The escape fraction of ionizing photons from dwarf galaxies

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Executive summary: Measuring the escape fraction of ionizing photons from galaxies is a crucial step in understanding the reionization of the Universe, a central question in the COR program. We highlight how this goal can be achieved with deep imaging down to 2000A (reaching NUV~32, i.e., about 10 times deeper than the currently deepest HST observations), over a large field of view (a few times Hubble's WFC3). We also briefly discuss the importance of deep spectroscopy in the NUV, to understand the mechanisms that allow the escape of ionizing radiation and to constrain the line-of-sight specific IGM absorption.

Introduction

The "dark ages" in the history of the Universe ended with a drastic change in the ionization state of the intergalactic medium (IGM), which went from completely neutral to completely ionized. The timing of this transition -hereafter reionization- is constrained observationally through the Gunn-Peterson absorption in the spectra of $z>6$ QSOs and through the polarization of the Cosmic Microwave Background. Results from these studies favor an inhomogeneous and extended reionization process, over the redshift range 6 – 15 (e.g., Songaila 2004, Fan, Carilli & Keating 2006, Jarosik et al. 2011).

Many aspects of the reionization process remain uncertain, with the most crucial one being the nature of the sources producing the bulk of the ionizing radiation (e.g., with energy below one Ry). It is generally accepted that the IGM is kept ionized by the combined UV radiation from AGN and star-forming galaxies, and at low-redshift there are easily enough sources (Cowie et al. 2009). At earlier stages, however, the large uncertainties in the evolution of the QSO/AGN luminosity function (LF), together with the weak constraints on the evolution of the faint end of the galaxy LF result in a much less clear picture (Fontanot et al. 2012). More important still, in order to estimate the ionizing contribution from any population of sources, the fraction of the intrinsic ionizing luminosity that is able to escape from them and reach the IGM – the escape fraction of Lyman continuum (LyC) photons, f^{LyC}_{esc} – must be known. Thus, f^{LyC}_{esc} currently represents the Holy Grail in the quest for the understanding of one of the most important changes in our Universe.

Constraining f^{LyC}_{esc}: what do we need

Ideally, we would like to measure the escape fraction from sources as close as possible to the reionization epoch. As Figure 1 shows, this is close to impossible. Albeit with a large line-of-

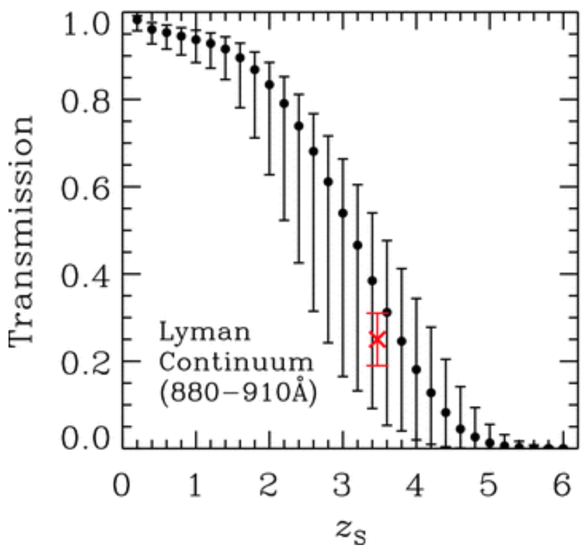

Figure 1: Average IGM transmission as a function of the source redshift, computed in the rest frame 880-910A (from Inoue & Iwata 2006).

sight variation, the average IGM transmission of ionizing photons decreases quickly with redshift from about 95% at $z\sim1$ to substantially zero at $z\geq5$. For this reason, the measurement has to be performed at lower redshifts, where the average IGM transmission allows it. Moreover, a serious problem in measuring f^{LyC}_{esc} is the contamination due to chance alignment between the high redshift target and a faint foreground galaxy (e.g., Vanzella et al. 2010). This can be alleviated with precise spatial information from space together with deep NIR spectroscopy (with 10-m class telescopes or, later, JWST) to rule out interlopers, and by performing the study in low(er) redshift galaxies. Because of the UV atmospheric cut-off, the lowest redshift at which the measurement can be performed from the ground is $z>2.7$, where the average IGM transmission is about 50%, just below the Lyman limit (Figure 1).

