LIMITS ON LYMAN CONTINUUM ESCAPE FROM $z = 2.2$ H$\alpha$-EMITTING GALAXIES

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ABSTRACT

The leakage of Lyman continuum (LyC) photons from star-forming galaxies is an elusive parameter. When observed, it provides a wealth of information on star formation in galaxies and on the geometry of the interstellar medium, and puts constraints on the role of star-forming galaxies in the reionization of the universe. H$\alpha$-selected galaxies at $z \sim 2$ trace the highest star formation population at the peak of cosmic star formation history, providing a base for directly measuring LyC escape. Here we present this method and highlight its benefits as well as caveats. We also use the method on 10 H$\alpha$ emitters in the Chandra Deep Field South at $z = 2.2$, also imaged with the Hubble Space Telescope in the ultraviolet. We find no individual LyC detections, and our stack puts a 5σ upper limit on the average absolute escape fraction of <24%, consistent with similar studies. With future planned observations, the sample sizes should rapidly increase and the method presented here should provide very robust constraints on the escape fraction.

Key words: dark ages, reionization, first stars – galaxies: evolution – ultraviolet: galaxies

1. INTRODUCTION

As galaxies undergo episodes of star formation, a fraction of the newly formed stars will be massive O- and B-type stars, producing hard ultraviolet (UV) radiation with $\lambda < 912$ Å, capable of ionizing hydrogen. Unless absorbed by dust, these Lyman continuum (LyC) photons are absorbed by neutral hydrogen and re-emitted as hydrogen recombination lines (e.g., Ly$\alpha$, H$\alpha$), while the fraction of ionizing radiation that escapes cleanly ($f_{\text{escape,ion}}$) is a difficult parameter to observe directly. This fraction relates to a multitude of different topics related to galaxy formation; it affects the normalization of star formation rates (SFRs) inferred from recombination lines, and could provide detailed information on the geometry of the interstellar medium in galaxies, as well as the diffuse UV background permeating the universe. Perhaps most importantly, ionizing radiation escaping from the first galaxies is thought to have been the main force driving the reionization of the universe at $z > 6$ (e.g., Robertson et al. 2013; Bouwens et al. 2015). These recent models of the reionization of the universe contain a large uncertainty in that $f_{\text{escape,ion}}$ for star-forming galaxies at high redshift is not well known. Detailed measurements of this quantity, even if they are only upper limits, can put strong constraints on the parameters of these models and thus help us understand if the first stars and galaxies could provide enough ionizing photons to drive reionization on their own.

Several attempts have been made to measure the relative fluxes on the blue and red side of the Lyman limit (912 Å) in $z > 3$ Lyman Break (LBG) and Ly$\alpha$-emitting selected galaxies using ground-based photometry and spectroscopy (Steidel et al. 2001; Iwata et al. 2009; Vanzella et al. 2012; Nestor et al. 2013; Grazian et al. 2015). However, these methods have several caveats. (1) The production rate of ionizing photons ($Q$) is a strong function of the star formation history (SFH), which is difficult to constrain with rest-frame near-UV observations or spectral energy distribution (SED) analysis. (2) Even if the SFH is known, there are theoretical uncertainties from stellar evolution models (IMF differences, contributions from high-mass binaries, etc.) that affect the predicted value of $Q$. For example, $Q$ can vary as much as a factor of five depending on the rotation rate of massive stars (Vázquez et al. 2007; Maeder & Meynet 2012; Leitherer et al. 2014). (3) As is known from studies of the cosmic SFR, the presence of dust means that UV observations only probe a small fraction of the total star formation. Hence, a UV-selected sample is not tracing the cosmic $Q$ in a fair way.

Another selection method for measuring $f_{\text{escape,ion}}$ is to use H$\alpha$-selected galaxies, since H$\alpha$ is directly related to the star formation and is unaffected by caveats 1 and 2: the H$\alpha$ emissivity is directly proportional to $Q$, where the only uncertainty comes from dust extinction. However, the fraction lost to dust is much smaller than in the UV: H$\alpha$-selected galaxies typically suffer about one magnitude of H$\alpha$ extinction (Reddy et al. 2008; Hayes et al. 2010; Sobral et al. 2013). An H$\alpha$-selected sample will thus contain proportionally more dusty galaxies (which are less likely to show LyC leakage), but they will be a less biased measure of the total cosmic star formation, and hence the global escape fraction. We note that for very high escape fractions, the H$\alpha$ luminosity would be lower since less nebular recombinations would take place. However, the escape fraction is not expected to be that high and this effect would probably not affect this type of study.

