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HIGH-Z GALAXIES & REIONIZATION

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Abstract. This paper is a short review on the state of the art regarding the study of sources responsible for the reionization, focusing on the contribution of high-z star-forming galaxies to this process. We discuss the current results on the abundance of this population, coming from deep surveys in lensing and blank fields. A robust estimate of the ionizing emissivity and its evolution with redshift requires a good knowledge on the physical parameters of star-forming galaxies, which in turn relies on detailed multi-wavelength and spectroscopic studies beyond the reach of current facilities for most samples. The complete census of ionizing sources could be facilitated by the use of 3D/IFU spectroscopy without any photometric preselection, as illustrated by recent results obtained with MUSE/VLT. Lensing clusters have become an indispensable tool to push the observational limits, in particular for galaxies formed during the first billion years, waiting for coming facilities such as the JWST and the E-ELT.

Keywords: Galaxies, cosmology, extragalactic surveys, dark ages, reionisation

1 Introduction

This paper is intended to be a short review on the state of the art regarding the study of sources responsible for the reionization, focusing on the contribution of high-z star-forming galaxies to this process. The interested reader can find excellent and exhaustive reviews in the literature (see e.g. Barkana & Loeb 2001; Loeb & Barkana 2001; Dijkstra 2014; Ellis 2014). Considerable efforts have been invested during the last decade to understand the process of structure formation in the early universe. The first generation of sources is the result of the growth of linear density fluctuations dominated by dark matter. Gas was attracted by dark-matter halos and cooled down to form stars. The first generation of stars and quasars ended the so-called "dark ages", and started the process of galaxy assembly. UV radiation coming from hot and massive stars progressively photoionized the surrounding hydrogen till the complete reionization about 1 billion years after the Big Bang. Figure 1 presents a schematic illustration of the hydrogen reionization process in the intergalactic medium driven by star-forming galaxies.

There are two main constrains on the reionization history. The first one comes from the evolution in the optical depth of the Lyman absorption series observed in high-z quasars, showing an increase in the optical depth to Lyman-α photons (the Gunn-Peterson effect, Gunn & Peterson 1965) at high z$\sim$6 (see e.g. Fan et al. 2006, and the references therein). However, this approach cannot be used to follow the reionization history beyond z$\sim$6 because saturation rapidly occurs: a tiny volume-averaged fraction of neutral hydrogen of a few $\sim 10^{-4}$ is enough to completely suppress the spectroscopic signal shortward of Lyman-α. A large variance is also observed as a function of the line-of-sight, with growing evidence for a "patchy" reionization showing inhomogeneities at $\sim$100 Mpc scales (Pentericci et al. 2014; Becker et al. 2015).

The second constrain comes from the optical depth to electron scattering to cosmic microwave background (CMB) photons, and the correlation of the polarization induced by these electrons and temperature fluctuations (see presentation by M. Langer & M. Douspis, this conference). This effect has been detected since the year-1 WMAP data (see e.g. Komatsu et al. 2011), and improved successively by Planck observations (see e.g. Planck Collaboration et al. 2016; Douspis et al. 2015). The last and best determination from the Planck consortium places the average redshift for reionization between z=7.8 and 8.8, depending on the model, with the a strong constrain on the ionization level of $\sim$10% at z$\sim$10.

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Despite all these recent and spectacular results around the reionization epoch, there is still room for improvement regarding the sources of the reionization and their physical properties, a topic which is closely related to the galaxy-formation process. Also the reionization itself is poorly understood as a detailed physical process, although some interesting models have been published recently (see e.g. Douspis et al. 2015; Manrique et al. 2015).

In Sect. 2 we summarize the methodology and the results obtained from current deep surveys looking for the sources responsible for the reionization in blank and lensing fields. In Section 3 we address the use of 3D/IFU spectroscopy to achieve a complete census of ionizing sources. A general discussion together with the perspectives for future facilities are presented in Section 4. Throughout this article a Λ-CDM cosmology with $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$ and $H_0 = 70$ km s^{-1} Mpc^{-1} is assumed, and all magnitudes are quoted in the AB system (Oke & Gunn 1983).

