COSMIC DAWN: STUDIES OF THE EARLIEST GALAXIES AND THEIR ROLE IN COSMIC REIONIZATION

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I review recent progress and challenges in studies of the earliest galaxies, seen when the Universe was less than 1 billion years old. Can they be used as reliable tracers of the physics of cosmic reionization thereby complementing other, more direct, probes of the evolving neutrality of the intergalactic medium? Were star-forming galaxies the primary agent in the reionization process and what are the future prospects for identifying the earliest systems devoid of chemical enrichment? Ambitious future facilities are under construction for exploring galaxies and the intergalactic medium in the redshift range 6 to 20, corresponding to what we now consider the heart of the reionization era. I review what we can infer about this period from current observations and in the near-future with existing facilities, and conclude with a list of key issues where future work is required.

Keywords: Galaxy evolution; cosmology

1. Introduction

Most would agree that the final frontier in piecing together a coherent picture of cosmic history concerns studies of the era corresponding to a redshift interval from 25 down to about 6; this corresponds to the period 200 million to 1 billion years after the Big Bang. During this time the Universe apparently underwent two vitally important changes. Firstly, the earliest stellar systems began to shine, bathing the Universe in ultraviolet radiation from their hot, metal-free stars. Although isolated massive stars may have collapsed and briefly shone earlier, the term *cosmic dawn* usually refers to the later arrival of dark matter halos capable of hosting star clusters or low mass galaxies. Secondly, the intergalactic medium transitioned from a neutral and molecular gas into one that is now fully ionized - a process termed *cosmic reionization.*

It is tempting to connect these two changes via a cause and effect as illustrated in Figure 1. Young stellar systems forming at a redshift of 25, corresponding to 200 Myr after the Big Bang, emit copious amounts of ultraviolet radiation capable of ionizing their surroundings. These ionized spherical bubbles expand with time and, as more stellar systems develop, they overlap and the transition to a fully ionized intergalactic medium is completed.

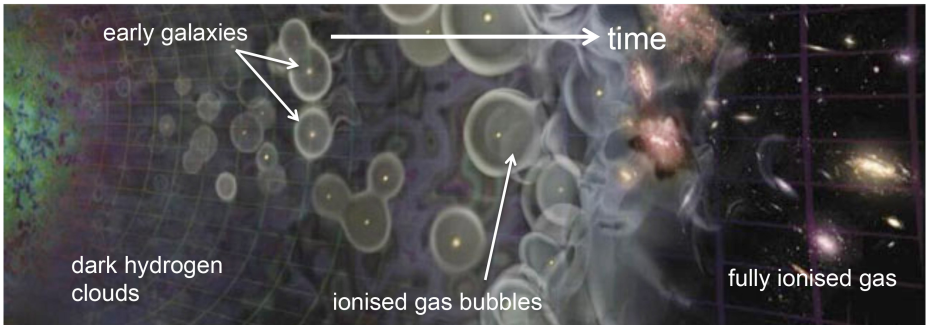


Fig. 1. An illustration of how early populations of star-forming galaxies reionized the Universe. Baryonic gas is attracted into assembling dark matter halos and it cools and collapses to form the first stellar systems. Ultraviolet radiation from their hot young stars photoionizes the surrounding neutral hydrogen creating ionized bubbles. As more systems collapse and the ionized bubbles increase in size, their volumes overlap and cosmic reionization is complete[1] .

In addition to determining when this transition occurred and whether this simple picture is correct, studies of galaxies and the nature of the intergalactic medium during this period are valuable in further ways. The relevant physical processes governing star formation at this time determine which primitive systems survive and which form the basic material for the subsequent evolution of galaxies. Indeed, relics of this period may be present in local low mass dwarf galaxies devoid of star formation. The abundance of the earliest low mass systems depends sensitively on the assembly history of the dark matter halos which, in turn, depends on its streaming velocity. Although the cold dark matter picture is favored by large scale structure observations, early galaxy formation would be delayed if the dark matter was somewhat warmer and so direct observations of very early galaxies could verify or otherwise the standard picture[2] .

