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SHEDDING LIGHT ON COSMIC REIONIZATION WITH THE JAMES WEBB SPACE TELESCOPE

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Abstract. Current observational constraints on cosmic reionization mainly rely on CMB-based measures of the electron Thomson scattering optical depth τ_e, and on the absorption signatures of neutral hydrogen on the spectra of distant QSOs and GRBs afterglow. These, however, only probe the last phase of reionization (QSOs and GRBs), or its duration (τ_e), therefore leaving most of the reionization history unconstrained. The origin of H-ionizing photons is also largely uncertain. While several observations suggest that star forming galaxies may be the primary sources of these photons, many uncertain quantities prevent a rigorous quantification of their role in ionizing the IGM. With the launch of JWST, scheduled in 2018, a new window will open to study cosmic reionization. The large wavelength coverage, unique sensitivity and different spectroscopic and imaging capabilities of JWST will provide new constraints on both the reionization history and contribution of different sources to the Universe ionizing budget. In this contribution, I will review current observational constraints on cosmic reionization, and discuss the role of JWST to improve our understanding of this phase.

Keywords: cosmic reionization, JWST

1 Introduction

Cosmic reionization is the last ‘phase transition’ experienced by the Universe. It starts with the appearance of the first sources of ionizing radiation, namely Population III stars and quasars. These, along with further generations of metal-enriched stars, create bubbles of ionized gas which grow, eventually percolating. By redshift $z \sim 6$ hydrogen in the intergalactic medium (IGM) has been fully ionized. Understanding the details of cosmic reionization requires measuring the properties of H-ionized bubbles and their evolution with time, and identifying the sources responsible for the production of H-ionizing photons. Our current knowledge of this phase is limited by the difficulty of measuring the rest-frame UV emission of distant, faint sources. The James Webb Space Telescope (JWST), and in the future Extremely Large Telescopes (ELTs) and the Square Kilometre Array (SKA), will open new windows to study in detail this phase. In the next sections, I will briefly recall the basic (analytic) formalism adopted to describe cosmic reionization, and briefly summarise the main characteristics of the different instruments onboard JWST. I will then discuss different observational constraints on the reionization history and sources of ionizing radiation, focusing on the role of JWST to improve these constraints. I will conclude with a summary.

2 Basic formalism

Cosmic reionization can be described with a differential equation expressing the competing processes of hydrogen ionization by Lyman-continuum photons (with $E >$ 13.6 eV) and hydrogen recombination (e.g. Madau et al. 1999):

$$\frac{dQ_{\mathrm{HII}}}{dt} = \frac{f_{\mathrm{esc}}\,\dot{n}_{\mathrm{ion}}}{\langle n_{\mathrm{H}} \rangle} - \frac{Q_{\mathrm{HII}}}{t_{\mathrm{rec}}}\,, \tag{2.1}$$

where Q_{HII} indicates the volume filling fraction of ionized hydrogen, $\dot{n}_{\mathrm{ion}}$ the comoving production rate of hydrogen ionizing photons within galaxies, f_{esc} the escape fraction of these photons into the IGM, $\langle n_{\mathrm{H}} \rangle$ the

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comoving average number density of hydrogen atoms, and $t_{\rm rec}$ the average recombination time of hydrogen.* The variation of the volume fraction of ionized hydrogen with time (the term on the left side of Equation 2.1) therefore depends on the availability of H-ionizing photons, produced by stars and AGN within galaxies and escaping into the IGM (first term on the right side of equation 2.1), and on the physical conditions of the IGM (density, temperature and ionisation fields), which determine the recombination rate of ionized H (second term on the right side of equation 2.1). We note that while equation 2.1 is an approximation, it provides an intuitive understanding of the different ingredients affecting cosmic reionization. Moreover, it has been shown that equation 2.1 provides an excellent approximation to more complex models (Finlator et al. 2012). Understanding the details of cosmic reionization therefore means constraining all physical quantities, and their time dependence, entering equation 2.1.