Pushing the search for escaping Lyman continuum to redshifts lower than 2.7 requires space based NUV observations, but provides four crucial advantages (apart from the obvious one of appearing brighter for a given UV luminosity):

1. already by $z\sim1.5$, the average IGM transmission is 90%, and

2. the scatter in the IGM transparency from different lines of sight is substantially smaller than at higher redshifts, reducing the uncertainty on the measured f^{LyC}_{esc} (see below).

3. The Hα line (required to constrain the *absolute* escape fraction[a]) is accessible up to $z\sim2.5$ with near-IR spectroscopy from the ground or wide-field space telescopes (Euclid to $z\sim2$ or WFIRST potentially to $z\sim2.5$).

4. The rate of contamination by lower redshift galaxies is substantially reduced.

Constraining f^{LyC}_{esc}: where do we stand

Measurements of galaxies at $z<3.5$ show the average f^{LyC}_{esc} to be very low or undetected at all redshifts. Despite the hundreds of hours invested on both HST and 8–10m class telescopes, the hunt for leaking ionizing photons has yielded an extremely small number of detections (Grimes et al. 2007, Iwata et al. 2009; Siana et al. 2010; Bridge et al. 2010, Bogosavlievich 2010, Nestor et al. 2011; Vanzella et al. 2012).

[a] Theoretical models use the *absolute* escape fraction of ionizing photons, i.e., the ratio between the number of escaping and produced ionizing photons ($f^{LyC}_{ABS}=F(Lyc)^{obs}/F(Lyc)^{int}$). In practice, we typically constrain the *relative* escape fraction ($f^{LyC}_{esc,rel}$), i.e., the ratio between the fraction of escaping LyC photons and the fraction of escaping photons at 1500A. f^{LyC}_{ABS} can be derived from observations of the LyC radiation and the extinction corrected Hα luminosity.

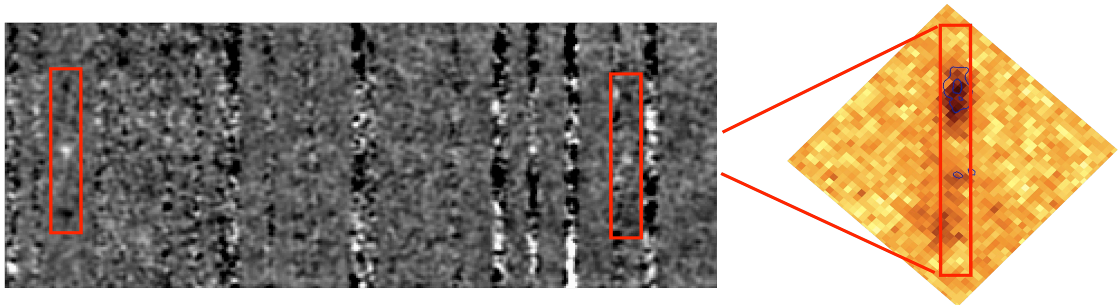

Figure 2: Left: The 2D K-band NIRSPEC spectrum of the candidate LyC emitter, MD32. Right: The rest-UV HST image of MD32 with the slit orientation shown. Faint [OIII] 5007 emission is seen at the expected redshift z=3.09. However, an additional line (spatially offset above the line on the slit) is seen at lower wavelength. Whether this line is from [OIII] 5007 or Hα, this indicates that the emission below 3700A is not LyC, but rather longer wavelength emission from a low-redshift interloper.

In the local universe, galaxies appear to be highly opaque to their own LyC. Upper limits have been presented for the few local galaxies studied to date[b] (Deharveng et al. 2001; Leitherer et al. 1995; Grimes et al. 2009). Statistics improve as the volume increases to z ~ 1, but in combined samples totaling over 600 galaxies, still no individual cases of LyC leakage are reported (Malkan et al. 2003; Siana et al. 2007, 2010; Cowie et al. 2009; Bridge et al. 2010). Stacking analyses on the various samples generally place upper limits on the escape fraction of a few percent (e.g., Bridge et al. 2010).

