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An ionized superbubble powered by a protocluster at $z = 6.5$

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ABSTRACT

We show herein that a proto-cluster of Ly α emitting galaxies, spectroscopically confirmed at redshift 6.5, produces a remarkable number of ionizing continuum photons. We start from the Ly α fluxes measured in the spectra of the sources detected spectroscopically. From these fluxes, we derive the ionizing emissivity of continuum photons of the protocluster, which we compare with the ionizing emissivity required to reionize the protocluster volume. We find that the sources in the protocluster are capable of ionizing a large bubble, indeed larger than the volume occupied by the protocluster. For various calculations, we have used the model AMIGA, in particular to derive the emissivity of the Lyman continuum photons required to maintain the observed volume ionized. Besides, we have assumed the ionizing photons escape fraction given by AMIGA at this redshift.

Key words: galaxies: high-redshift – galaxies: star formation – cosmology: reionization – cosmology: early universe.

1 INTRODUCTION

Reionization followed the dark ages when enough Population III stars and galaxies were in place that their ionizing output was sufficient for the task. Population III stars and star-forming galaxies started the reionization process by forming primordial bubbles of ionized gas. These bubbles grew, illuminated by galaxies with strong ionising Lyman continuum, and merged, till the entire Universe became ionized. High-z Ly α emitters are perhaps the most important witnesses and key players of the re-ionization process. Indeed, at redshifts larger than 6, low-luminosity Ly α sources would not be visible, unless they are located within sizeable bubbles of ionized gas.

The last decades have witnessed a surge in studies of the cosmic history of the Universe. In particular, the reionization of the Universe has received much attention, though it is a process not yet completely understood. Population III stars and star-forming galaxies started the re-ionization process by $z \sim 30$. Reionization proceeded by forming primordial bubbles of ionized gas. Bubbles that grew and merged till through percolation the Universe became ionized. Beyond $z \geq 3$, the best strategy to find distant galaxies and proto-clusters (Kakiichi et al. 2018; Naidu et al. 2018; Harikane et al. 2019; Higuchi et al. 2019) is to look for the so-called Ly α emitters (LAEs), or the prominent rest-frame UV continuum galaxies, also known as Lyman break galaxies (LBGs). Furthermore, there is increasing evidence that low-luminosity star-forming galaxies were the main culprits for reionizing the Universe (Ouchi et al. 2009; Bouwens et al. 2010; Finkelstein et al. 2012; Robertson et al. 2015)

The most distant, overdensity discovered so far is at $z \approx 7$ (Castellano et al. 2018). These authors did find an overdensity in the Bremer Deep Field, which they claim to be ionized. Other medium and high-z proto-clusters have been reported in recent years (Abdullah, Wilson & Klypin 2018; Jiang et al. 2018; Oteo et al. 2018), such as those discovered at $z \sim 5.7$ and 6.6 by Higuchi et al. (2019) and Harikane et al. (2019). Finally, while this work was being refereed, a paper was published showing evidences of a bubble ionized by three Lyman α emitting galaxies at $z = 7.7$ (Tilvi et al. 2020).

This paper deals with the ionization state of a proto-cluster at redshift 6.5, discovered by us (Chanchaiworawit et al. 2017, 2019; Calvi et al. 2019). In particular, in Calvi et al. (2019), we show the

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spectroscopic confirmation of a sample of the protocluster sources. Moreover, we claim that the mechanical energy thrown out by supernovae and stellar winds in the protocluster is huge (Calvi et al. 2019). Thus we expect that this mechanical energy will pierce holes in the circumgalactic medium (CGM) throughout which Lyman continuum photons would be able to escape to the intergalactic medium (IGM), hence ionizing it.