3 James Webb Space Telescope

JWST is a joint effort of three major space agencies, NASA, ESA and CSA, and is expected to be launched in October 2018. Equipped with a $\sim$ 6.5 m primary mirror (7× HST collecting area) and observing in a wide wavelength range, from the near- to mid-infrared, it will represent a real 'game changer' for the characterisation of the most distant galaxies in the Universe and of cosmic reionization. JWST is equipped with four main instruments, a Near-InfraRed Camera (NIRCam), Near-InfraRed Spectrograph (NIRSpec), Mid-InfraRed Instrument (MIRI), and Near-InfraRed Imager and Slitless Spectrograph (NIRISS). Below, we briefly summarise the main characteristics of these instruments. All quoted sensitivities refer to a point source, an integration time of 10^4 s, and S/N=10.

NIRCam covers the wavelength range 0.6 to 5.0 μm, with a field-of-view (FoV) of $\sim$ 10 arcmin^2. Its unique sensitivity will allow high S/N observations of 10 nano Jy sources, extending, and improving, HST sensitivity up to 5 μm.

NIRSpec provides a complete set of spectroscopic capabilities in the range 0.6 to 5 μm, with resolution ranging from R $\sim$ 100 (prism) to R $\sim$ 1000 and 2700 (gratings). Three different slits will allow one to perform slit spectroscopy at R $\sim$ 100, 1000 and 2700, while the 'multi-object spectrograph' (MOS) mode will allow one to observe multiple sources on a $\sim$ 11.5 arcmin^2 FoV. Finally, the 'integral filed unit' (IFU) mode will allow one to take 3D data cubes on a 3×3 arcsec FoV. NIRSpec sensitivity will allow the detection at low-resolution (R = 100) of the continuum of $\sim$ 100 nano Jy sources, and emission lines in the medium resolution mode down to a luminosity of $\sim 10^{-18}\,{\rm erg\,s^{-1}\,cm^{-2}}$.

NIRISS will be able to take broad-band images in the range 1 to 5 μm in a $\sim$ 5 arcmin^2 FoV. Although about 10 times less sensitive than NIRSpec in the same wavelength range, it will also perform R $\sim$ 150 grism spectroscopy in the range 1 to 2.5 μm.

MIRI covers the range 5 to 28 μm, providing broad-band imaging on a $\sim$ 2.3 arcmin^2 FoV, with a sensitivity decreasing from 0.1 micro Jy at $\lambda \sim 5$ μm ($\sim$ 2 dex better than *Spitzer*), to 30 micro Jy at $\lambda \sim 28$ μm ($\sim$ 1 dex better than *Spitzer*). MIRI also provides slit low-resolution spectroscopy R $\sim$ 100 in the range 5 to 10 μm, with a sensitivity varying (from the blue to the red side) from 1 to 10 micro Jy ($\sim$ 1.5 dex better than *Spitzer*). IFU spectroscopy provides a resolution R = 3000 at $\lambda = 5$ μm, decreasing to R = 1000 at $\lambda = 28$ μm, allowing one to measure line luminosities down to $\sim 10^{-17}\,{\rm erg\,s^{-1}\,cm^{-2}}$ at $\lambda = 5$ μm ($\sim$ 2 dex better than *Spitzer*), and $\sim 10^{-16}\,{\rm erg\,s^{-1}\,cm^{-2}}$ at $\lambda = 28$ μm ($>$ 1 dex better than *Spitzer*).

4 Observational constraints on cosmic reionization and the role of JWST

Current observations, such as the Cosmic Microwave Background (CMB) radiation, spectra from high-redshift quasars (QSOs) and Gamma Ray Bursts (GRBs) afterglow, mainly constrain the end and duration of the reionization process. The main reason for this is the difficulty of obtaining high-quality rest-frame UV spectra of $z \geq 6$ sources from the ground. JWST will revolutionise this situation, (potentially) contributing to the improvement of several current, and proposed, observational constraints, except for those based on CMB observations.

