Mission: impossible (escape from the Lyman limit)

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ABSTRACT

We investigate the intrinsic opacity of high-redshift galaxies to outgoing ionizing photons using high-quality photometry of a sample of 27 spectroscopically identified galaxies of redshift 1.9 < z < 3.5 in the Hubble Deep Field. Our measurement is based on maximum-likelihood fitting of model galaxy spectral energy distributions – including the effects of intrinsic Lyman-limit absorption and random realizations of intervening Lyman-series and Lyman-limit absorption – to photometry of galaxies from space- and ground-based broad-band images. Our method provides several important advantages over the methods used by previous groups, including most importantly that two-dimensional sky subtraction of faint-galaxy images is more robust than one-dimensional sky subtraction of faint-galaxy spectra. We find at the 3σ statistical confidence level that on average no more than 4 per cent of the ionizing photons escape galaxies of redshift 1.9 < z < 3.5. This result is consistent with observations of low- and moderate-redshift galaxies but is in direct contradiction to a recent result based on medium-resolution spectroscopy of high-redshift (z ≈ 3) galaxies. Dividing our sample into subsamples according to luminosity, intrinsic ultraviolet colour and redshift, we find no evidence for selection effects that could explain such a discrepancy. Even when all systematic effects are included, the data could not realistically accommodate any escape fraction value larger than ≈15 per cent.

Key words: galaxies: formation – cosmology: observations – diffuse radiation.

1 INTRODUCTION

The diffuse ultraviolet (UV) background is one of the key ingredients in the recipe leading to galaxy formation (Miralda-Escudé & Ostriker 1990; Giroux & Shapiro 1996). The intensity of the diffuse ultraviolet background has been estimated at moderate and high redshifts using the proximity effect on quasi-stellar object (QSO) absorbers (Kulkarni & Fall 1993; Fernández-Soto et al. 1995; Liske & Williger 2001; Scott et al. 2001), and results obtained so far suggest that it is too large to be explained by QSOs alone (Madau & Shull 1996, but see also, e.g., Giallongo et al. 1996). Although systematic errors may make these measurements uncertain (Loeb & Eisenstein 1995; Pascarelle et al. 2001), several suggestions have been put forward to explain the observed extra intensity. One of the most popular suggestions calls for the escape of a large fraction of ionizing photons from high-redshift galaxies. If correct, this would imply that the interstellar media of high-redshift galaxies must be at least partially transparent to ionizing photons.

However, the best measurements available at low and moderate redshifts show that galaxies are (at least nearly) opaque to ionizing photons. The large column densities of neutral hydrogen that surround most galaxies should be enough, depending on how they are distributed, to very effectively quench any outgoing flux of ionizing photons. In fact, Leitherer et al. (1995) find, in a sample of four starburst galaxies at an average redshift of (z) ≈ 0.02, that the limits to the escape fraction of Lyman-limit photons range from f_{esc} < 0.0095 to f_{esc} < 0.15 (with an observed flux ratio at 900 and 1500 Å of F_{900}/F_{1500} < 0.10–0.20). Hurwitz, Jelinsky & Dixon (1997) analyse the same data and obtain slightly less stringent limits, ranging from f_{esc} < 0.032 to f_{esc} < 0.57. Deharveng et al. (2001) find a more stringent limit, f_{esc} < 0.064, for a starburst galaxy of redshift z = 0.0448. Bland-Hawthorn and Putman (2001) obtain f_{esc} ≈ 0.05 in the Milky Way, and Zurita et al. (2002) show that a significant fraction of ionizing photons may locally escape H II regions in NGC 157. At higher redshifts (z = 1), Ferguson (2001) finds similar upper limits f_{esc} < 0.20 to the escape fraction.

It is much less clear whether galaxies at still higher redshifts are as opaque to ionizing photons as galaxies at low and moderate redshifts. Accurate measurements become progressively more difficult at higher redshifts, because galaxies are much fainter and the
presence of Lyman \( \alpha \) forest absorption introduces further uncertainties. The only two measurements available so far are from Steidel, Pettini & Adelberger (2001) and Giallongo et al. (2002). Adopting a correction factor for intervening Lyman-\( \alpha \) absorption determined from a composite QSO spectrum, Steidel et al. reported \( F_{\lambda 15} = 0.22 \pm 0.05 \) using 29 galaxies at \( z \approx 3.40 \), while Giallongo et al. reported a 1\( \sigma \) upper limit \( F_{\lambda 15} \lesssim 0.05 \) using two galaxies at \( z \approx 3.0 \). The former measurement indicates that galaxies at \( z \approx 3 \) are much more transparent to ionizing photons, contributing an equal amount of ionizing flux to the ultraviolet background radiation as the QSOs. The latter measurement indicates otherwise.