Correcting the UV flux requires detailed knowledge of the UV extinction law, where differences between extinction laws in different environments can lead to very large correction factors with uncertainties of over an order of magnitude. An H$\alpha$-selected sample also needs extinction corrections, but the uncertainties are considerably smaller. In principle, other SFR tracers could be used, such as mid-IR emission. However, these are based on empirical relations, trace star formation on different timescales, are subject to uncertainties in stellar evolution theory that are similar to those incurred for the UV method, and are not sensitive enough for the faintest galaxies.

Ideally, one would measure $f_{\text{escape,ion}}$ close to the end of the epoch of reionization, but due to the opacity of the Earth’s atmosphere at longer wavelengths, H$\alpha$ can be efficiently surveyed from the ground only up to $z \sim 2.4$. At these redshifts the Lyman limit is in the UV and requires space-based observations. At higher $z$ ($>3$) the LyC can be probed from the...
ground, but at $z > 2$ the opacity of the IGM due to intervening absorption systems increases rapidly with $z$. Correcting for this in small to moderate samples is intrinsically difficult because the amount of intervening material varies from sightline to sightline. At $z = 2$ the average transmitted LyC fraction at $\sim 900$ Å is $\sim 75\%$ according to the latest estimates (Inoue et al. 2014), requiring a correction factor of 1.3. At $z = 4$ the same correction factor is 5, and is very sensitive to cosmic variance.

Moreover, ground-based rest-frame UV surveys typically have a seeing of $\sim 1''$ and are prone to spurious results from low-redshift interlopers. Indeed, most ground-based detections have on closer inspection been found to be interlopers (e.g., Vanzella et al. 2012; Siana et al. 2015, who argue that HST imaging and deep spectroscopy with 8 m class telescopes are required to confirm or reject LyC candidates).

An H$\alpha$-selected sample of galaxies in fields with deep HST UV and multi-wavelength imaging is thus advantageous for probing $f_{\text{esc,ion}}$, at $z \sim 2$, when the universe was only $\sim 20\%$ of its current age and peaking in star formation (e.g., Madau & Dickinson 2014, and the references therein). It was these considerations that led us to start an observing campaign, targeting fields with deep UV observations with H$\alpha$ narrow-band imaging. The current paper represents a small pilot study, demonstrating the strengths of the project and the results that it may bring in the future.

2. MATCHING H$\alpha$ EMITTERS TO WFC3/F225W DATA

The H$\alpha$ observations were presented in Hayes et al. (2010). This was a matched study of H$\alpha$ and Ly$\alpha$ emitters at $z = 2.2$ in the GOODS-South field. H$\alpha$ emitters were selected by a narrow-band excess, requiring $W_{\text{H} \alpha} > 20$ Å as measured by the difference in color between the continuum $K_s$ and the narrow NB2090 filter. Sources were also required to have a narrow-band flux of a factor of $\Sigma = 5$ greater than the noise in the continuum image, and a photometric redshift consistent with $z = 2.2$. The final sample consisted of 55 H$\alpha$ emitter candidates.

The Hubble Ultra Deep Field (UDF), which is a part of GOODS-South, was observed with HST/WFC3 in the UV, using the F225W, F275W, and F336W filters, as part of the UVUDF HST treasury program (Teplitz et al. 2013; Rafelski et al. 2015). At $z = 2.2$, any pure LyC emission will only be in the F225W filter, whereas F275W would also contain non-ionizing continuum emission.

