-mass systems at similar redshifts will also provide more evidence for or against the idea that low-mass galaxies, and possibly those involved in mergers or other dynamical events, are responsible for producing the flux needed for reionization.

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ORCID iDs
Alex Griffiths @ https://orcid.org/0000-0003-1880-3509
Christopher J. Conselice @ https://orcid.org/0000-0003-1949-7638
Leonardo Ferreira @ https://orcid.org/0000-0002-8919-079X
Daniel Ceverino @ https://orcid.org/0000-0002-8680-248X
Pablo G. Pérez-González @ https://orcid.org/0000-0003-4528-5639
Daniel Rosa-González @ https://orcid.org/0000-0003-1327-0838
Anton M. Koekemoer @ https://orcid.org/0000-0002-6610-2048
Danilo Marchesini @ https://orcid.org/0000-0001-9002-3502
José Miguel Rodríguez Espinosa @ https://orcid.org/0000-0002-0674-1470
Lucía Rodríguez-Muñoz @ https://orcid.org/0000-0002-0192-5131

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