In this article, we present a new measurement of \( f_{\text{esc}} \) using 27 galaxies at redshifts \( 1.9 < z < 3.5 \) in the Hubble Deep Field (HDF). All of these galaxies have secure spectroscopic redshifts (see Cohen et al. 2000, hereafter C00; Dawson et al. 2001, hereafter D01) and accurate broad-band photometry from HST/WFPC2 observations in the F300W, F450W, F606W and F814W bandpasses. Our measurement is based on deep space-based images, which provides two important advantages over the methods used by previous groups: first, our sky subtraction is more accurate, because two-dimensional sky subtraction in faint-galaxy images is more robust than one-dimensional sky subtraction in faint-galaxy spectra. Secondly, the wavelength interval below the rest-frame Lyman limit begins to affect the photometry in the ultraviolet spectral slopes and higher escape fractions (at the 2\( \sigma \) level of significance). We also search for other possible systematic effects that could be inherent to our method, and find that other effects cannot account, in any realistic way, for a large increase in the escape fraction.

### 2 DATA

We consider all galaxies in the HDF with known spectroscopic redshifts in the range \( 1.9 < z < 3.5 \). The lower limit is chosen so that the rest-frame Lyman limit begins to affect the photometry in the F300W bandpass. The upper limit is chosen so that we can still reasonably distinguish absorption due to the Lyman-\( \alpha \) forest from the intrinsic Lyman-limit absorption. We previously measured high-quality photometry of these galaxies using HST/WFPC2 through the F300W, F450W, F606W and F814W filters (Fernández-Soto, Lanzetta & Yahil 1999, FLY99 hereafter; Lanzetta et al. in preparation). The sample includes 27 galaxies, as given in Table 1. The reader is referred to FLY99, C00, D01 and Fernández-Soto et al. (2001) for more details on individual galaxies.

We determine the absolute \( AB \) magnitude of each galaxy using a fiducial spectral energy distribution determined from a template fitting technique that we will describe in the next section. We adopt a cosmological model with vacuum energy density \( \Omega_\Lambda = 0.65 \), matter density \( \Omega_M = 0.35 \) and Hubble constant \( H_0 = 65 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1} \). Absolute \( AB \) magnitudes of the galaxies at rest-frame wavelengths \( \lambda = 1500 \, \text{Å} \) range from \( \approx -21.8 \) to \( \approx -25.4 \). Apart from these absolute magnitudes, all other results in this paper are independent of the chosen cosmological model.

### 3 METHOD

Our method is based on maximum-likelihood fitting of model galaxy spectral energy distributions, including the effects of intrinsic Lyman-limit absorption and random realizations of intervening Lyman-series and Lyman-limit absorption, to space- and ground-based broad-band images. In practice, our method proceeds in several steps as follows.

First, we determine a fiducial spectral energy distribution of each galaxy by fitting model spectral energy distributions to the broad-band photometric measurements that fall between rest-frame wavelengths \( \lambda = 1250 \) and \( 2800 \, \text{Å} \). The wavelength range is chosen to avoid the spectral discontinuity produced by the Lyman series (rest-frame wavelength \( \lambda < 1215 \, \text{Å} \)) and the Balmer break (rest-frame wavelengths \( \lambda \gtrsim 3000 \, \text{Å} \)). The fiducial spectral energy distributions are based on the six spectrophotometric templates (of E, Sbc, Scd, Irr, SB1 and SB2 galaxies) of our previous photometric redshift measurements (Yahata et al. 2000; see also Benítez 2000) together with a power-law form \( f_\nu \propto \lambda^\alpha \). (The power-law form is required because a few of the galaxies are found to be bluer – in the ultraviolet rest-frame – than any of the starburst spectrophotometric templates. In each of these cases, \( \alpha \approx 0.5 \).) The spectral energy distributions are selected according to a \( \chi^2 \) analysis similar to the analysis used for our previous photometric redshift measurements (Lanzetta, Yahil & Fernández-Soto 1996; FLY99).
Next, we modify the fiducial spectral energy distribution of each galaxy by adding the effect of intrinsic Lyman-limit absorption, which is characterized by an assumed Lyman-limit optical depth \( \tau_g \) that is taken to be universal across all galaxies. For a Lyman-limit optical depth \( \tau_g \), the output spectrum \( f(\lambda, \tau_g) \) in terms of the input spectrum \( f(\lambda, 0) \) at rest-frame wavelength \( \lambda \) is

