Reionization after HST and before JWST: An Updated Timeline and Protagonists for the Reionization of the Universe

Rohan Naidu
Advisor: Charlie Conroy
Proposed Committee: Daniel Eisenstein, Avi Loeb

ABSTRACT

We propose to update the paradigms around cosmic reionization–which sources were responsible, when did it occur, how fast did it proceed–in the face of a recent series of observational and theoretical advances: the final census of galaxies from HST in the faintest limits revealing a dearth both at $z \sim 8-10$ and at $M_{UV} < -15$, a significantly constrained Tau from Planck Collaboration et al. (2018), the first quasars and statistical Lyman-Alpha emitter samples at $z > 7$, and the recognition of binaries and rotating stars as being critical to galaxy UV SEDs. At the heart of the matter lies the escape fraction of ionizing photons from star-forming galaxies (the leading candidate-protagonists for reionization). The escape fraction has been observed to be miniscule ($< 5-10\%$) out to $z \sim 4$–older reionization calculations estimated this quantity should be at least $15-20\%$ or exotic scenarios would need to be invoked to balance the budget of ionizing photons. Using an empirical model that folds in all the afore-mentioned advances we will revisit the star-forming-galaxy-driven reionization scenario and come up with a revised timeline and new protagonists for it. The proposed work, executed in the twilight between the setting of HST and rise of JWST will make testable predictions and explore which are the most constraining observations to guide the most efficient use of these facilities in unraveling the last great phase transition of the universe.

Subject headings: galaxies: high-redshift — galaxies: evolution — dark ages, reionization, first stars

1. Introduction

The protagonists of Cosmic Reionization have been notoriously elusive. Leaking ionizing radiation into their surroundings, these sources ("Lyman Continuum (LyC) leakers") rapidly turned the universe filled with neutral Hydrogen into one of galaxies in the throes of star-formation and stellar-mass buildup in a mere blink of a billion years (Planck Collaboration et al. 2016, 2018). These enigmatic sources are currently expected to be extremely low-mass, faint star-forming galaxies, but this has mostly been concluded from elimination of other candidates like quasars and AGN, and hedging on what the faint end (> -15 mag) of the UV-Luminosity function may look like rather than through convincing, direct observations of LyC emission from star-forming galaxies (e.g. Cristiani et al. (2016); Robertson et al. (2015); Bouwens et al. (2016). Since ionizing photons cannot directly be observed during the thick of reionization at $z > 6$ due to the opaque intervening inter-galactic medium (IGM), observational attempts to understand reionization have resorted to searching for analogs of LyC leakers at lower redshifts (Inoue et al. 2014; Stark 2016).

The prevailing paradigm from various reionization calculations is that for star-forming galaxies to drive reionization, their f_{esc} must exceed $15-20\%$ (e.g., Madau & Haardt 2015; Mitra et al. 2016; Feng et al. 2016). However, the current observational picture is that of extremely humble, negligible escape fractions out to $z \sim 4$ (e.g Japelj et al. 2017; Grazian et al. 2017; Naidu et al. 2017, 2018).

Against this context, several developments over

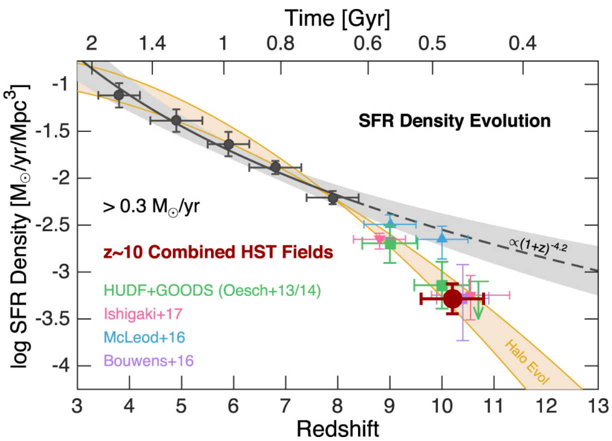

Fig. 1.— Figure from (Oesch et al. 2018). The star-formation rate density falls drastically between $z \sim 8 - 10$ as per what are likely the most definitive constraints from the Hubble Space Telescope. Previous reionization studies that evaluated star-forming galaxy-driven reionization (e.g. Robertson et al. (2013, 2015); Sun & Furlanetto (2016) used SFRDs consistent with the grey shaded region. This drop has immediate implications for the timeline of reionization.

the last year motivate revisiting the widely held dogma that faint star-forming galaxies are the only viable protagonists to drive reionization. In particular:

(a) Oesch et al. (2018) confirm a drastic drop in the star-formation surface density between $z \sim 8-10$ (also see Ishigaki et al. 2018). Which is to say, the ionizing photon contribution from these earlier epochs is much humbler compared to that assumed in reionization calculations mentioned earlier.