At redshift *z*~3 high escape fractions (~50% and higher) have been reported in about 10% of Lyman-break galaxies (LBGs, Shapley et al. 2006) and Lyα emitters (LAEs, Iwata et al. 2009; Nestor et al. 2011). In these results, the LAEs appear to be more strongly emitting in Lyman continuum, which is not surprising because the two UV features (LyC and Lyα) have high absorption cross-sections to both dust and HI. However, an inferred absolute f^{LyC}_{esc} of above unity in some cases (Iwata et al. 2009) makes these results difficult to interpret (Vanzella et al. 2012), and the lack of Ha accessibility limits further investigation. To complicate the issue more, none of the z>2.7 LyC leaking candidates followed up with high spatial-resolution imaging and spectroscopy has been confirmed (Siana et al. 2012a; see Figure 2). Similarly, the largest sample of LyC detections (Bogosavlievich 2010) is hard to interpret, due the unknown number of contaminated sources.

To reconcile the observed ionized Universe with the low measurements/limits of f^{LyC}_{esc}, it is possible that f^{LyC}_{esc} may evolve with redshift (e.g., Siana et 2010, Mitra et al. 2012; Haardt & Madau 2012, see Figure 3), and/or that f^{LyC}_{esc} may be higher in faint/low mass galaxies (e.g., Yajima et al. 2009, Nestor et al. 2011).

Yajima et al. (2011) studied the radiation transport of LyC in galaxies drawn from cosmological SPH simulations: at z = 3 − 6 they predict substantial LyC f^{LyC}_{esc} =8–20%) emission from galaxies with halo masses M_{halo} <~ 10^{10} M*, but little or nothing from more massive systems (Figure 1). Similar trends but with higher f^{LyC}_{esc} are reported by Razoumov & Sommer-Larsen (2010). f^{LyC}_{esc} is found to increase with decreasing metallicity and SFR – both of which are thought to positively correlate with M_{halo}. Alternatively, Conroy & Kratter (2012) attribute the higher escape fraction to the ability of high-velocity O-stars to escape the smaller galaxies at lower mass and higher redshifts. Moreover, because stars form more asymmetrically within the halo at low masses, f^{LyC}_{esc} is also found to depend on the particular line-of-sight to the

[b] Although see Leitet et al. (2011) for a debate regarding one potential low f^{LyC}_{esc} LyC emitting object.

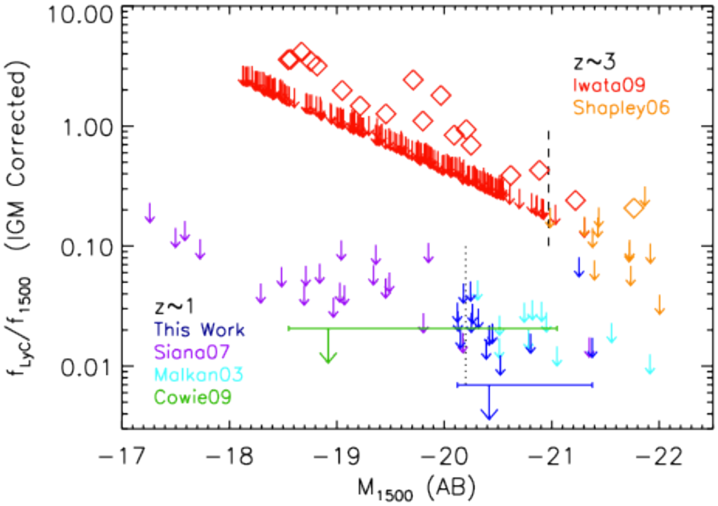

Figure 3: L_{yC}/f_{1500} measurements (versus UV luminosity) from several large surveys at $z \sim 1$ and $z \sim 3$ corrected for the average IGM attenuation at the relevant wavelengths.

galaxy. *All this suggests that high escape fractions and a variation with viewing angle may be found observationally in galaxies at the low mass end.*

Samples targeted for LyC studies at *z~3* mainly contain galaxies that are bright in the rest-frame UV (with L_{UV}>L*, Vanzella et al. 2010, Boutsia et al. 2011): with the current technology and at these redshifts, it is observationally challenging to reach relative $f^{LyC}_{esc,rel}$ of 50% in individual lower luminosity objects. Further progress even with HST will require very deep imaging such as CANDELS and UVUDF (Grogin et al. 2011, Tepitz et al. 2012) and will rely on rare, bright objects or the use of lensing magnification (see below; Vanzella et al. 2012, Siana et al. 2012b).