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[*] Equation 2.1 does not account for collisional ionization and implicitly assumes that the ionization sources are widely separated, as it mixes mass-averaged (ionization fraction) and volume-averaged (recombination time) quantities (see the discussion in section 5 of Finlator et al. 2012).

4.1 Cosmic Microwave Background

The most accurate estimate of the electron Thomson scattering optical depth τ_e obtained by the *Planck* team corresponds to a redshift of *instantaneous* reionization $z_{\rm re} \sim 8.8$ ($\tau_e \sim 0.066$). This was obtained by combining the CMB temperature, polarisation and lensing maps obtained by *Planck* with measurements of Baryon Acoustic Oscillation from different galaxy/QSOs redshift surveys (Planck Collaboration et al. 2015). The major limitation of using τ_e to constrain the cosmic reionization history is its dependence on the time *integral* of $Q_{\rm HII}(t)$, which means that an infinite number of potential reionization histories (with equal integral) are consistent with the same value of τ_e. Independent observations are therefore required to constrain the evolution of the H-ionized fraction with time, and of the sources responsible for the production of H-ionizing photons.

4.2 Constraints from background sources

Another family of observational constraints relies on measurements of the light emitted by luminous, distant sources, such as QSOs and GRBs afterglow. The signatures of neutral hydrogen in the spectra of these sources allow one to probe the intervening IGM between source and observer. Different signatures have been used in the past to constrain the fraction and distribution of neutral H along the line-of-sight. These include the 'Gunn-Peterson' (GP, Gunn & Peterson 1965) trough and distribution of 'dark gaps' in the spectra of distant QSOs, and the Lyα damping wing in the spectra of QSOs and GRBs.

The GP trough is the complete absorption of photons with $\lambda_{\rm em} \le \lambda_{\rm Ly\alpha}$ (i.e., $\lambda_{\rm em} < 1216$ Å), caused by the presence of clouds of neutral hydrogen along the QSO line-of-sight, and the resonant scatter of photons with frequency coinciding with the rest frequency of Lyα at the cloud frame. Measurements of the GP trough in $z \sim 6$ QSOs indicate a rapid increase of the hydrogen neutral fraction in the IGM (e.g. Fan et al. 2006). However, these measurements are insensitive to neutral fractions $\rm f_{HI} \ge 10^{-4}$, due to the Lyα line saturation, and they probe single line-of-sights of a highly inhomogeneous IGM.

In some cases, the flux blueward Lyα is not completely absorbed, but shows regions of complete absorption spaced out by regions with non-null flux. The distribution of these 'dark gaps' can be used to infer the properties of a partly ionized IGM. In particular, the number of these regions, their redshift and extension (in redshift space) are related to the time and size evolution of H-ionized bubbles, and their clustering properties (e.g. Fan et al. 2006).

The spectra of background QSOs and GRBs afterglows contains other signatures of the state of IGM. The effect of intervening clouds of neutral hydrogen is expected to create a characteristic 'damping wing' redward $\lambda_{\rm Ly\alpha}$ (Miralda-Escudé 1998). The advantage of such a measurement is that it allows one to probe much larger $\rm f_{HI}$ than the GP trough. Tentative detections of the Lyα damping wing have appeared in the literature in last few years, both adopting a QSO at $z = 7.08$ (Mortlock et al. 2011; Bolton et al. 2011) and a GRB afterglow at $z = 5.91$ (Totani et al. 2014) as background sources, with claims of a substantial H neutral fraction ($\rm f_{HI} \ge 0.1$) at these redshifts.