Ambitious facilities are now under construction, motivated in part by studies of the reionization era. These include the James Webb Space Telescope (JWST) which has the unique capability to undertake spectroscopy longward of 2μm, thereby accessing familiar rest-frame optical nebular lines as measures of the ionizing radiation field and the evolution of the gas phase metallicity. Three next-generation 25-40 meter aperture ground-based telescopes (the European Extremely Large Telescope, the Thirty Meter Telescope and the Giant Magellan Telescope) are also under development which will improve the spectroscopic capabilities. High order adaptive optics will give these facilities impressive imaging capabilities, a highly relevant advantage as the faintest sources at early epochs are otherwise unresolved. Deep near-infrared imaging over large areas of sky by survey facilities such as the European Space Agency's *Euclid* and NASA's WFIRST-AFTA missions will significantly improve information on the demographics of early galaxies which is currently limited by cosmic variance uncertainties associated with the small fields of view of the Hubble and Spitzer Space Telescopes.

These impressive upcoming facilities will be complemented by independent probes of the distribution of cold and ionized gas charted tomograpically using the redshifted 21cm line. Initial *pathfinder* projects such as the Low Frequency Radio Array (LOFAR) will address the statistical distribution over a limited redshift range, whereas the Square Kilometer Array (SKA) will have the power to directly image the evolving distribution of neutral gas. The combination of clustering statistics for the early galaxy distribution and equivalent data for the neutral gas will delineate the evolution of ionized regions in the context of the radiation from observed sources. This will revolutionize our understanding of the reionization era.

In this brief review I take stock of what we currently know about the two principal questions that address the picture illustrated above: when did reionization occur and were galaxies the primary reionizing agents? Although we can address these questions using a variety of approaches, I will focus primarily on what we are learning from studies of early star-forming galaxies. This naturally leads to a discussion of the prospects for the next few years, including those possible with the future facilities listed above. Finally, I list some of the fundamental challenges faced in interpreting the growing amount of data on early galaxies. My review is to be read in conjunction with a complementary discussion presented by Steve Furlanetto in this volume which focuses more on the theoretical aspects of reionization and the future prospects with 21cm tomography.

2. When Did Reionization Occur?

The earliest constraints on the reionization history arose from the Gunn-Peterson test[3] applied to the absorption line spectra of $z > 5.5$ QSOs (see [4]). The decreasing transmission due to thickening of the Lyman alpha forest was initially used to argue that the reionization process ended at a redshift close to 6. However, only a very small change in the volume-averaged fraction of neutral hydrogen, $x(HI) \simeq 10^{-3}$, is required to completely suppress the spectroscopic signal shortward of Lyman alpha in the spectrum of a QSO, above which saturation rapidly occurs. Accordingly, this method is only useful for detecting a subtle change at the end of the reionization process. Since the bulk of the high redshift QSOs were analyzed some 8-10 years ago,[4,5] progress in locating higher redshift QSOs has been slow. Fortunately, some additional constraints have been provided through equivalent spectroscopy of a handful of $z >6$ long duration gamma ray burst (GRB) afterglows[6] . Unfortunately, none of the more distant GRBs discovered beyond $z \simeq 7$ was followed up in detail. Indeed, only one source above a redshift of 7 - a QSO - has a relevant absorption line spectrum above a redshift of 7 [7] . The initial analysis of this spectrum suggested that the IGM may indeed be significantly neutral ($x(HI) \simeq 10^{-1}$) at this redshift ([7,8] but see Boseman & Becker, in prep.), although confirmation from additional lines of sight is clearly desired.

A second constraint on the reionization history arises from the optical depth τ to electron scattering to cosmic microwave background (CMB) photons and the cross-correlation of the polarization signal induced by these electrons and the temperature fluctuations. τ therefore acts as a integral constraint on the line of sight distribution of ionized gas. The angular correlation can be interpreted in structure formation theory as providing an approximate redshift of the reionization era. Usually the quoted result corresponds to that assuming an (unrealistic) an instantaneous reionization. Over the past few years WMAP has provided a series of improved constraints[9] corresponding to instantaneous reionization at $z \simeq 10.6 \pm 1.1$. No polarization results are yet available from Planck mission but early constraints based on temperature fluctuations alone[10] are consistent. It will be very important to secure independent confirmation of τ from the Planck mission. The prospects of using higher order CMB data to improve our understanding of reionization in the future is discussed by Calabrese et al[11] .