A key point in this paper is the derivation of the total emissivity of Lyman continuum photons in the observed volume, as well as the required value to keep it ionized. For these calculations, we have used AMIGA (analytic model of intergalactic-medium and Galaxies (Manrique & Salvador-Solé 2015; Salvador-Solé et al. 2017), a very complete model of galaxy formation that is able to recover all the observed cosmic properties at high-z and meets the observational constraints on re-ionization drawn from the cosmic microwave background anisotropies (Salvador-Solé et al. 2017). In particular, we have assumed the ionizing photon escape fraction and luminosity function considered by this model at this redshift.

The paper uses the Ly α escape fractions from Chanchaiworawit et al. (2019) Section 2. Then in Section 3, we establish a set of definitions, which are meant to set-up the grounds for the rest of the paper. Section 4 corrects for the number of sources in the mask. We continue with Section 5 where we compute the ionizing emissivity, produced by the protocluster, which is available to ionize the IGM. Finally, in Section 6, we evaluate the ionizing emissivity necessary to ionize the overdensity. We end up with the conclusions.

2 THE DATA

We have used the Ly α Luminosities from Calvi et al. (2019). Besides, we have taken the Ly α escape fractions from Chanchaiworawit et al. (2019). We would like to mention that the values we have used are consistent with previous works in the SXDS field, which estimated the Lyman α escape fraction at $z \approx 6.5$ at 0.30 ± 0.18 (Ouchi et al. 2010).

3 DEFINITIONS

To clarify a few concepts that will be used throughout the paper we define them here:

(i) Intrinsic Ly α luminosity ($L_{\mathrm{Ly}\,\alpha,\,\mathrm{intr}}$): This is the Ly α luminosity emitted by the local ionized nebula itself, before any absorption or scattering effects. It is derived from the observed Ly α luminosity (Calvi et al. 2019) by dividing it by the Ly α escape fraction ($f_{\mathrm{esc,\,Ly}\,\alpha}$). The values of the $f_{\mathrm{esc,\,Ly}\,\alpha}$ were taken from Chanchaiworawit et al. (2019). The $f_{\mathrm{esc,\,Ly}\,\alpha}$ and the Ly α luminosities are listed in Table 1.

We have taken the intrinsic Ly α luminosities ($L_{\mathrm{Ly}\,\alpha,\,\mathrm{intr}}$) from the 10 sources detected spectroscopically in Calvi et al. (2019). We have also added two sources already known from the literature (Ouchi et al. 2010) in the same field. However, while C1–01 was in the spectroscopy mask, thus its Ly α luminosity was derived similarly (Calvi et al. 2019), the C1–02 was not. For this reason, we have taken its Ly α luminosity from Ouchi et al. (2010).

(ii) Effective number of ionizing continuum photons per second (Q_{ion}). This is the rate of ionizing continuum photons that corresponds to the intrinsic Ly α luminosity in a typical H II region.

(iii) Intrinsic number of stellar ionizing continuum photons per second (Q^{*}_{ion}). This is the rate of ionizing continuum photons directly emitted by the massive stars, not considering any absorption, scattering, or escape of photons from the nebula without effectively ionizing the gas. They are derived from the number of effective ionizing continuum photons (Q_{ion}) dividing it by ($1 - f_{\mathrm{esc,\,LyC}}$), where $f_{\mathrm{esc,\,LyC}}$ is the Lyman continuum escape fraction. Note that the $f_{\mathrm{esc,\,LyC}}$ is different from $f_{\mathrm{esc,\,Ly}\,\alpha}$.

(iv) Finally, $\dot{\mathrm{N}}_{\mathrm{ion}}$ is the number of ionizing continuum photons that actually participate in reionizing the intergalactic medium (IGM). $\dot{\mathrm{N}}_{\mathrm{ion}}$ is derived multiplying Q^{*}_{ion} by $f_{\mathrm{esc,\,LyC}}$, which has been assumed to be 0.053 (see the discussion below).