The major challenge in improving the above constraints stands in the difficulty of obtaining high-quality, rest-frame far-UV spectra of sources at $z \ge 7$ with ground-based telescopes. This will change with NIRSpec, which will be able to take high S/N ratio, medium resolution (R=1000 and 2700) spectra of bright QSOs and GRBs afterglows at $z > 7$, probing the rest-frame UV spectrum (around Lyα) of these objects. Moreover, NIRCam may alleviate the problem of the rarity of high-z bright QSOs, by providing new, and more numerous, lower luminosity QSOs candidates for the spectroscopic follow-up with NIRSpec.

4.3 Lyα emitters

A different class of observables is related to the measurements of Lyα photons emitted by galaxies. Both the occurrence of these galaxies, called 'Lyman-alpha emitters' (LAE), over the global Lyman-break population, and the redshift evolution of their luminosity function, provide useful constraints on cosmic reionization. Resonant scattering of Lyα photons make them very sensitive to the presence of neutral hydrogen along the line-of-sight, hence LAE can in principle be used to trace the last phase of cosmic reionization (e.g. Stark et al. 2010; Tilvi et al. 2014; Konno et al. 2014; Matthee et al. 2015; Bacon et al. 2015). However, the interpretation of observed trends in the LAE population is hampered by other effects, acting within or nearby the emitters, which can also affect the observability of Lyα emission. These include the effect of dust attenuation, gas kinematics and gas geometry (i.e. 'covering fraction'), which all influence the Lyα photons escape fraction. Other difficulties in using LEA to study cosmic reionization are the need to observe large areas of sky, to obtain statistical significant samples, and the difficulty of correcting for incompleteness, i.e. unobserved emitters. This problem appears even more serious after recent observations with the *MUSE* integral-field unit spectrograph, which have revealed the ubiquitous presence of an 'extended' Lyα emission around galaxies at $3 \leq z \leq 6$. This can have important consequences on the calculation of LEA luminosity function evolution, given the effect of surface brightness limits and aperture sizes (Wisotzki et al. 2015).

Besides the LAE luminosity function, the clustering properties of LAE can be used to constraint different reionization scenarios. Simulations have suggested that such a measurement is less sensitive to the intrinsic evolution of the sources than them LAE luminosity function. In particular, the redshift evolution of HII bubbles (size, clustering) is predicted to leave unique imprints on the clustering properties of LAE at scales ≥ 1 Mpc (e.g. McQuinn et al. 2007; Zheng et al. 2011; Jensen et al. 2014; Sobacchi & Mesinger 2015).

JWST will likely give a substantial contribution for the interpretation of the LAE luminosity function evolution, by allowing one to characterise the physical properties of LAE. The unique spectroscopic capabilities of NIRSpec will allow the measurement of several nebular emission lines in the spectra of distant ($z \geq 6$) LAE, allowing one to constrain the dust and gas (ionization state, metallicity) properties of these galaxies. This will be a promising way to separate the effect of the intrinsic evolution of the sources and of the H neutral fraction on their luminosity function evolution. JWST will also allow the identification of LAE at redshifts not covered by the *MUSE* instrument at the VLT. The LAE identification can be performed by appealing to the 'prism' mode of NIRSpec, and to the slitless spectrograph on NIRISS. This will allow the detection of faint LAE, hence pushing the LEA luminosity function to low fluxes, and allowing a measurements of the LAE clustering signal at small scales. The major challenge for this type of study is the relatively small FoV of NIRSpec (compared to ground-based telescopes), which would require ~ 100 pointings to scan a large enough area of ~ 1000 arcmin^2.

4.4 Nebular emission lines

A fundamental, and largely unknown, quantity entering equation 2.1 is the escape fraction of H-ionizing photons from galaxies. This depends on the gas and dust properties in star forming regions. Recently, Verhamme et al. (2015) proposed the use of the Lyα line profile to measure the properties of distant star forming regions. The shape of the line, and in particular its peak and width, are in fact sensitive to the geometry of gas, i.e. its 'covering factor', and density distribution (optically thin vs thick). The medium resolution mode ($R \sim 2700$) of NIRSpec will be sufficient to provide high-quality measurements of Lyα profiles of very distant galaxies.