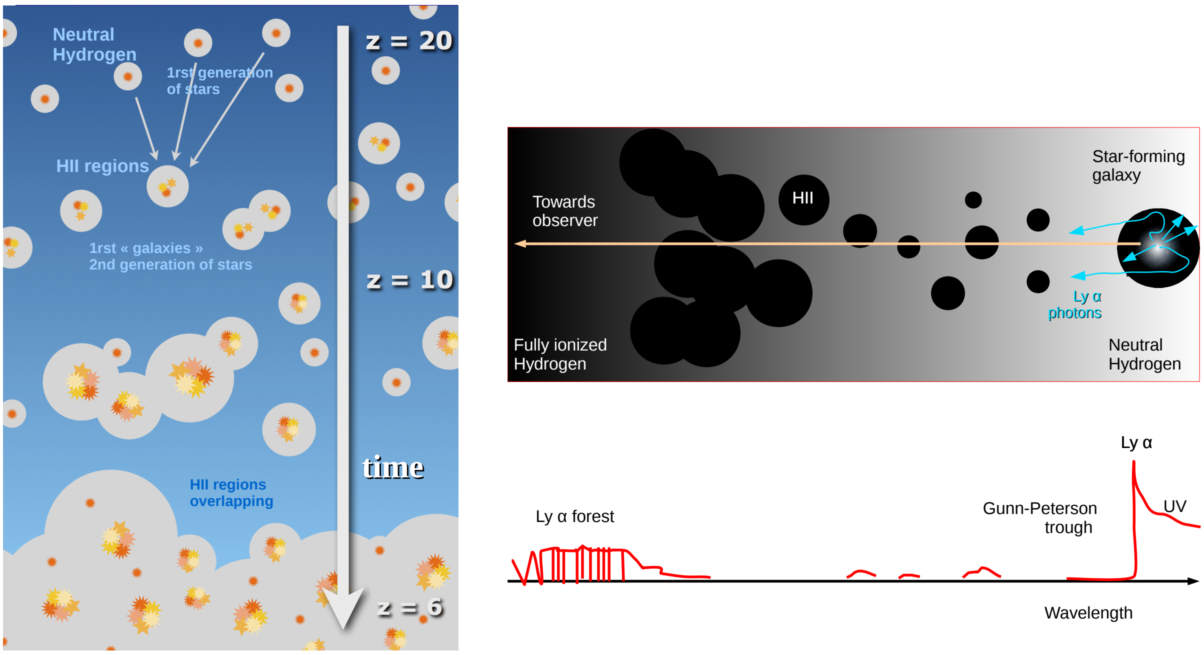

Fig. 1. Left: Illustration of the reionization process by star-forming galaxies. Gas is attracted by dark-matter halos and cools down to form stars. With increasing time/decreasing redshift, the HII bubbles increase in size and overlap. **Right:** Figure showing the spectrum expected for a star-forming galaxy observed at a redshift above the reionization.