4 CORRECTION FOR THE NUMBER OF SOURCES IN THE MASK

The sources that we were able to insert in the observing mask were only 16 out of the 45 Ly α emitter candidates detected photometrically (Chanchaiworawit et al. 2017), in the Subaru/*XMM–Newton* Deep Survey field. Out of these 16 sources, we had reliable spectra for only 10. Note that these sources were selected for being the brighter. But also to include as many sources as possible without the spectra falling on top of each other. In fact, the average Ly α luminosity of the 45 candidate sources is 6.87×10^{42} erg s^{-1}, while the average from the 10 sources for which we had spectra is 6.77×10^{42} erg s^{-1}. Thus the galaxies we detected had a similar average Ly α luminosity as the whole sample.

Given the number of spectroscopic detections, if we were to have enough slits to accommodate all of the candidates (45) we assume that we would have detected a similar fractional number of sources. Thus we need to include a correction factor to account for those sources not present in the mask. Assuming the same fraction of detections for the 45 candidates, we get $10/16 \times 45 = 28.125$. Since we detected 10, the correction factor is 2.81. The last row in Table 1 is computed as follows: we added together sources C1–05 till C2–46. That sum is multiplied by 2.81, and then, we added the two sources (C1–01 and C1–02) that were previously known (Ouchi et al. 2010).

5 IONIZING PHOTON FLUXES PRODUCED BY THE PROTOCLUSTER

Although observing the ionizing Lyman continuum flux in high-redshift sources is far from the reach of current facilities (Madau 1995; Shapley et al. 2006; Siana et al. 2007), the effective ionizing continuum photon rate (Q_{ion}) can be derived from the intrinsic Ly α luminosity, using the relation

$$L_{\mathrm{Ly}\,\alpha_{\mathrm{intr}}} = 1.19 \times 10^{-11}\, Q_{\mathrm{ion}} \ \mathrm{erg\,s^{-1}}. \quad (1)$$

The above equation is based on Case B recombination with $T = 10^{4}$ K and density of $\approx$500 cm^{-3} (Otí-Floranes & Mas-Hesse 2010). From this we can compute the effective number of ionizing continuum photons, that is the number of Lyman continuum photons (wavelength below 912 Å) emitted per unit time that are not absorbed by dust and do not escape from the galaxy. Therefore, these photons participate effectively in ionizing the interstellar medium. The effective ionizing continuum photon fluxes, Q_{ion}, are also given in Table 1.

We are ready now to derive the intrinsic stellar ionizing photon flux (Q^{*}_{ion}). This is the total number of ionizing continuum photons per unit time, with wavelength shorter than 912 Å, produced by the massive stars. This value has to be necessarily equal to or higher than the ‘effective ionizing continuum photon flux’ (Q_{ion}), since a fraction of this stellar ionizing flux escapes from the galaxy, hence it does not participate in the ionization of the interstellar medium, but instead ionizes the IGM. Q^{*}_{ion} is also shown in Table 1.

Table 1. Columns: (1) Name; (2) Ly α escape fraction; (3) Intrinsic Ly α Luminosity; (4) Effective number of ionizing continuum photons per second; (5) intrinsic or 'stellar' number of photons per second (assuming $f_{\rm esc,\,LyC}=0.053$); (6) Number of ionizing continuum photons escaping from the galaxy and eventually participating in reionizing the IGM. Note that the last row is the sum of sources C1–05 till C2–46 multiplied by the completeness factor (2.8125) plus the two Ouchi sources C1–01 and C1–02. Errors have been propagated quadratically.