Another way to constrain the gas properties of high-z star forming regions is to combine information from Balmer emission lines and UV continuum. As shown by Zackrisson et al. (2013), the 'leak' of UV photons produced within star forming regions is predicted to leave an impact on the equivalent width of hydrogen Balmer lines, at fixed UV slope. This picture is however complicated by the effect of dust, metallicity and variation in the galaxy star formation history, which also affect nebular emission and UV continuum slope. For this, a complete characterisation of the physical properties of such galaxies is required. This can be accomplished by combining the different instrument onboard JWST: NIRSpec will provide ratios of different emission lines, that can be sued to constrain the gas metallicity and dust content; NIRCam will allow one to measure the shape of the rest-frame far-UV; MIRI will allow one to access the rest-frame optical/NIR, which is sensitive to the past history of star formation.

4.5 UV luminosity function

In the last years, theoretical and observational evidence has accumulated pointing towards a dominant role of low-mass star forming galaxies in providing the bulk of H-ionizing photons necessary for cosmic reionization. Many works have suggested that the contribution of other sources, such as mini-QSOs (e.g. Willott et al. 2010; McQuinn 2012; Grissom et al. 2014), high-mass X-ray binaries (e.g. Mirabel et al. 2011; McQuinn 2012) and Pop. III stars (e.g. Paardekooper et al. 2013; Wise et al. 2014; Kulkarni et al. 2014) is secondary. Observationally, the detected steepening of the galaxy UV luminosity function with increasing redshift (e.g. Atek et al. 2014; Bouwens et al. 2015b; Oesch et al. 2014) suggests that these low-mass galaxies were more abundant in the early Universe ($z \geq 6$) than at more recent times, hence potentially providing enough H-ionizing photons to reionize the IGM (e.g. Robertson et al. 2015; Bouwens et al. 2015a). Major uncertainties, however, affect such an interpretation: the quality of current data do not allow to break the degeneracies between the different parameters describing the galaxy UV luminosity function, such as faint-end slope, normalization, and magnitude of the exponential cutoff (e.g. Finkelstein et al. 2015). Also, current, deep surveys cannot resolve magnitudes fainter than $M_{\mathrm{UV}} \sim -17$, except in a few lensed fields (e.g. Atek et al. 2015b,a), hence any interpretation relies on an extrapolation of the observed luminosity function by several magnitudes. Finally, the luminosity function itself must be converted to the production rate of H-ionizing photons within galaxies, and to the number of these photons escaping the galaxies. This 'escape fraction' is observationally unconstrained at $z \geq 2$

JWST will likely play a pivotal role also in the determination of the far-UV luminosity function at high-z. Deep observations with NIRCam will allow the measurement of the galaxy UV luminosity function at $z \geq 6$ down to $M_{\rm UV} \sim -15$. Even deeper observations would however be required to detect the predicted turn-over of the luminosity function at $M_{\rm UV} \leq -13$, due to the effect of stellar and supernova feedback on low mass ($\log(\rm M_{vir}/M_{\odot}) \leq 8.5$) haloes (e.g. Gnedin & Kaurov 2014; Wise et al. 2014).

5 Conclusions

Despite great observational efforts, our current knowledge of cosmic reionization is limited by the difficulty of measuring the rest-frame UV emission of galaxies at $z \geq 6$. This situation will be revolutionised with the launch of JWST. The complementarity of the different instruments onboard JWST will allow to trace the state of the IGM at $z \geq 7$ by using background sources (NIRSpec and NIRCam), to study the evolution of LAE down to faint magnitudes (NIRSpec and NIRISS), to precisely characterise the properties of gas in high-redshift star forming regions (NIRSpec), and of stellar population in primeval galaxies (NIRCam, NIRSpec and MIRI), besides providing the most accurate measurements of the galaxy UV luminosity function and its redshift evolution (NIRCam).