2 From Dark Ages to Reionization: Current constraints on ionizing sources

Star-forming galaxies appear as the main contributors to the reionization. Indeed, luminous quasars show a rapid decline in their Luminosity Function (hereafter LF) beyond z∼5, although there is still some uncertainty on the slope towards the faint end of the LF (McGreer et al. 2013). Regarding the identification of star-forming galaxies around and beyond the reionization epoch, there are two main signatures susceptible to be used for this exercise, as shown in Fig. 1. The first one is the Lyman "drop-out" in the continuum bluewards with respect to Lyman-α, due to the combined effect of interstellar and intergalactic scattering by neutral hydrogen. The identification of galaxies at $6 \leq z \leq 12$ requires an homogeneous and deep coverage of the near-IR domain in combination with (ultra-deep) optical data. Different redshift intervals can be defined using the appropriate color-color diagrams or photometric redshifts. An extensive literature is available on this topic since the pioneer work by Steidel et al. (1996) on *Lyman Break Galaxies* (hereafter LBG) (see e.g. Ouchi et al. 2004; Stark et al. 2009; McLure et al. 2009; Bouwens et al. 2015b, and the references therein). Figure 2 provides an example of LBG candidates at z∼8 based on HST (0.3-1.6μm), VLT/HAWK-I (K_s), and Spitzer/IRAC (3.6-4.5μm) data. The second method is the detection of Lyman-α emission, based on wide-field narrow band surveys, targeting a precise redshift bin (see e.g. Rhoads et al. 2000; Kashikawa et al. 2006; Konno et al. 2014), or efficient 3D/IFU spectroscopy in pencil beam mode (e.g. using MUSE/VLT, Bacon et al. 2015), although the last technique is presently limited to z∼6.7 in the optical domain. It is worth to mention that all photometrically-selected samples, either LBG or *Lyman-α emitters* (hereafter LAE), need a spectroscopic follow up to confirm both the redshift and the nature of these candidates.

Impressive results have been obtained during the last ∼5 years on the determination of the UV LF and its evolution between z∼4 and 10 based on LBG studies (see e.g. Bouwens et al. 2015b). The new instrumentation available on the *Hubble Space Telescope* (HST) on one hand, namely the wide-field WFC3 and its near-IR camera WFC3/IR, and the completion of (ultra)deep and/or wide-field surveys on the other hand (CANDELS, GOODS, HUDF, BoRG, ...), associated to Spitzer/IRAC and deep ground-based observations, have provided a reliable estimate of the UV LF based on ∼1000 $arcmin^2$ effective "deep" survey, reaching m∼27-28 for typical candidates at z∼7-8. In addition to blank field surveys, specific studies have been conducted in lensing clusters (e.g. CLASH* and the Hubble Frontier Fields†, hereafter HFF, still ongoing), taking advantage from the magnification effect to explore the faintest end of the LF. As pointed out by different authors (see e.g. Maizy et al. 2010) lensing clusters are more efficient to conduct detailed (spectroscopic) studies in the sensitive redshift domain, and also to explore the faint-end of the LF, whereas observations in wide blank fields are needed and fully complementary to set reliable constraints on the "bright" end of the LF, given the strong field to field variance in number counts in this regime. Results obtained on the HFF fully confirm the benefit expected from gravitational magnification (Laporte et al. 2014; Atek et al. 2014; Infante et al. 2015; Laporte et al. 2016, see also Laporte, this conference).

The last results on the UV LF for LBGs at z∼4 to 10 are nicely summarized in a recent paper by Bouwens et al. (2015b). This LF exhibits a clear evolution at z≥4, with a depletion of bright galaxies with increasing redshift in one hand, and the slope of the faint end becoming steeper on the other hand. Using a Schechter parametrization for the LF, this trend is consistent with an evolution in the normalization Φ^* (with constant M^*_{UV}) between z∼4 and 7, while the slope α varies between -1.64 at z∼4 and -2.06 at z∼7. The trend in the evolution of the normalization is also seen in lensing clusters (Infante et al. 2015; Laporte et al. 2016). The overall evolution in the UV LF seems to be consistent with expectations for the evolution of the halo mass function. However, samples at z>8 are still dramatically small.

Regarding LAE studies, there is a deficit of strongly-emitting Lyman-α galaxies at z≥6.5, whereas no significant evolution is observed below z∼6 (Kashikawa et al. 2006; Pentericci et al. 2014; Tilvi et al. 2014). This trend is attributed to either an increase in the fraction on neutral hydrogen in the IGM or an evolution of the parent population, and the two trends could be also combined together (see also Sect. 4). LAE studies seem to show that the reionization is still in progress at z∼8 (see Tilvi et al. 2014).