(b) Atek et al. (2018) and Bouwens et al. (2017) report a shallow UV luminosity function at $M_{UV} > -15$ $z > 6$, i.e. the scenario in which an infinite reservoir of ultra-faint galaxies $M_{UV} > -15$ comfortably reionize the universe with humble escape fractions as suggested in Livermore et al. (2017) may not be as viable as previously though.

(c) It has been recently realized that accounting for the effect of binaries and rotating stars drastically boosts the UV spectra of galaxies, and these harder ionizing photons potentially alter the reionization budget (Choi et al. 2017; Ma et al. 2016; Steidel et al. 2016).

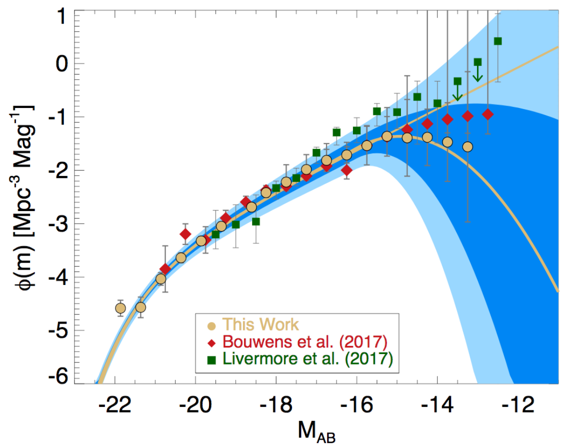

Fig. 2.— Figure from (Atek et al. 2018). Without a plethora of ultra-faint galaxies as proposed by Livermore et al. (2017) at extremely faint magnitudes, the scenario of reionization driven by ultra-faint galaxies (e.g. Stark 2016) is in need of revision. Accordingly, in this study we truncate the UVLF at $M_{UV} < -14$ to explore if reionization is still viable by star-forming galaxies.

(d) The Planck Collaboration et al. (2018) value for the optical depth for Thomson scattering (0.054 ± 0.007) is lower and more constrained than the earlier Planck Collaboration et al. (2016) (0.058 ± 0.012) and WMAP (0.084 ± 0.013) results– the tight error bars rule out several previously permissible models for early reionization and independently support the findings in (a).

(e) The discovery of two quasars right in the heart of the Epoch of Reionization ($z > 7$) (Bañados et al. 2018; Davies et al. 2018), and large-scale Lyman-Alpha (LyA) surveys at $z > 6$ (Mason et al. 2018) have for the first time produced robust, principled, tight constraints on the neutral fraction of the IGM at $z > 7$.

2. Proposed Study

Given these recent advances, the time is ripe to paint a fresh picture of reionization. Here we propose to self-consistently fold in these new data (neutral fractions, Thomson optical depth) and state-of-the-art models to derive updated constraints on the timeline and nature of sources that drove reionization.

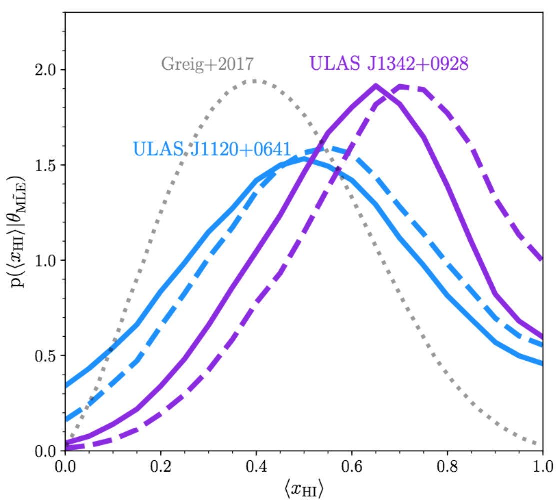

Fig. 3.— Figure from (Davies et al. 2018). Absorption features in the spectra of quasars at $z > 7$ yield constraints on the neutral fraction at these high redshifts for the first time. We constrain our free parameter, f_{esc} against these measurements, similar measurements from LAEs (Mason et al. 2018), and the recent Planck Collaboration et al. (2018) measurement of τ.

2.1. Approach and Methods

The primary goal of this project is to constrain the escape fraction of ionizing photons (f_{esc}) from star-forming galaxies, and thus reconstruct the reionization history of the universe. The quantity at the heart of the problem is the co-moving production rate of Hydrogen-ionizing photons (which depends on f_{esc}) as a function of redshift and is parametrized as follows (Robertson et al. 2013):

$$\dot{n_{ion}}(z) = \rho_{SFRD}\xi_{ion}f_{esc}$$

The right hand side of the equation, to first order, translates to: how many galaxies are present at a given redshift (ρ_{SFRD})? how many ionizing photons are they producing (ξ_{ion})? how many of those produced photons escape the labyrinths of the galaxy into the IGM and proceed to reionize the IGM (f_{esc})? Of these three quantities, f_{esc} has proven notoriously difficult to constrain observationally as described earlier–so we leave it as a free parameter.