The most recent development in tracing reionization history follows studies of the rate of occurrence of Lyman alpha (Lyα) emission in star-forming galaxies. Miralda-Escudé[12] and Santos[13] discussed the prospect of using Lyα as a resonant transition, one which is readily absorbed if a line emitting galaxy lies in a neutral IGM. Early results based on the luminosity functions of narrow-band selected Lyα emitting galaxies over the redshift range $5.7 < z < 6.5$ supported the notion of a rapidly-changing IGM via a marked decline in the abundance of emitters over a short period of cosmic history (corresponding to an interval of less than 200 Myr)[14,15] . However, although a striking result, it is hard to separate the effect of an increasingly neutral IGM at high redshift from the declining abundance of star-forming galaxies deduced from the overall population observed beyond $z \simeq 4$ [16] .

An improved test that removes this ambiguity involves measuring the *fraction* of line emission in well-controlled, color-selected Lyman break galaxies. First introduced as a practical proposition by Stark[17] this method has been variously applied in the last 3 years[18–20] and most recently, by Schenker et al[21] . The availability of large numbers of $z > 7$ candidates from deep HST imaging and new multi-object near-infrared spectrographs has enabled considerable progress of late. These observations confirm a marked decline in the visibility of Lyα beyond a redshift $z \simeq 6.5$, consistent with the Gunn-Peterson constraints discussed above (Figure 2). Although Schenker et al report spectroscopic data for 102 $z > 6.5$ Lyman break galaxies, only a handful beyond $z \simeq 7$ show Lyα emission, the current record-holder being at $z = 7.62$.

The challenge lies in interpreting the fairly robust decline in the visibility of Lyα emission in the context of an increasing neutral fraction $x(HI)$ at earlier times. Radiative transfer calculations have suggested the fast decline in Figure 2 could imply a 50% neutral fraction by volume as late as $z \simeq 7.5$[22,23] . The uncertainties in this interpretation include (i) cosmic variance given the limited volumes so far probed with ground-based spectrographs[24] , (ii) the assumed velocity offset of Lyα with respect to the systemic velocity of the galaxy which is critical in understanding whether the line resonates with any neutral gas[25,26] and (iii) the possible presence of optically-thick absorbing clouds within the ionized regions[8] . A final variable is the escape fraction of ionizing photons from the galaxy, f_{esc}. If this were much higher at earlier times as a result of less neutral gas in the galaxies, the production of Lyα in the intrinsic spectrum would be reduced[27] .

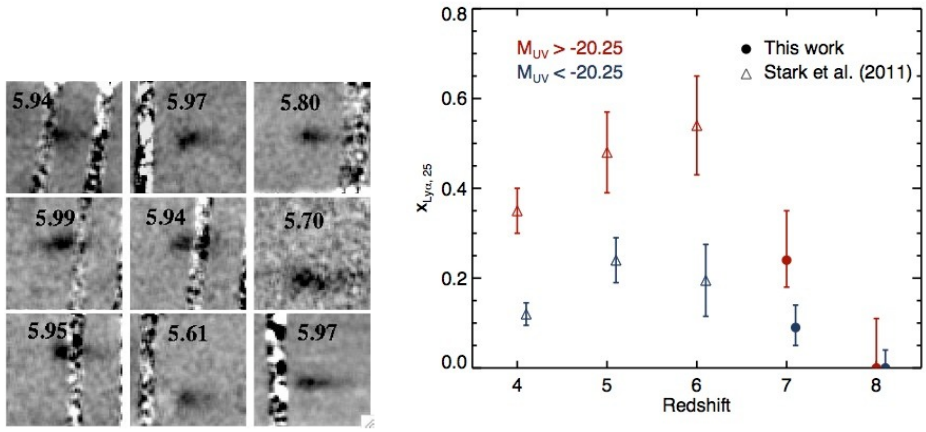


Fig. 2. **Left:** Keck spectra for $z \simeq 6$ galaxies showing the high rate of occurrence of Lyα emission. Each sub-panel represents a 2-D spectrum of a Lyman break galaxy and the black regions represent line emission at the redshift marked[17] . **Right:** The evolving fraction of Lyman break galaxies in various luminosity bins that present a detectable Lyα emission line from the recent survey of Schenker et al[21] . The rising fraction over $4 < z < 6$ is interpreted via a reduced dust extinction at early times, whereas the sudden reversal beyond $z \simeq 6$ is attributed to an increasingly neutral intergalactic medium.