\[
f(\lambda, \tau_g) = f(\lambda, 0) \exp \left[ -\tau_g(\lambda/\lambda_{LL})^\gamma \right]
\]

at rest-frame wavelengths \( \lambda < \lambda_{LL} \), where \( \lambda_{LL} \) is the rest-frame wavelength of the Lyman limit.

Next, we modify the fiducial spectral energy distribution of each galaxy by adding the effect of random realizations of intervening Lyman series and Lyman-limit absorption. Here we characterize the galaxy by adding the effect within the scatter present in the observational data.

As can be seen, our model produces slightly fewer Lyman-limit systems at the lowest redshifts than have been observed. Whereas this effect could produce a bias favouring lower escape fraction values, we have checked that this effect is not important (see Sections 4.2 and 4.3 for details). This slight defect is the result of our decision to adopt a single parametrization to generate all of the Lyman-\( \alpha \) forest absorption \( D_A \) and average Lyman series absorption \( D_B \). In Fig. 1 we show the average values of \( D_A \) and \( D_B \), compared with values found in the literature. The agreement is perfect within the scatter present in the observational data.

The incidence of Lyman-limit systems (those with hydrogen opacity \( r > 1 \)) is an important factor in our simulation, as they are among the main drivers of the absorption bluewards of the galactic Lyman edge. In Fig. 2 we plot the density of Lyman-limit systems generated by our Lyman-\( \alpha \) forest model, and compare it with the numbers measured by different authors (as described in the figure).

Next, we measure the simulated spectrum of each galaxy from the fiducial spectral energy distribution of each galaxy modified by the effects of intrinsic Lyman-limit absorption with an assumed Lyman-limit optical depth \( \tau_g \) and of random realizations of intervening Lyman series and Lyman-limit absorption – at short-wavelengths, i.e. over the F300W bandpass, which is sensitive at wavelengths below the rest-frame Lyman limit, and we compare observed energy fluxes \( f^{\text{obs}}_i \) and uncertainties \( \sigma^{\text{obs}}_i \) and simulated energy fluxes \( f^{\text{sim}}_i \) of the \( i \)th galaxy in the \( j \)th simulation. To randomize the effects of intervening Lyman series and Lyman-limit absorption, we repeat this procedure a large number of times, and we form the likelihood as a function of the Lyman-limit optical depth \( \tau_g \) as

\[
\mathcal{L}(\tau_g) = \prod_{i=1}^{N_{\text{gal}}} \left\{ \frac{1}{N_{\text{sim}}} \sum_{j=1}^{N_{\text{sim}}} \exp \left[ -\frac{\left( f^{\text{obs}}_i - f^{\text{sim}}_j(\tau_g) \right)^2}{2\sigma^{\text{obs}}_i^2} \right] \right\}
\]

where the product extends over the \( N_{\text{gal}} \) galaxies of the sample and where the sum extends over the \( N_{\text{sim}} \) simulations of the analysis.
We find that $N_{\text{sim}} = 100$ is enough to represent the variation of intervening Lyman series and Lyman-limit absorption.

4 RESULTS AND DISCUSSION

Fig. 3 shows results of the method described in Section 3 applied to five examples of the galaxies. The examples are chosen to span a range in spectral type, redshift and luminosity. For clarity, only 10 of the 100 realizations are presented for each galaxy. It is obvious from inspection of Fig. 3 that in many cases (especially at the lowest redshifts) the fluxes observed through the F300W filter are lower than the fluxes expected, if the galaxies were completely transparent to ionizing photons. This trend is also present in the other galaxies of the sample. Our quantitative maximum-likelihood analysis of this trend across the entire sample of galaxies establishes a lower limit to the optical depth at the Lyman limit or an upper limit to the escape fraction for these galaxies. In this section, we discuss these limits.