Lensing Magnification: We have recently obtained 33 HST orbits to study a dozen of known *z*~2.5 galaxies lensed by the well-studied massive cluster Abell1689 (Siana et al. 2012b). The galaxies have intrinsic luminosities well below L* (0.03L*<L_{UV}<L*), and the lensing magnification allows us to probe relative f^{LyC}_{esc} of ~40% in individual galaxies, comparable with the values typically reached in bright unlensed galaxies. We identified one galaxy with escaping ionizing radiation. Spectroscopic observations exclude the possibility of foreground contamination (see Figure 4). This galaxy has a stellar mass of only $3x10^7$ M_{sun}, supporting the idea that LyC photons are coming from the smallest, rather than the brightest galaxies.

Constraining f^{LyC}_{esc} in dwarf galaxies with new telescopes: scaling from the current technological limit

A clear physical picture seems to be emerging in which the metagalactic ionizing field is fueled by the more abundant low-mass galaxies. With current technology, we can constrain the escape fraction in dwarf galaxies only through the magnification provided by gravitational lensing.
Although lensing is -and will be for the next decade- the only way to study intrinsically faint sources at redshifts *z>2,* these studies will be limited by the small sample size, due to the very small volumes magnified even by the most massive clusters. Moreover, uncertain cluster magnification factors introduce some level of uncertainty in the intrinsic luminosity/mass of the lensed galaxies. Also, interpreting any detection of LyC photons requires making an assumption about the IGM absorption, which we can currently only apply as an average correction.

Overcoming these limitations will require improved technology and/or much larger telescopes.

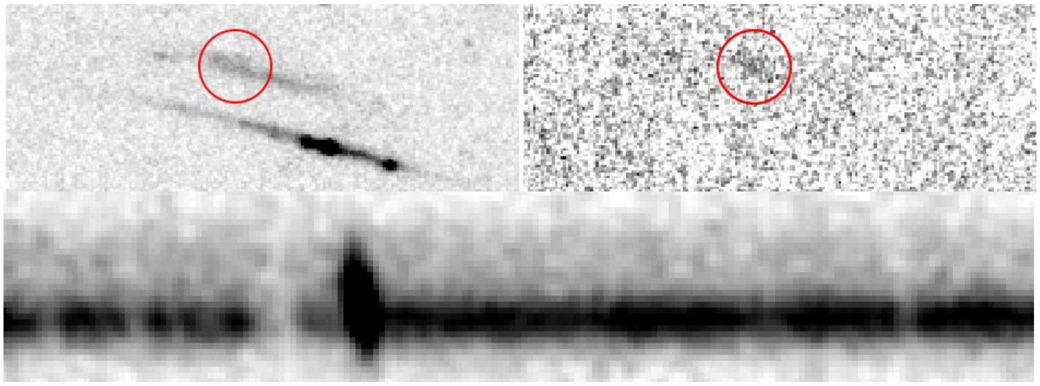

Figure 4 LyC escaping radiation from a dwarf galaxy at z~2.5. Top: the left panel shows the V band of two galaxies at z=2.51, while the right panel shows the UV image, sampling the LyC region at this redshift. Bottom: two dimensional spectrum of the galaxies, obtained with Keck. Both objects show common absorption lines and Lya in emission at the same redshifts (Siana et al. 2012).

In the next section, we discuss the IGM question, but for the moment we will look at where we stand with regards to detecting LyC emissivity in large samples of dwarf galaxies versus where we need to be.

We need to be able to measure LyC in unlensed dwarf galaxies at z<2.5 for three reasons: (1) to obtain necessary number statistics; (2) to remove the uncertain magnification factor; (3) to acquire spatially resolved LyC images without relying on (approximate) lensing reconstruction methods, (4) to reduce the rate of contamination by foreground objects.