A complementary and promising method for tracing reionization is to statistically chart the evolving distribution of neutral gas directly via redshifted 21cm emission using radio interferometers such as LOFAR[28] and the Murchison Wide Field Array[29] . No direct detections are yet available but the prospects are discussed by Steve Furlanetto elsewhere in this volume.

Figure 3 represents a recent summary of the various constraints on reionization and includes several methods not described in this brief review[30] . As can be seen, the redshift range 6 to 20, corresponding to a period of 800 Myr is considered to be the window of interest.

3. Were Galaxies Responsible for Cosmic Reionization?

Potential contributors to the reionizing photons include star-forming galaxies, non-thermal sources such as quasars and low luminosity active galactic nuclei, primordial black holes and decaying particles. Luminous QSOs decline rapidly in their abundance beyond $z \simeq 6$ so the only prospect for non-thermal sources contributing significantly to reionization might be if the faint end of their luminosity function is unusually steep. Current estimates of the high redshift AGN luminosity function suggest this is not the case although the observational uncertainties are still

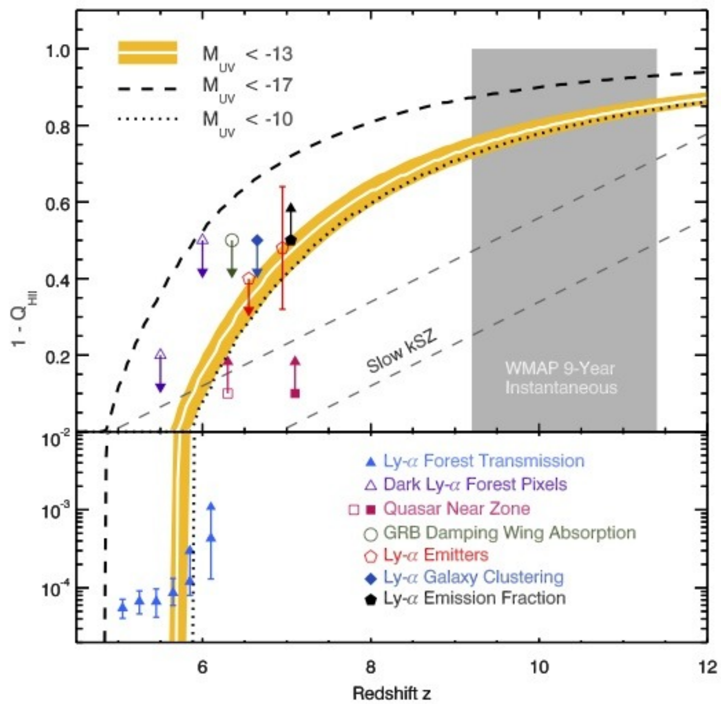


Fig. 3. Reionization histories for models that include galaxies to various luminosity limits from the UDF12 survey ($M_{UV} < 13$ white line; 68% credibility region: orange area; < 17, dashed line; < 10, dotted line) plus other claimed constraints on the neutral fraction $1 - Q_{HII}$ (see lower panel for legend). Methods not discussed in the text include the fraction of dark pixels in the Lyα forest (purple open triangles), QSO near-zone measurements (open and solid magenta squares), damping wing absorption in a GRB (open green circle), the clustering of Lyα emitters (filled dark blue diamond). The gray dashed lines labeled Slow kSZ illustrate the slowest evolution permitted by small-scale CMB temperature data and the shaded gray region shows the redshift of instantaneous reionization according to WMAP[30] .

large[31,32] .

Star-forming galaxies represent the most promising reionizing source given they are now observed in abundance in the relevant redshift range from deep surveys such as the Hubble Ultra Deep Field (UDF)[33] . These and other data reveal a steep luminosity function at the faint end[34–36] , such that it is reasonable to assume we are only observing the luminous fraction of a much larger population. However, a quantitative calculation of the photon budget requirements for maintaining reionization involves additional parameters, some of which are largely unconstrained (see recent review by [30]).