4.1 Galaxy escape fraction

Fig. 4 and Table 2 show results of the method described in Section 3 applied to the data described in Section 2. The first panel of Fig. 4 shows the relative likelihood as a function of $\log (\tau_g)$ determined from the entire sample of galaxies. The best-fitting value of the galaxy Lyman-limit optical depth determined from the entire sample of galaxies is

$$\tau_g = 5.2^{+1.4}_{-0.8}$$

and the corresponding best-fitting value of the galaxy escape fraction determined from the entire sample of galaxies is

$$f_{\text{esc}} = 0.008 \pm 0.006.$$  

These results apply at the average redshift of the entire sample of galaxies, which is

$\langle z \rangle = 2.77.$

The $3\sigma$ upper limit to the galaxy escape fraction determined from the entire sample of galaxies is

$$f_{\text{esc}} < 0.039.$$  

Apparently, our analysis rules out the possibility of a large galaxy escape fraction at high significance but cannot rule out (at the $3\sigma$ level) the possibility of a galaxy escape fraction identically equal to zero. Based on these results, we conclude that galaxies of redshift $z \approx 3$ are highly opaque to ionizing photons.

Figure 3. Photometry and model spectra (10 simulations each time) of a sample of galaxies with no intrinsic Lyman-limit absorption ($\tau_g = 0$, left) and strong intrinsic absorption ($\tau_g = 10$, right). The vertical lines mark the positions of the Lyman limit, Lyman $\beta$ and Lyman-$\alpha$ lines, and $\lambda = 2800$ Å in the rest frame. Circles with error bars show the photometric measurements. The squares show the photometry obtained from the fitted spectrum+H I absorption. The galaxies have been chosen to show the full range in redshift, type and luminosity.
fraction at 1500 ˚

The other panels show the results for different subsamples, broken according to (left to right) type, redshift, and luminosity. In all panels the horizontal lines correspond to statistical 1, 2 and 3σ confidence intervals.

4.2 Possible selection effects

The results of our analysis are apparently at odds with the results of Steidel and collaborators (2001) that galaxies of (z) ≈ 3.4 are not highly opaque to ionizing photons. These authors observed in the average spectrum of 29 galaxies a flux ratio of \( F_{9/15} = 0.056 \). After correcting for the effects of the Lyman-α forest absorption using a composite QSO spectrum at the same redshift, they found an intrinsic flux ratio of \( F_{9/15} = 0.22 \pm 0.05 \), where the effects of intrinsic galactic absorption and attenuation by dust or gas have not been eliminated. The authors also incorporated in this measurement a plausible estimate of the flux discontinuity at the Lyman limit due to absorption in stellar atmospheres to derive an escape fraction \( f_{\text{esc}} \geq 0.10 \).

Steidel and collaborators suggested that the high escape fraction found in their work might result from some selection bias of their galaxy sample. The galaxies incorporated in their analysis include only 29 out of 875 galaxies for which they obtained spectroscopic observations with the Keck telescope, selected on the basis of the quality of the observations at blue wavelengths. This selection condition quite naturally selects galaxies that are either very blue, very luminous or both. QSOs are known to be transparent to ionizing photons at ultraviolet wavelengths (Zheng et al. 1997), so it is not unreasonable to speculate that very blue or very luminous (or both) galaxies might exhibit larger escape fractions than average galaxies.

To examine this possibility, we repeated the analysis described in Section 3 for various subsamples of the galaxy sample.

Colour

First, we repeated the analysis for two subsamples of the galaxy sample divided according to colour. Results are shown in the second panel of Fig. 4 and the second group of entries in Table 2. Here ‘bluer’ galaxies are galaxies best described by SB1 or power-law spectrophotometric templates and ‘redder’ galaxies are galaxies best described by Scd, Irr and SB2 spectrophotometric templates. Results obtained from both subsamples are consistent with each other and with results obtained from the entire sample of galaxies, although there is a (statistically insignificant) trend for the bluer galaxies to indicate a smaller galaxy escape fraction than is indicated by the redder galaxies. This result runs contrary to the idea described above.