Looking at the detailed numbers for the first lensed dwarf galaxy observed with escaping LyC radiation (Figure 4) perfectly illustrates the point. The object has a NUV[F275W] magnitude – which probes the rest frame LyC at *z*=2.5– of 26.9 (AB, detected at a significance of 5s in 33 orbits), and has a magnification factor of 82. The demagnified NUV magnitude for this galaxy is therefore 31.7(AB).
HST is the only UV telescope currently available with the required spatial resolution and filter set for this study. Detecting this galaxy without the aid of the lensing magnification would require a much longer integration, even though removing the spatial broadening effect of the lensing would improve the sensitivity. We would need to detect a compact object at AB~32. We know from the deepest HST exposures (Siana et al. 2012, Teplitz et al. 2012) that in about 30 orbits we can reach AB~29.5, thus requiring a factor of 10 improvement. With HST, reaching AB~32 would take 100 times the exposure time, accounting for the necessary correction for charge transfer inefficiency.

Although the WFC3-UVIS+F275W combination offers the best compromise between telescope/camera transmission and redshift coverage for LyC studies, observations with this setup are severely limited by the low overall transmission (the telescope + camera + filter peak throughput is 13%), the high read-out-noise ($3e^-$), and the poor charge transfer efficiency of CCDs in a high radiation orbit.

Given the current limit of the deepest NUV HST observations, it is reasonable to expect that a telescope of comparable collecting area to the HST, but with a substantial improvement in detector/filter characteristics, would allow us to push the deepest images to NUV~31. Given the uncertainties in the magnification factor quoted above, this depth will be sufficient to perform the crucial direct measurement of the escape fraction in unlensed dwarf galaxies. Furthermore, one could envision the use of NUV medium band filters –as opposed to the broad-band filters currently available on the HST– to isolate the wavelength range where most of the ionizing radiation is emitted. Because the escape of the ionizing radiation is predicted to vary depending on the particular line-of-sight to the galaxy, large samples of galaxies will need to be observed. Clusters can magnify rather small volumes, while a blank field, observed with a large field-of-view camera (a few times the current WFC3) could observe a large number of dwarf galaxies simultaneously.

Constraining f^{LyC}_{esc}: remove the last uncertainty with next generation space telescopes

With a new UV-optimized HST-size telescope we could directly measure the escape fraction in large samples of unlensed dwarf galaxies. However, the measurement would still be affected by the completely unknown contribution of the IGM absorption toward the specific line of sight to the galaxy. Moreover, to be able to extend the z~1 results to the reionization epoch (where f^{LyC}_{esc} cannot be measured directly), we will also need to measure the physical properties of the ionizing galaxies, in order to identify the mechanisms allowing a large ionizing escape fraction in some of them. Properly correcting for IGM absorption and studying the galaxies' properties will require deep UV spectroscopy (possibly with multiplexing capabilities).

In current f^{LyC}_{esc} measurements, any measured flux below the Lyman limit is corrected for using an average absorption due to the intervening IGM. This correction depends on the wavelength range covered (i.e., on the volume probed) by the filter used to measure the ionizing emissivity. Although the averaged IGM transmission is well determined observationally, the amount of attenuation along any specific line-of-sight is stochastic in nature, due to the absorption from rare Lyman Limit systems (LLSs). With high-resolution (R>5000, Songaila 2004) spectroscopy in the rest-frame 800-912Å of the LyC emitting galaxy, the presence of nearby absorbers could be identified, and the correction could be determined for the specific line-of-sight to each galaxy. This goal is obviously ambitious, and will require a substantial increase in aperture size for the next generation space-based telescopes.
Deep NUV spectroscopy covering the rest frame ~1800 Å will also be essential to measure absorption and emission line diagnostics useful to determine the physical conditions of the galaxies' ISM (including gas metallicity, kinematics, and stellar population properties). The detailed UV view will be perfectly complemented by IR spectroscopy with JWST that will cover the rest frame optical of these galaxies.

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