How compatible are these results on the density of ionizing sources with the reionization epoch, as discussed in Sect. 1? Bouwens et al. (2015a) have recently addressed this point. They computed the empirical evolution of the cosmic ionizing emissivity with redshift, taking into account all available observational constraints, and compared it with the evolution of the UV luminosity density derived from the above UV LF. The conversion factor from UV luminosity density into ionizing emissivity is consistent with plausible physical values for the escape fraction and clumping factor, provided that the UV LF is integrated down to M(UV)∼-13. Now, at z∼7, present-day observations are limited to M(UV)∼-17 in the HUDF (record-breaking in a blank field), and can reach as faint as M(UV)∼-15.5 behind lensing clusters (Atek et al. 2015; Infante et al. 2015). Also according to Atek et al. (2015), based on the available candidates at z∼6-8 in the HFF lensing clusters and Parallel fields, the UV luminosity density derived at z∼7 seems sufficient to keep the universe reionized, assuming standard conditions for the escape fraction of ionizing radiation. On the contrary, the faint end of the UV LF is not constrained enough at z∼8.

3 Towards a complete census of reionizing sources: the MUSE experience

LBGs and LAEs constitute different observational approaches, partly overlapping, to select ionizing sources. The prevalence of Lyman-α emission in well-controled samples of star-forming galaxies as also a test for the reionization history, as discussed in the next section. The complete census of ionizing sources could be facilitated by the use of 3D/IFU spectroscopy without any photometric preselection, as illustrated by recent results obtained

*http://www.stsci.edu/ postman/CLASH

†http://www.stsci.edu/hst/campaigns/frontier-fields/

with MUSE/VLT in deep blank fields (Bacon et al. 2015) and lensing clusters (Richard et al. 2015; Bina et al. 2016).

Regarding lensing clusters, 17 LAEs were found up to $z \leq 6.7$ behind A1689, with luminosities ranging between 40.5≤log(Lyα)≤42.5 after correction for magnification. Figure 2 displays the comparison between the number density of these sources observed with MUSE at $3 \leq z \leq 6.7$, and expectations based on the simple extrapolation of the LF found in the literature towards the low-luminosity regime covered by the MUSE survey (for details see Bina et al. 2016). In this figure we have corrected for an error affecting the determination of the effective covolume. Luminosity bins are independent in this figure, and there is no correction for incompleteness. Contrary to other surveys presented in Figure 2, where the fit is only sensitive to L^* and the normalization, the samples built in lensing clusters are typically ∼10 times fainter than the usual samples available in the literature, in particular at $z \geq 4$, and comparable to the faintest samples currently available at lower redshifts (e.g. the sample Lyman-α emitters observed by MUSE in the HDFS at $z \geq 2.9$ Bacon et al. 2015; Wisotzki et al. 2016). Therefore, they are particularly sensitive to the value of the slope parameter α, for which a constant value is often assumed in the literature. Despite the obvious caveats regarding the small size of the present sample, the density of intrinsically-faint sources observed in this field seems roughly consistent with the steepest values used by the different authors to fit their data, namely $\alpha \leq$ -1.5, and inconsistent with flatter values of the slope. Correction for completeness in the faintest bins should exacerbate this trend. The authors acknowledge the need for further investigation to fully confirm this result, based on larger samples of LAE detected in lensing fields.