Figure 1 shows a cutout of the NB2090 H$\alpha$ image, with our H$\alpha$ candidates marked, and the overlap with the F225W observations. We originally found 14 H$\alpha$ sources within the UV footprint. One source is located at the very edge of the WFC3 detector and is therefore not included. We find that one of our remaining sources has a spectroscopic redshift in the 3dHST catalog (Brammer et al. 2012; Skelton et al. 2014), identifying it as an active galactic nucleus at $z = 3.193$, which is perfectly consistent with [O ii] 4959 emission falling into the NB2090 filter. We then look for individual sources by eye in the UV image that match the positions of our H$\alpha$ emitters. We find matches for 2 of our 12 sources within an arcsecond of the H$\alpha$ central coordinates. These sources have clear counterparts in the multi-wavelength 3dHST catalogs, and their photometric redshifts are $z \sim 1.43$ and $z \sim 1.06$, with small uncertainties. Examining the SEDs of these two objects by eye, they both show very clear breaks that are consistent with the estimated photometric redshifts. These are not spectroscopically confirmed redshifts, but with their high F225W–F275W colors we see these sources as very probable foreground contaminating sources that are unrelated to any possible $z = 2.2$ H$\alpha$ or LyC emission. We have excluded these two sources from our stacking analysis so as not to contaminate the sample. Our final sample thus consists of 10 H$\alpha$ emitter candidates at $z = 2.2$ (see Figure 1).

3. STACKED UV DATA AND LIMITS ON $f_{\text{esc,ion}}$

We make cutouts of the WFC3/F225W image, centered on the coordinates of the 10 remaining photometric narrowband H$\alpha$ detections. We then stack these cutouts, both using the median and the average. Note, however, that any non-isotropic signal will be effectively removed in a median stack, and we show only the average stack here (see Figure 2). Our final stacks contain no significant signal at the 1$\sigma$ level.

In order to estimate an upper limit on $f_{\text{esc,ion}}$ we must make a few assumptions. Following Kennicutt (1998), we can express the H$\alpha$ luminosity in terms of the number of ionizing photons...
produced per second \( (Q) \), taking into account the escaping photons: \( L_{H\alpha} = 1.4 \cdot 10^{-12} \times Q \times (1 - f_{\text{esc}, Ly\alpha}) \text{ erg s}^{-1} \). In order to estimate the relation between \( Q \), \( f_{\text{esc}, Ly\alpha} \), and the LyC luminosity \( (L_{Ly\alpha}) \), we use a Starburst 99 spectral model (Leitherer et al. 1999), with a Salpeter IMF, metallicity \( Z = 0.004 \), and 10 Myr of constant star formation.

The F225W filter is slightly asymmetric, and samples LyC at \( z = 2.2 \), mostly in a range from 660 to 815 Å, with a long red tail extending up to \( \sim 900 \) Å. We therefore do not observe the total LyC luminosity, but rather the portion that falls into the filter. We denote this luminosity density by \( L_{Ly\alpha} \), and by convolving the LyC flux of our model with the F225W transmission curve, we arrive at an expression for the observed LyC luminosity density:

\[
L_{Ly\alpha} = 5.5 \cdot 10^{-14} \times Q \times f_{\text{esc}, Ly\alpha} \text{ erg s}^{-1} \text{ Å}^{-1}.
\]

Note, however, that we also experiment with other spectral synthesis parameters to get a handle on how the result changes based on these assumptions. Any parameter that could alter the shape shortward of the Lyman break will have an effect on the scaling between \( Q \) and \( L_{Ly\alpha} \), and the factor is also dependent on how representative this window is of the total \( L_{Ly\alpha} \). For an age of 1 Myr (3 Myr), we find the scaling factor to be \( 4.8 \cdot 10^{-14} \) (5.2 \( \cdot 10^{-14} \)). Increasing the metallicity to \( Z = 0.02 \) raises the scaling factor by about 12%, and truncating the IMF at 30 \( M_\odot \) (instead of 100 \( M_\odot \)) increases it by 20%. Changing the SFR to a single burst has a large effect; the scaling factors are 4.8 \( \cdot 10^{-14} \), 6.2 \( \cdot 10^{-14} \), and 7.9 \( \cdot 10^{-14} \) for ages of 1, 3, and 10 Myr, respectively. We must also factor in the possible effects of rotation on the production of ionizing photons, as described in Leitherer et al. (2014). Judging from their models, the total \( Q \) might increase by as much as 40% if all stars rotate with 40% of the break-up velocity. We are trying to constrain the upper limit on the LyC escape, so the smallest values of the scaling factor are the most important, since they allow for the largest \( f_{\text{esc}, Ly\alpha} \).

Taking these considerations into account, we choose to use a more conservative scaling of \( L_{Ly\alpha} = 4 \cdot 10^{-14} \times Q \times f_{\text{esc}, Ly\alpha} \text{ erg s}^{-1} \text{ Å}^{-1} \), and we arrive at a relation between \( L_{H\alpha} \), \( L_{Ly\alpha} \) and the escape fraction; \( f_{\text{esc}, Ly\alpha} = \frac{1}{\left(1 + \frac{3.5}{L_{H\alpha}/L_{Ly\alpha}}\right)^{1/14}} \).