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References

Atek, H., Richard, J., Jauzac, M., et al. 2015a, ArXiv e-prints [arXiv] 1509.06764
Atek, H., Richard, J., Kneib, J.-P., et al. 2014, ApJ, 786, 60
Atek, H., Richard, J., Kneib, J.-P., et al. 2015b, ApJ, 800, 18
Bacon, R., Brinchmann, J., Richard, J., et al. 2015, A&A, 575, A75
Bolton, J. S., Haehnelt, M. G., Warren, S. J., et al. 2011, MNRAS, 416, L70
Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015a, ApJ, 811, 140
Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015b, ApJ, 803, 34
Fan, X., Strauss, M. A., Becker, R. H., et al. 2006, AJ, 132, 117
Finkelstein, S. L., Ryan, Jr., R. E., Papovich, C., et al. 2015, ApJ, 810, 71
Finlator, K., Oh, S. P., Özel, F., & Davé, R. 2012, MNRAS, 427, 2464
Gnedin, N. Y. & Kaurov, A. A. 2014, ApJ, 793, 30
Grissom, R. L., Ballantyne, D. R., & Wise, J. H. 2014, A&A, 561, A90
Gunn, J. E. & Peterson, B. A. 1965, ApJ, 142, 1633
Jensen, H., Hayes, M., Iliev, I. T., et al. 2014, MNRAS, 444, 2114
Konno, A., Ouchi, M., Ono, Y., et al. 2014, ApJ, 797, 16
Kulkarni, G., Hennawi, J. F., Rollinde, E., & Vangioni, E. 2014, ApJ, 787, 64
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Matthee, J., Sobral, D., Santos, S., et al. 2015, MNRAS, 451, 400
McQuinn, M. 2012, MNRAS, 426, 1349
McQuinn, M., Hernquist, L., Zaldarriaga, M., & Dutta, S. 2007, MNRAS, 381, 75
Mirabel, I. F., Dijkstra, M., Laurent, P., Loeb, A., & Pritchard, J. R. 2011, A&A, 528, A149
Miralda-Escudé, J. 1998, ApJ, 501, 15
Mortlock, D. J., Warren, S. J., Venemans, B. P., et al. 2011, Nature, 474, 616
Oesch, P. A., Bouwens, R. J., Illingworth, G. D., et al. 2014, ApJ, 786, 108
Paardekooper, J.-P., Khochfar, S., & Dalla Vecchia, C. 2013, MNRAS, 429, L94
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2015, ArXiv e-prints [arXiv] 1502.01589
Robertson, B. E., Ellis, R. S., Furlanetto, S. R., & Dunlop, J. S. 2015, ApJ, 802, L19
Sobacchi, E. & Mesinger, A. 2015, MNRAS, 453, 1843
Stark, D. P., Ellis, R. S., Chiu, K., Ouchi, M., & Bunker, A. 2010, MNRAS, 408, 1628

Tilvi, V., Papovich, C., Finkelstein, S. L., et al. 2014, ApJ, 794, 5
Totani, T., Aoki, K., Hattori, T., et al. 2014, PASJ, 66, 63
Verhamme, A., Orlitová, I., Schaerer, D., & Hayes, M. 2015, A&A, 578, A7
Willott, C. J., Delorme, P., Reylé, C., et al. 2010, AJ, 139, 906
Wise, J. H., Demchenko, V. G., Halicek, M. T., et al. 2014, MNRAS, 442, 2560
Wisotzki, L., Bacon, R., Blaizot, J., et al. 2015, ArXiv e-prints [arXiv] 1509.05143
Zackrisson, E., Inoue, A. K., & Jensen, H. 2013, ApJ, 777, 39
Zheng, Z., Cen, R., Trac, H., & Miralda-Escudé, J. 2011, ApJ, 726, 38