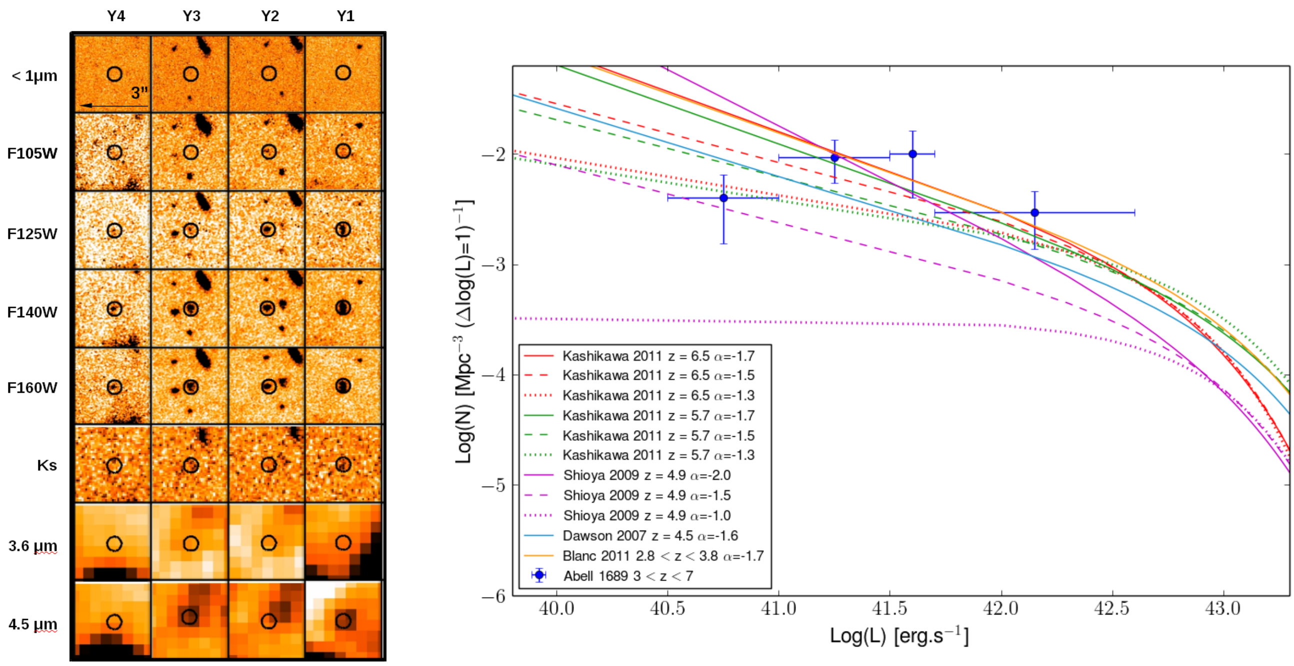

Fig. 2. Left: Example of four LBG candidates at z∼8 behind the lensing cluster MACS0416 found by Laporte et al. (2015) based on HST Frontier Fields (0.3-1.6μm), VLT/HAWK-I (K_s), and Spitzer/IRAC (3.6-4.5μm) data (see also Laporte, this conference). **Right:** Corrected version of Fig. 11 by Bina et al. (2016), showing the comparison between the density of Lyman-α emitters observed at $3 \leq z \leq 6.7$ behind the lensing cluster A1689, and the extrapolation of various LF in the literature towards the low-luminosity regime covered by the MUSE survey (see Bina et al. 2016, and the text for details). References are given in the figure for different redshifts and values of the slope parameter α (Dawson et al. 2007; Shioya et al. 2009; Blanc et al. 2011; Kashikawa et al. 2011). Note that solid lines display the steepest slopes adopted for the LF fit. Error bars include Poisson noise statistics and field-to-field variance.

4 Discussion and Perspectives

Present-day results are consistent with the reionization being dominated by faint star-forming galaxies. However, several issues remain to be addressed before a consistent picture of the galaxy-formation process could be achieved, as discussed below. Our current observations are just at the limits, and most of these questions will be answered with the arrival of new instruments and telescopes in the next coming years, such as EMIR/GTC[‡], NIRSpec/JWST[§], NIRCam/JWST[¶] and the E-ELT[‖].

Reionization scenarios emerging from current results need an appreciable fraction of star-formation located in small-size halos to reach a UV photon budget required with a LF integrated down to M(UV)$\sim$-13 (Bouwens et al. 2015a). As pointed out by Boylan-Kolchin et al. (2014), based on simulations of early galaxy formation, this implies a substantial star-formation activity in halos of M(virial)$\sim 10^8$ $M_\odot$ at z$\sim$8, which seems to be in serious tension with galaxy counts in the Local Group. A possible implication to match these counts could be that star-formation became inefficient in halos smaller than M(virial)$\sim 10^9$ $M_\odot$ at early epochs; therefore, the UV LF must break at some point towards M(UV)$\sim$-14. JWST observations are clearly needed to reach such depth, in particular at z$\sim$8, but a first constrain could be also derived from lensing fields (e.g. in the HFF).