The limiting magnitude at \( 5\sigma \) in the F225W filter is \( \sim 27.8 \) (Teplitz et al. 2013), which corresponds to 1.49 \( \cdot 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \). This is consistent with the noise that we measure in the images as well (see the right panel of Figure 2). The double-blind H\( \alpha \) sources are faint, with a mean H\( \alpha \) luminosity of \( L_{H\alpha} = 4.6 \cdot 10^{41} \text{ erg s}^{-1} \).

For estimating the transmissivity through the IGM, we use a recent model (Inoue et al. 2014) at \( z = 2.2 \) and convolve it with the F225W response curve. In this way, we estimate the transmissivity to 42%, and we estimate the escape fraction detection limit to be \( \sim 50\% \) for a single source. If we assume all of our 10 sources to be real H\( \alpha \) emitters at \( z = 2.2 \), the final upper limit on \( f_{\text{esc},ion} \) is \( \sim 24\% \).

4. CONCLUSIONS AND OUTLOOK

This study is currently strongly restricted due to the small fields probed, especially in the UV. For larger fields, the number of bright H\( \alpha \) emitters available would increase greatly. These brighter galaxies produce intrinsically more ionizing photons (higher values of \( Q \)), which immediately puts stronger constraints on the detectability of LyC escape. The improved statistics of larger surveys also mitigate viewing angle and cosmic variance effects that can otherwise seriously bias the results. As is clearly visible in Figure 1, the sample of H\( \alpha \) emitters that we present here is very strongly affected by cosmic variance and may not be representative of the average \( z \sim 2 \) galaxy population.

GOODS-South is currently being imaged further with HST in the F275W filter (P.I. Oesch), which will greatly increase the footprint of the existing Teplitz et al. (2013) and Rafelski et al. (2015) F275W data. The H\( \alpha \) data that we consider here are at too low of a redshift to use F275W, allowing non-ionizing continuum photons to contaminate the photometry. However, a similar near-infrared study with narrowbands at slightly longer wavelengths (corresponding to \( z \gtrsim 2.38 \)) would allow a similar study to that presented here, including much more UV data.

Other notable imaging campaigns with the HST in the UV involve the six Frontier Fields and Abell 1689, which have already been imaged in F275W, and more data are on their way (P.I. Siana). We hope to observe these fields with extensive near-infrared narrowband imaging in the near future.

Our results can be compared with the recent findings of Mostardi et al. (2015), who find a single LyC-emitting galaxy with an absolute escape fraction of \( 14 \pm 7\% \) in a sample of 16 candidates at \( z \sim 3 \). Grazian et al. (2015) study 45 galaxies at \( z \sim 3.3 \), revealing only 2 LyC leaking candidates, for a total average relative escape fraction below 2%. These studies suffer from the caveats mentioned in the introduction, but do indicate that bright galaxies seem unlikely to have contributed enough to reionization on their own without invoking rapid changes in their physical properties until \( z \gtrsim 6 \).

Our stacked 24\% limit on the absolute escape fraction assumes that all 10 candidates are real H\( \alpha \)-emitting galaxies at \( z = 2.2 \), but they are intrinsically faint and not spectroscopically confirmed. Note, however, that our average H\( \alpha \) luminosity assumes no dust extinction. A typical dust extinction of 1 mag (Reddy et al. 2008; Hayes et al. 2010; Sobral et al. 2013) would raise the intrinsic median \( L_{H\alpha} \) to \( \sim 10^{42} \text{ erg s}^{-1} \), and lower the stacked limit to \( \sim 13\% \). At the same time, LyC escape is very likely to be non-isotropic (due to outflows and/or low covering fractions along certain sightlines), which can still allow for high escape fractions in individual objects. However, the cosmologically interesting quantity is of course the average escape fraction.

As pointed out by, e.g., Bouwens et al. (2015), a galactic relative escape fraction in the range of 5\%-40\% might be enough for galaxies to reionize the universe, although the exact details are highly model dependent. There are of course uncertainties in the possible evolution of the escape fraction from \( z = 6-8 \) until \( z = 2 \), but as we have mentioned, the escape fraction can only be reliably estimated at these lower redshifts.

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