Source	$f_{\rm esc,\,Ly\,\alpha}$	$L_{\alpha,\,\rm intr.}$ 10^{42} erg s^{-1}	$Q_{\rm ion}$ 10^{54} s^{-1}	$Q^*_{\rm ion}$ 10^{54} s^{-1}	$\dot{\rm N}_{\rm ion}$ 10^{52} s^{-1}
C1–01	0.19 ± 0.10	78.95 ± 41.55	6.62 ± 3.49	6.99 ± 3.68	37.07 ± 1.96
C1–02	0.17 ± 0.02	17.65 ± 5.92	1.48 ± 0.50	1.56 ± 0.52	8.29 ± 0.44
C1–05	0.20 ± 0.09	6.00 ± 3.08	0.50 ± 0.26	0.53 ± 0.27	2.82 ± 0.15
C1–11	0.18 ± 0.09	15.56 ± 8.49	1.31 ± 0.71	1.38 ± 0.75	7.30 ± 0.39
C1–13	0.20 ± 0.10	25.50 ± 13.73	2.14 ± 1.15	2.26 ± 1.22	11.97 ± 0.64
C1–15	0.19 ± 0.07	12.11 ± 5.03	1.02 ± 0.42	1.07 ± 0.45	5.68 ± 0.30
C2–20	0.18 ± 0.10	7.78 ± 4.68	0.65 ± 0.39	0.69 ± 0.41	4.65 ± 0.19
C2–29	0.18 ± 0.08	18.33 ± 8.97	1.54 ± 0.75	1.62 ± 0.80	8.61 ± 0.46
C2–35	0.26 ± 0.14	6.15 ± 4.85	0.52 ± 0.41	0.55 ± 0.43	2.89 ± 0.15
C2–40	0.19 ± 0.07	21.58 ± 8.77	1.81 ± 0.74	1.91 ± 0.78	10.13 ± 0.54
C2–43	0.19 ± 0.08	5.26 ± 2.43	0.44 ± 0.20	0.47 ± 0.22	2.47 ± 0.13
C2–46	0.20 ± 0.07	12.00 ± 5.22	1.01 ± 0.44	1.06 ± 0.46	5.63 ± 0.30
Sum			38.85 ± 4.02	41.02 ± 4.24	217.37 ± 2.32

The value of the average Lyman continuum photons escape fraction, $f_{\rm esc,\,LyC}$, has been derived from the results of the AMIGA simulations as discussed in Salvador-Solé et al. (2017). AMIGA, is a very complete and detailed, self-consistent model of galaxy formation particularly well suited to monitor the intertwined evolution of both luminous sources and the IGM. The multiparameter fitting to different observables done by AMIGA, constrains the value of the Lyman continuum escape fraction to $f_{\rm esc,\,LyC}=0.053\pm0.007$ at $z=6.5$. A very similar value, $f_{\rm esc,\,LyC}=0.05$, has been derived by Finkelstein et al. (2019) using a different methodology. We use the escape fraction obtained from AMIGA, $f_{\rm esc,\,LyC}$, for computing $\dot{N}_{ion}$, whose values are also listed in Table 1.

Considering the estimated true comoving volume occupied by the protocluster, $V=11\,410\,{\rm Mpc}^3$ (Chanchaiworawit et al. 2019), we derive an ionizing emissivity, from the confirmed and probable LAE candidates in the overdense region, equal to $\dot{\mathcal{N}}_{\rm ion}=1.91\times10^{50}$ phot s^{-1} Mpc^{-3}. However, those LAEs lie in haloes of masses $\gtrsim10^{11}$ M$_{\odot}$ (Chanchaiworawit et al. 2019), while, according to AMIGA, galaxies in lower mass haloes contribute up to 80 per cent of the whole ionizing emissivity. Thus, the full ionizing emissivity in the overdense region should typically be 100/20 times higher, i.e. $\dot{\mathcal{N}}_{\rm ion}\sim9.53\times10^{50}$ s^{-1} Mpc^{-3}. We want to note that we found (Chanchaiworawit et al. 2017) a similar fraction for the luminosity originated in the observed LAEs with respect to the total one, namely ~76 per cent. This figure was obtained comparing the number of LAEs observed down to the limiting luminosity of the photometric sample, ($L_{\rm Ly\,\alpha}=10^{42.4}$ erg s^{-1}), with this later value obtained integrating the luminosity function to lower luminosity galaxies.