For ρ_{SFRD} and ξ_{ion} we rely on an empirical model for galaxy evolution (Tacchella et al. 2018) that makes a simple assumption–the star-formation efficiency of halos depends on the growth rate of the halo–and remarkably reproduces high-z observations like UV luminosity functions out to $z \sim 6$ and the drop in SFRD between $z \sim 8 - 10$ to very high fidelity. This model further provides information on the spatial distribution of galaxies, and properties of individual galaxies (e.g. SFR, star-formation rate surface densities) by producing spectra via cutting-edge FSPS[1]/MIST[2] and FSPS/BPASS[3] models that account for the presence of massive rotating stars and binaries (Stanway et al. 2016; Choi et al. 2017). We truncate the ρ_{SFRD} at $M_{UV} < -15$ as per the results from (Atek et al. 2018; Bouwens et al. 2017) and integrate the FSPS spectra to find ξ_{ion}. We will explore variations in the IMF and the effects of evolving metallicity on the output of ionizing photons, but for our fiducial model we assume a Chabrier (2003) IMF and hold metallicity constant to $Z = 0.02Z_{\odot}$.

We then pass the resultant $\dot{n_{ion}}$ through standard reionization equations under the Case-B recombination assumption by holding the IGM temperature and clumping factor fixed as is standard in this flavor of study (see e.g. equations 1-3 in Robertson et al. 2013). From these equations we get out the neutral fraction of the universe as a function of redshift, and the Thomson optical depth (τ). We then constrain our free parameter (f_{esc}) against the neutral fraction data and latest τ measurements in a maximum-likelihood manner.

For f_{esc} we will first make the standard assumption of a constant, unevolving f_{esc} to make for an easy comparison with previous studies. Then we will also consider redshift-evolving models of f_{esc} which e.g. move in lockstep with the star-formation rate surface density (SFRSD) or the specific star-formation rate (sSFR) motivated both by observations of the handful of known LyC leakers (Naidu et al. 2017; Vanzella et al. 2016; Izotov et al. 2016) and recent high-res simulations (Trebitsch et al. 2017). Being able to link f_{esc} to

[1]Flexible Stellar Population Synthesis (Conroy et al. 2009, 2010; Conroy & Gunn 2010)

[2]MESA (Modules for Experiments in Stellar Astrophysics Paxton et al. (2013)) Isochrones and Stellar Tracks (Dotter 2016; Choi et al. 2016)

[3]Binary Population and Spectral Synthesis (Eldridge et al. 2017)

galaxy by galaxy properties is a unique aspect of our study enabled by the empirical model.

2.2. Proposed Outcomes

Our study will yield some of the most robust answers to date, to the following pressing issues in extragalactic astronomy:

- Can a $z-$invaraiant f_{esc} model reionize the universe? What is the most likely f_{esc} fit? Is this higher or lower than what has been observed at $z \sim 3-4$? If the obtained value wildly diverges from the observed limits on f_{esc} we may be able to rule out the family of unevolving f_{esc} models (e.g. Mitra et al. 2015, 2016).
- Can $M_{UV} > -15$ galaxies reionize the universe without requiring exotic escape fractions?
- In the models where f_{esc} depends on galaxy properties–which are the galaxies that reionize the universe? If they are bright and massive, why haven't we been able to observe them yet? If they are faint, how faint, and will they be detectable by future surveys? What JWST observations will definitively reveal them to be the reionization-drivers?
- How quickly does the universe reionize? When is the universe 50% neutral? What implications does this have for 21-cm experiments? What implications does this have for the quenching of star-formation by the heating up of low-mass halos?
- Which observations are the most constraining to the history of reionization? Say, at what redshift does measuring the neutral fraction rule out the most amount of f_{esc} parameter space?
- Is there room for contribution from quasars? Or are star-forming galaxies able to handle the job?

2.3. Parting Notes

The proposed project will be executed during a liminal period, during the twilight of the Hubble Space Telescope, which has pushed to its faintest limits, and before the dawn of the James Webb Space Telescope which will produce the first statistical samples of reionization-era galaxies. We will re-evaluate the prevailing paradigms around reionization for the interim period of preparation between these two eras. We will get at the mechanics of how the reionizing budget is balanced–are star-forming galaxies able to do it all, how, and how fast? The constraints on f_{esc} we will derive will inform the acquisition of new data (e.g. we may find that measuring the neutral fraction at a certain redshift versus another is the most efficient way of ruling out various models), and drive the most efficient use of JWST in casting light on the last great phase transition of the universe (e.g. if we find bright galaxies are comfortably able to reionize the universe then we might prioritize more detailed observations of a small number of such galaxies to confirm this hypothesis).