Luminosity

Next, we repeated the analysis for two subsamples of the galaxy sample divided according to luminosity. Results are shown in the third panel of Fig. 4 and the third group of entries in Table 2. Here ‘low-luminosity’ galaxies are galaxies of absolute magnitude \( AB > -23.75 \) and ‘high-luminosity’ galaxies are galaxies of absolute magnitude \( AB < -23.75 \). Results obtained from both subsamples are consistent with each other and with results obtained from the entire sample of galaxies, although there is a (statistically insignificant) trend for the lower-luminosity galaxies to indicate a smaller galaxy escape fraction than is indicated by the higher-luminosity galaxies.

Redshift

Finally, we repeated the analysis for two subsamples of the galaxy sample divided according to redshift. The results are shown in the third panel of Fig. 4 and the third group of entries in Table 2. Here ‘low-redshift’ galaxies are galaxies of redshift 1.95 < z < 2.85 and ‘high-redshift’ galaxies are galaxies of redshift 2.85 < z < 3.50. Results obtained from both subsamples are consistent with each other and with results obtained from the entire sample of galaxies.

### Table 2. Measurements of \( f_{\text{esc}} \)

| Sample       | \( N^2 \) | \( f_{\text{esc}} \) | 1σ interval          | 2σ interval          | 3σ interval          |
|--------------|----------|-----------------------|-----------------------|-----------------------|-----------------------|
| All          | 27       | 0.008                 | (0.001–0.013)         | (0.000–0.023)         | (0.000–0.039)         |
| Redder       | 15       | 0.008                 | (0.004–0.020)         | (0.000–0.036)         | (0.000–0.054)         |
| Bluer        | 12       | 0.000                 | (0.000–0.003)         | (0.000–0.018)         | (0.000–0.047)         |
| High luminosity | 13       | 0.026                 | (0.017–0.050)         | (0.008–0.072)         | (0.002–0.093)         |
| Low luminosity | 14       | 0.000                 | (0.000–0.001)         | (0.000–0.004)         | (0.000–0.013)         |
| Low redshift | 13       | 0.004                 | (0.000–0.008)         | (0.000–0.018)         | (0.000–0.030)         |
| High redshift | 14       | 0.169                 | (0.056–0.389)         | (0.008–0.857)         | (0.000–1.000)         |

\(^2\)Number of objects included in the sample.
although there is a (statistically insignificant) trend for the lower-redshift galaxies to indicate a smaller galaxy escape fraction than is indicated by the higher-redshift galaxies. To some extent, this statistically insignificant difference could be due to the already mentioned relative lack of Lyman-limit systems in our model at low redshift. Given that the results from the high-redshift sample (where our model reproduces exactly the observed number of Lyman-limit systems) are not significantly different from the results obtained using the low-redshift sample, we infer that the difference in the model does not induce a large change.

It should be remarked that none of the subsamples analysed is different from the values given by the complete sample at the 3σ level. Neither are any of the subsamples incompatible with their complementary subsamples at the same level. With this in mind, it is nevertheless interesting that the apparent effects of luminosity and ultraviolet blueness on \( f_{\text{esc}} \) seem to pull in opposite directions, suggesting that the higher escape fraction reported by Steidel and collaborators is unlikely to be due to selection effects.

4.3 Systematic uncertainties

All the confidence limits reported above refer only to the statistical properties of the sample of galaxies we are analysing. It is very likely that the method we are using to analyse the data may introduce errors of a systematic nature, which could potentially be of the same order as the statistical ones. We have performed some checks in order to estimate which could be contribution from several sources of uncertainty.

4.3.1 Uncertainties induced by the Lyman-\( \alpha \) forest model

As was shown in Section 3 above, our Lyman-\( \alpha \) forest model has been checked against the observed properties, and agrees with them within observational limits. In order to estimate the uncertainty in \( f_{\text{esc}} \) that could originate from the uncertainties in the model, we have performed new measurements of \( f_{\text{esc}} \) using forest models that differ from our ‘standard’ one by applying a 10 per cent increase/decrease in the normalization of the line density. We must remark that this 10 per cent change does largely overestimate the possible uncertainties in our model – the models with 10 per cent more or fewer lines represent poor fits to the observed forest properties.