6 NUMBER DENSITY OF PHOTONS REQUIRED TO IONIZE THE PROTOCLUSTER

A non-zero Lyman continuum escape fraction implies that the escaping photons will be able to ionize regions farther out from the galaxy that contains the stars that produce the ionizing photons. For instance, let us assume the case of C1–01. As shown in Table 1, assuming an overall escape fraction of Lyman continuum photons of 5.3 per cent, this would imply that out from the 6.99×10^{54} Lyman continuum photons emitted per second by the massive stars of C1–01, 6.62×10^{54} are used in ionizing the local interstellar medium (ISM), while the rest, 3.70×10^{53} photons per second, would escape this individual galaxy becoming available for ionizing the IGM.

In Section 5, we derived an ionizing emissivity of the overdense region of $\dot{\mathcal{N}}_{\rm ion}=9.53\times10^{50}$ s^{-1} Mpc^{-3}. Is such an ionizing emissivity enough for the overdense region to be fully ionized? The answer to this question is not straightforward because the ionizing photons emitted by all sources in a given volume at one redshift are used to first, balance the recombinations that take place in the ionized bubbles around them, and second, increase the size of those ionized bubbles. More specifically, the equation for the evolving hydrogen ionized fraction, $\dot{\rm Q}_{\rm II}$, in our overdense volume is the same as for the whole Universe (Salvador-Solé et al. 2017; see also Manrique & Salvador-Solé 2015 for the derivation).

$$\dot{Q}_{\rm II}=\frac{\dot{\mathcal{N}}_{\rm ion}}{\langle n\rangle}-\left[\left\langle\frac{\alpha(T)}{\mu^{\rm e}}\right\rangle\frac{C\,\langle n\rangle}{a^3}+\frac{{\rm d}\ln\langle n\rangle}{{\rm d}t}\right]Q_{\rm II}, \tag{2}$$

where $\dot{\mathcal{N}}_{\rm ion}$ and the averages in angular brackets are now restricted to that volume instead of to the whole Universe. That is, $\langle n\rangle$ is the overdensity (1.67; Chanchaiworawit et al. 2019) times the mean cosmic density of hydrogen atoms; $\alpha(T)$ is the temperature-dependent recombination coefficient to neutral hydrogen, where the typical temperature of the ionized bubble in the overdense volume is equal to that of the whole Universe, calculated as explained in Salvador-Solé et al. (2017), times $1.67^{2/3}$ so as to account for the adiabatic contraction produced in the overdensity; $C\sim3$ is the clumping factor (Finkelstein et al. 2012; see also Salvador-Solé et al. 2017); $\mu^{\rm e}$ is the electronic contribution to the mean molecular weight of the cosmic IGM, assuming the usual hydrogenic composition; and $a=0.13$ is the cosmic scale factor at $z=6.5$.

Equation (2) shows how, in order to determine the ionized fraction Q II , it is not enough to know the emissivity $\dot{N}_{\rm ion}$ of the sources in the volume; we also need the rate at which the ionized fraction Q II grows. The AMIGA code provides the mean ionization fraction Q II in the Universe at any z. However, such a fraction is not known for any particular volume with an arbitrary density. The problem is thus undetermined.

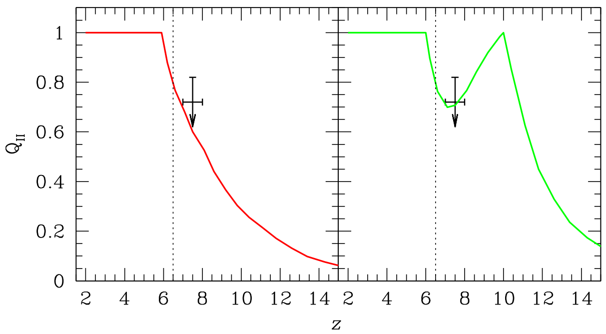

Figure 1. Evolving average cosmic ionized fraction for the single (left-hand panel) and double (right-hand panel) reionization solutions obtained in Salvador-Solé et al. (2017). The vertical dotted black line marks the redshift $z = 6.5$. The point with error bars gives the upper limit for Q II at $z = 7.5$ drawn from the rapid decrease of the LAE abundance at those redshifts (Salvador-Solé et al. 2017). This upper limit puts severe constraints on the ionized fraction at $z = 6.5$, which must be lower than Q II ~ 0.85.