In this case, the reionization process is a balance between the recombination of free electrons with protons to form neutral hydrogen and the ionization of hydrogen by Lyman continuum photons. The dimensionless volume filling factor of ionized hydrogen Q_{HII} can be expressed as a time-dependent differential equation:

$$\dot{Q}_{HII} = \frac{\dot{n}_{ion}}{< n_H >} - \frac{Q_{HII}}{t_{rec}}$$

The recombination time t_{rec} depends on the baryon density, the primordial mass fraction of hydrogen, the case B recombination coefficient and the clumping factor $C_{HII} \equiv < n_H^2 > / < n_H >^2$ which takes into account the effects of IGM inhomogeneity through the quadratic dependence of recombination on density. Simulations suggest $C_{HII} \simeq$1-6 at the relevant redshifts[37] , although there has been much discussion of its redshift dependence depending on the epoch when the ultraviolet (UV) background becomes uniform. If the clumping factor C_{HII} is time invariant, t_{rec} declines with increasing redshift. For the expected values above, at redshifts $z < 10$, t_{rec} exceeds 100-200 Myr[38,39] ensuring recombination is unlikely. However, if the source of ionizing photons is not steady in the redshift range $10 < z < 25$, there remains the possibility of an intermediate recombination era, perhaps inbetween reionization from the first isolated massive stars and that subsequently from early galaxies.

The main uncertainty in understanding the contribution of galaxies can be understood via the relative contributions to the ionizing photon rate $\dot{n_{ion}}$:

$$\dot{n}_{ion} = f_{esc}\xi_{ion}\rho_{SFR}$$

where ρ_{SFR} represents the most direct observable, the integrated volume density of star-forming galaxies. This involves measuring the redshift-dependent luminosity function, typically in the rest-frame UV continuum ($\simeq$ 1500 Å) which is accessible at $z \simeq 7 - 10$ with HST's near-infrared camera WFC3/IR, and above $z \simeq$10 with NIRCam on JWST. The faint end slope of the luminosity function is a critical factor given it contributes the major portion of the integrated luminosity density[34–36] . ξ_{ion} is the ionizing photon production rate which encodes the number of photons more energetic than 13.6 eV that are produced per unit star formation rate. This requires knowledge of the stellar population which can currently only be estimated by modeling the average galaxy color. Finally, f_{esc} represents the fraction of ionizing photons below the Lyman limit which escape to the IGM. This is the least well-understood parameter. It can only be directly evaluated through rest-frame UV imaging or spectroscopy at $z \simeq 2-3$([40,41]) where values as low as 5% are typical. At higher redshift, any photons below the Lyman limit are obscured along the line of sight by the lower redshift Lyman alpha forest.

There are several ways to address the question of whether galaxies can meet the ionization budget and these depend critically on the assumed value of the currently unobserved quantities, e.g. f_{esc}. A fundamental requirement is that the integrated electron path length to the start of reionization should match the optical depth of Thomson scattering, τ, in the CMB. When this requirement is imposed, in the context of the results from the Hubble UDF, three conditions are necessary for galaxies to be the main reionization agents[30] . Firstly, the escape fraction f_{esc} has to rise with redshift or be sufficiently luminosity-dependent so that at least 20% on average of the photons escape a typical low luminosity $z \simeq 7-10$ galaxy. Secondly, galaxies must populate the luminosity function to absolute magnitudes below the limits of the deepest current HST images at $z \simeq 7-8$ ($M_{UV} = -17$). Finally, the galaxy population must extend beyond a redshift $z \simeq 10$ to provide a sustained source of ionizing radiation. Various combinations of these three requirements have been discussed in the literature and presented alternatively as reasonable assumptions or as critical shortfalls in the ionizing budget!