REFERENCES

Atek, H., Richard, J., Kneib, J.-P., & Schaerer, D. 2018, MNRAS, 479, 5184

Bañados, E., Venemans, B. P., Mazzucchelli, C., et al. 2018, Nature, 553, 473

Bouwens, R. J., Oesch, P. A., Illingworth, G. D., Ellis, R. S., & Stefanon, M. 2017, ApJ, 843, 129

Bouwens, R. J., Smit, R., Labbé, I., et al. 2016, ApJ, 831, 176

Chabrier, G. 2003, Publications of the Astronomical Society of the Pacific, 115, 763

Choi, J., Conroy, C., & Byler, N. 2017, ApJ, 838, 159

Choi, J., Dotter, A., Conroy, C., et al. 2016, ApJ, 823, 102

Conroy, C., & Gunn, J. E. 2010, ApJ, 712, 833

Conroy, C., Gunn, J. E., & White, M. 2009, ApJ, 699, 486

Conroy, C., White, M., & Gunn, J. E. 2010, ApJ, 708, 58

Cristiani, S., Serrano, L. M., Fontanot, F., Vanzella, E., & Monaco, P. 2016, MNRAS, 462, 2478

Davies, F. B., Hennawi, J. F., Bañados, E., et al. 2018, ArXiv e-prints, arXiv:1802.06066

Dotter, A. 2016, ApJS, 222, 8

Eldridge, J. J., Stanway, E. R., Xiao, L., et al. 2017, , 34, e058

Feng, Y., Di-Matteo, T., Croft, R. A., et al. 2016, MNRAS, 455, 2778

Grazian, A., Giallongo, E., Paris, D., et al. 2017, ArXiv e-prints, arXiv:1703.00354

Inoue, A. K., Shimizu, I., Iwata, I., & Tanaka, M. 2014, MNRAS, 442, 1805

Ishigaki, M., Kawamata, R., Ouchi, M., et al. 2018, ApJ, 854, 73

Izotov, Y. I., Orlitová, I., Schaerer, D., et al. 2016, Nature, 529, 178

Japelj, J., Vanzella, E., Fontanot, F., et al. 2017, MNRAS, 468, 389

Livermore, R. C., Finkelstein, S. L., & Lotz, J. M. 2017, ApJ, 835, 113

Ma, X., Hopkins, P. F., Kasen, D., et al. 2016, MNRAS, 459, 3614

Madau, P., & Haardt, F. 2015, ApJ, 813, L8

Mason, C. A., Treu, T., Dijkstra, M., et al. 2018, ApJ, 856, 2

Mitra, S., Choudhury, T. R., & Ferrara, A. 2015, MNRAS, 454, L76

—. 2016, ArXiv e-prints, arXiv:1606.02719

Naidu, R. P., Forrest, B., Oesch, P. A., Tran, K.-V. H., & Holden, B. P. 2018, MNRAS, 478, 791

Naidu, R. P., Oesch, P. A., Reddy, N., et al. 2017, ApJ, 847, 12

Oesch, P. A., Bouwens, R. J., Illingworth, G. D., Labbé, I., & Stefanon, M. 2018, ApJ, 855, 105

Paxton, B., Cantiello, M., Arras, P., et al. 2013, ApJS, 208, 4

Planck Collaboration, Adam, R., Aghanim, N., et al. 2016, A&A, 596, A108

Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2018, ArXiv e-prints, arXiv:1807.06209

Robertson, B. E., Ellis, R. S., Furlanetto, S. R., & Dunlop, J. S. 2015, ApJ, 802, L19

Robertson, B. E., Furlanetto, S. R., Schneider, E., et al. 2013, ApJ, 768, 71

Stanway, E. R., Eldridge, J. J., & Becker, G. D. 2016, MNRAS, 456, 485

Stark, D. P. 2016, ARA&A, 54, 761

Steidel, C. C., Strom, A. L., Pettini, M., et al. 2016, ApJ, 826, 159

Sun, G., & Furlanetto, S. R. 2016, MNRAS, 460, 417

Tacchella, S., Bose, S., Conroy, C., Eisenstein, D. J., & Johnson, B. D. 2018, ArXiv e-prints, arXiv:1806.03299

Trebitsch, M., Blaizot, J., Rosdahl, J., Devriendt, J., & Slyz, A. 2017, MNRAS, 470, 224

Vanzella, E., de Barros, S., Vasei, K., et al. 2016, ApJ, 825, 41

This 2-column preprint was prepared with the AAS LaTeX macros v5.0.