Nevertheless, we can circumvent that indeterminacy by asking the minimum emissivity $\dot{\mathcal{N}}_{\rm ion}^{\rm min}$ needed to just balance the recombinations that would take place in the overdense region, were it fully ionized. The quantity $\dot{\mathcal{N}}_{\rm ion}^{\rm min}$ can then be drawn by equation (2), setting $\dot{Q}_{\rm II} = 0$ and Q II $= 1$. The result is $\dot{\mathcal{N}}_{\rm ion}^{\rm min} = 4.2 \times 10^{50}\,{\rm s}^{-1}\,{\rm Mpc}^{-3}$, i.e. a factor 2 less than the estimated ionizing emissivity of the galaxies in the overdense volume, $\dot{\mathcal{N}}_{\rm ion} = 9.53 \times 10^{50}\,{\rm s}^{-1}\,{\rm Mpc}^{-3}$. Thus, the rate at which ionizing photons are produced in that volume is clearly enough to keep it fully ionized and still increase the size of the ionized superbubble at a rate even higher than the average rate found for the whole Universe at $z = 6.5$. This rate can be obtained using equation (2) with a mean cosmic ionized fraction of Q II $= 0.80$ as found by AMIGA at $z = 6.5$ for the single reionization solution (see Fig. 1). Alternatively, the ionized superbubble could be even larger, even if the rate at which it grows is smaller than the average growth rate of ionizing regions in the whole Universe. This latter possibility is, in fact, the most likely because, the small fraction of neutral hydrogen present in the Universe, at $z = 6.5$, should predominantly lie in underdense regions with a lower density of ionizing sources. Such underdense regions would need to be ionized more rapidly than average. And the converse is thus expected for overdense regions.

The preceding discussion relies on the results of AMIGA for single reionization. Actually, AMIGA reaches two acceptable solutions, one with single reionization and the other with double reionization (see Fig. 1), depending on the initial mass function of Population III stars (Salvador-Solé et al. 2017). However, both solutions are very similar for redshifts around $z = 6.5$, so the double reionization solution leads to essentially the same results. On the other hand, the single reionization model is most widely accepted so the results given here can be readily compared to those obtained with other ionization models. The AMIGA model is particularly reliable as it is very complete, self-consistent, and monitors the formation and evolution of galaxies and their feedback from trivial initial conditions at the 'Dark Ages'. The two solutions mentioned are the only ones that satisfy all the observational constraints pertaining to the high-z Universe and the CMB anisotropies. Note that, the independent reionization model recently published by Finkelstein et al. (2019), at the redshifts of interest, finds very similar values for all quantities. In particular, they find $f_{\rm esc,\,LyC} = 0.05$ and Q II ($z = 6.5$) $= 0.85$, which are very similar to our own. This fact gives strong support to our calculations.

7 CONCLUSIONS

We have confirmed spectroscopically a protocluster of LAEs in the SXDS/*XMM–Newton* deep Survey field. For the 10 sources, we have spectroscopically confirmed (Calvi et al. 2019), we have determined their intrinsic Ly α photon luminosities as well as their ionizing photon fluxes. We have also derived the corresponding intrinsic 'stellar' ionizing continuum photon fluxes. We find that the sources in the protocluster produce sufficient Lyman continuum photons to ionize a large bubble. We have done the calculation taking into account the overdensity contrast and the fact that most of the low-mass galaxies produce a large fraction of the ionizing photon fluxes. For the latter calculation and that of the emissivity of ionizing photons required to keep the observed volume ionized, we have relied on the AMIGA model and the Lyman α escape fraction derived from it at $z = 6.5$. Thus, we find that there are sufficient ionizing photons to not only ionize the volume occupied by the protocluster, but also a larger ionized bubble that increases with time. Therefore, we claim that we have discovered a large ionized bubble such as those that through percolation completed the re-ionization of the universe by $z \approx 6$.

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