When determining the ionizing emissivity for a given population, e.g. when using the UV LF and the density of UV photons to account for the evolution of the cosmic emissivity, the estimate depends on the physical parameters of star-forming galaxies, which is still poorly constrained, in particular for the faint population. Needless to say that the presence of dust in these populations will completely change the interpretation of the UV photon budget. The direct measurement of dust content and UV attenuation at z$\geq$6 requires deep sub-mm data, in particular using ALMA, and very few measurements exist so far (Schaerer et al. 2015). Most samples of photometric candidates presently available from ultra-deep HST data are beyond the reach of current instrumentation for detailed studies. Ideally, multi-wavelength /spectroscopic studies reaching as faint as m(AB)$\sim$30 are needed to make progress in this respect, i.e. reaching the depth of JWST or present HFF (lensing magnification), not only for redshift measurements (based on Lyman-α and other strong emission-lines), but also to determine the precise nature of genuine high-z galaxies and extreme mid-z interlopers. The progress in this area follows the availability of efficient near-IR spectrographs such as ground-based MOSFIRE/Keck, KMOS/VLT or EMIR/GTC, and devoted surveys with these facilities targeting z$\geq$7 candidates (see e.g. Schenker et al. 2014; Oesch et al. 2015; Zitrin et al. 2015), waiting for the JWST.

There is still a large uncertainty on the escape fraction of ionizing photons in the low-luminosity galaxies responsible for the reionization. It is likely that this fraction depends on both the physical properties of galaxies (kinematics, size, star-formation rate, dust, ...) and geometrical considerations (morphology, orientation,...). The physics of Lyman-α emission is particularly complex and could potentially introduce severe biases in the selection function of LAE (see e.g. Verhamme et al. 2012). The prevalence of Lyman-α emission in well-controled samples can be used as a test for reionization history (see e.g. Schenker et al. 2014). The usual assumption is that, on average, the prevalence of Lya emission in galaxies beyond the reionization is a simple extrapolation of observations below the reionization (z<6), and departures from the general trend are interpreted as an increasing fraction of neutral hydrogen. Based on this approach, the "filling factor" of ionized hydrogen is supposed to evolve from $\sim$66% at z$\sim$7 to <35% at z$\sim$8, with large uncertainties (Pentericci et al. 2014; Tilvi et al. 2014; Schenker et al. 2014). The recent results obtained with MUSE/VLT on the detection of LAE at $3 \leq z \leq 7$, in particular behind lensing clusters, without any photometric preselection, illustrate the efficiency of 3D/IFU spectroscopy in completing the census of ionizing sources. This approach could be extended to the sensitive range at z$\sim$6–12, both in lensing and blank fields, using current or coming facilities (e.g. HARMONI/E-ELT Thatte et al. 2010). There are two main motivations for this approach. In one hand, a large fraction of LAE are not detected in deep photometric surveys up to m$\sim$28-29 (e.g., $\sim$1/3 of the current LAE detected behind lensing clusters do not exhibit continuum emission); therefore, a pointed survey will miss them. On the other hand, a large fraction (still to be confirmed) of high-z galaxies display extended Lyman-α emission (see e.g. Wisotzki et al. 2016, based on MUSE data). This trend is also found in galaxies observed beyond the reionization, (see e.g. Tilvi et al. 2016), as expected since the pioneer work of Loeb & Rybicki (1999). This means that pointed surveys will miss a large fraction of the Lyman-α emission associated to LBG samples, with strong implications on the reionization budget.

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[‡] http://www.gtc.iac.es/instruments/emir/emir.php
[§] http://www.stsci.edu/jwst/instruments/nirspec
[¶] http://www.stsci.edu/jwst/instruments/nircam
[‖] https://www.eso.org/sci/facilities/eelt/instrumentation/

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