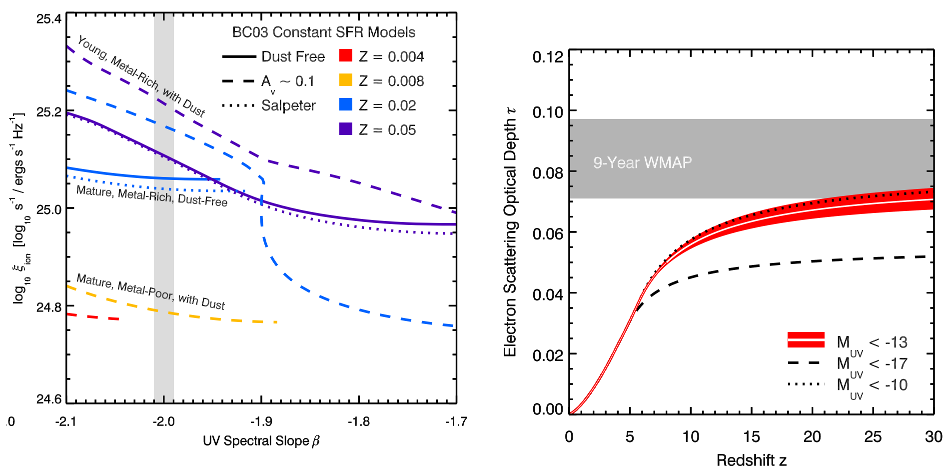


Fig. 4. **Left:** Degeneracies in inferring the ionizing photon production factor ξ_{ion} in terms of the observed slope β of the ultraviolet continuum, the gray shaded area being that observed for $z \simeq 7-8$ galaxies[42] . Time tracks are shown for stellar population synthesis models of varying dust content, metallicity and the initial mass function[30] . **Right:** One aspect of the UV 'photon shortfall' for galaxies as agents of reionization given the abundance of galaxies in the UDF. Assuming a 20% escape fraction and continuity in the declining star formation rate density beyond $z \simeq 10$, the figure shows the need to extend the UV luminosity function lower than the current $M_{UV} = -17$ detection limit to reproduce the optical depth of electron scattering in the WMAP data[30] .

A further constraint on the above is the requirement that the sum of the star formation during the reionization era cannot exceed the stellar mass density observed using the Spitzer satellite at the end of reionization, say $z \simeq 5-6$ ([43]). This mid-infrared satellite is uniquely effective in this regard given its infrared camera, IRAC, surveys high redshift galaxies at rest-frame optical wavelengths where longer-lived stars can be accounted for. Formally, this can be expressed:

$$\rho_*(z=6) = C \int_{z=6}^{\infty} \int \Phi(L_{UV}, z) L_{UV} dL dz$$

where ρ_* is the required stellar mass density per comoving volume at the end of reionization, and C represents the necessary factor to convert the observed redshift-dependent UV luminosity function $\Phi(L_{UV})$ and its associated luminosity density, into a star formation rate density. Stellar masses for individual galaxies are usually determined by deriving a mass/light ratio from fitting the spectral energy distribution and multiplying by the luminosity. To secure the integrated mass density is challenging given only a more massive subset of the $z \simeq 6$ population is currently detectable with Spitzer. Additionally the Spitzer photometric bands are likely contaminated by nebular line emission at $z \simeq 6$ and significant, but uncertain, downward corrections are required to estimate the true mass density.[25,44] When reasonable estimates are made of the unseen stellar mass at $z \simeq 5$-6 and corrections applied for nebular emission based on spectroscopic evidence at lower redshift, the stellar mass densities ρ_* can be reconciled with the earlier star formation history[30] .

4. The Near Future

Fortunately we observers have not yet reached a threshold in exploring the early galaxy population pending the arrival of new facilities such as JWST and the next generation of large ground-based telescopes. There are several interesting and immediate initiatives available for making further progress.

In addition to probing the reionization history with the fractional rate of occurrence of Lyα emission, the spatial distribution of line emitters in principle contains data on the topology of ionized regions where emission can be transmitted. Narrow-band filters are being used with panoramic cameras to locate Lyα emitters at discrete redshifts where the line is favorably placed with respect to the night sky emission, for example at redshifts z=5.7, 6.6 and 7.1 with the HyperSuprime-Cam 1.5 degree field imager on the Subaru 8.2m telescope (see an example of earlier work of this nature in Figure 5). The correlation of such line emission with redshifted 21cm emission would be a particularly fruitful program.

Strong gravitational lensing by foreground clusters offers a valuable tool for exploring the redshift range $7 < z < 10$ population. HST and Spitzer are investing significant resources in deep imaging of selected clusters via the CLASH[45] and Frontier Fields[a] programs. Lensing facilitates two broad applications depending on the source magnification involved. Bradley et al[46] discuss the magnification distribution for the CLASH survey and Richard et al[47] for the upcoming Frontier Field clusters. Most of the lensed sources have magnifications of $\times$1.5-3 with less than 5% greater than $\times$10 (Figure 6a).