As expected, an increase in the forest density implies an increase in the measured value of the escape fraction: more of the UV photons can escape each galaxy while keeping the observed photometric properties, as their mean free path is reduced by the increased density of absorbers. *Mutatis mutandis*, when the forest density is reduced, the value of \( f_{\text{esc}} \) moves down. The change is small however: at the 3σ confidence level, the original limit (\( f_{\text{esc}} < 0.039 \)) becomes \( f_{\text{esc}} < 0.030 \) (\( f_{\text{esc}} < 0.046 \)) when the line density is decreased (increased) by 10 per cent.

Another potential problem in our forest model could be the lack of clustering in our simulations, as opposed to what is shown by the observations. Our measurement is not affected by the small-scale clustering that has been observed in the Lyman-\( \alpha \) forest lines (Fernández-Soto et al. 1996) because we are integrating over much larger scales. Of potential importance is the observed clustering of high-column density absorbers (Sargent, Boksenberg & Steidel 1988). It is difficult to quantify its effect, but we expect it should be diluted by the size of our sample, and estimate that it produces a smaller variance than that induced by the \( \pm 10 \) per cent change in the number of lines presented above.

4.3.2 Uncertainties induced by the choice of the spectral templates

In the case of some of the galaxies, the photometric data available could allow for the assigning of two different fiducial spectral templates with similar goodness-of-fit values. The choice of one of them over the other (which we perform algorithmically via the minimum chi-squared criterion) could produce an extra uncertainty in the measurement of \( f_{\text{esc}} \). The same effect can be produced if our selection of templates is not dense enough to cover the possible UV shapes or if the photometric uncertainties are too large.

We have evaluated the uncertainty induced by this effect by performing the following exercise: we have forced all spectral templates to be one step bluer (always along the sequence formed by Ell, Sbc, Scd, Irr, SB2, SB1) than that which is the best-fit choice,

We have also performed the opposite exercise, forcing all galaxies to be one step redder than their best-fitting template.\(^3\) Under this assumption the galaxies emit far fewer ionizing photons than what their UV continua actually suggests, and this results in an increase in the acceptable escape fraction, which reaches \( f_{\text{esc}} = 0.065 \), with a 3σ upper limit \( f_{\text{esc}} < 0.156 \).

As we explained before, these limits must be taken as very large overestimates of the possible systematic effects induced by our spectroscopic templates, as we do not realistically expect to mistake all galaxies in the same direction. However, even under this extreme assumption, and also incorporating the effects described in Section 4.3.1, the upper limit to the measured escape fraction is still far below the values measured by Steidel et al. (2001).

5 CONCLUSIONS

We have presented a new method to measure the escape fraction of ionizing photons from galaxies at \( z \approx 3 \). Our method provides a cleaner measurement compared with the classical spectroscopic technique because the problem of the sky subtraction is reduced almost to insignificance and we can use a wider bandpass.

The value we obtain (\( f_{\text{esc}} = 0.008 \), with \( f_{\text{esc}} < 0.039 \) at a 3σ confidence level) is in agreement with most previous measurements of the escape fraction of ionizing photons at high and low redshift, being more stringent than most previous upper limits. It is largely in contradiction with the value presented by Steidel et al. (2001) for high-redshift galaxies.\(^4\) We have studied possible selection effects that could cause this apparent difference and conclude that, within the limits set by the size of our sample, they cannot explain the large discordance between our results. Neither can the difference be explained by possible systematic effects induced by our method, as we have also shown. A (very conservative) estimate of the confidence limits when all systematic effects are included leads to a 3σ upper limit to the escape fraction that cannot be higher than \( f_{\text{esc}} \lesssim 0.15 \).

If the escape fraction of ionizing photons reported here represents the general situation at high redshift, then normal galaxies cannot

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\(^2\)Exception made of those that are already fitted by a SB1 template or a power law.

\(^3\)Exception made of those galaxies fitted by a power law.

\(^4\)Steidel et al. (2001) remark that their results ‘should be treated as preliminary until high-quality observations of individual galaxies exhibiting clear evidence for Lyman continuum photon leakage become available’.

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be responsible for any significant fraction of the high-redshift ionizing background. On the other hand, if the proximity effect measurements of the background flux are confirmed, then the problem persists to find the objects responsible for the ionization state of the high-redshift universe. Deep, narrow-band imaging of local and high-redshift galaxies at wavelengths slightly above and below their intrinsic Lyman limits could settle this argument. Such imaging campaigns would be less expensive, in terms of observing time, than the spectroscopic observations performed to date.

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