The first regime involves very highly-magnified and usually multiply-imaged sources observed close to the critical line of the cluster. With magnifications of $\times 10 - 30$[48–51] such systems offer the prospect of valuable detailed studies. A good example is the $z \simeq 6.02$ galaxy in the rich cluster Abell 383 which has a magnification of $\times 11.4 \pm 1.6$ corresponding to a $0.4\,L^*$ galaxy[52] . The significant boost in brightness enables a much more precise spectral energy distribution for a representative subluminous system than would otherwise be the case providing a fairly robust stellar

[a] http://frontierfields.org

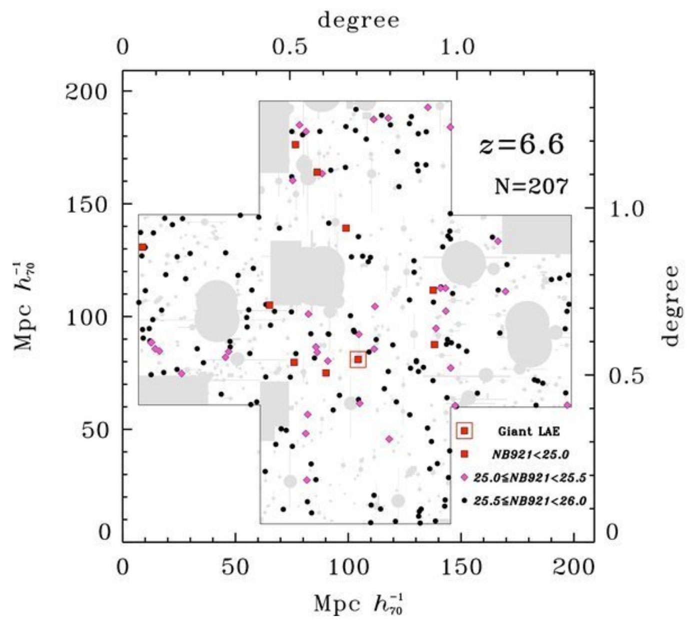


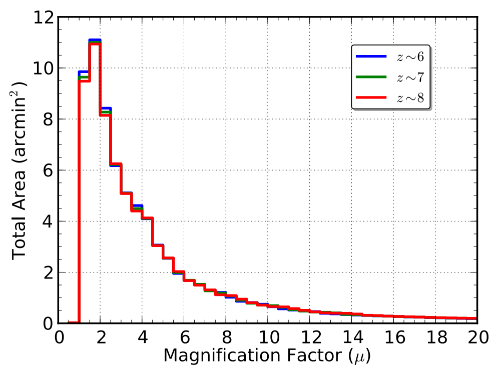
Fig. 5. Angular distribution of 207 Lyα emitters at a redshift of z=6.565 $\pm$ 0.054 selected from a mosaic of narrow band images taken with the Suprime Camera on the 8.2m Subaru telescope, color coded according to their luminosity (decreasing from red squares, through magenta diamonds to black circles[15] . The open red square denotes the extended and luminous emitter 'Himiko' (see Section 5).

age of 640- 940 Myr, corresponding to a formation redshift of $z > 15$. However, such configurations are rare and do not represent a straightforward route to large samples.

The second regime involves more modest magnifications of larger numbers of background sources. The benefits here are not in detailed studies of individual sources but rather for statistical purposes, e.g. in extending the $z \simeq$7-8 luminosity function fainter than was possible in the deepest blank field studies[53] (Figure 6b). Robertson et al[54] recently projected the likely gain in depth over all 6 Frontier Field clusters incorporating the increased cosmic variance in lensed surveys. They claim the uncertainty in the faint end slope α of the luminosity function would be significantly reduced compared to the value in the UDF ($\Delta\alpha = \pm 0.05$ c.f. $\pm$ 0.18).

Detailed spectroscopy of $z \simeq 7-8$ galaxies can also provide further information on the ionization state and metallicity of the gas. Stark et al[26] illustrate how, even when Lyα is suppressed by neutral gas, other nebular lines such as CIII] 1909 and CIV 1550 Å are within reach of current near-infrared spectrographs, although this is highly challenging work even for lensed sources.

This leads naturally to the longer term goal of gathering *gas-phase metallicities* for early galaxies thereby adding *chemical enrichment* as the next logical tracer of earlier activity. Metallicity measurements will very much be the province of JWST



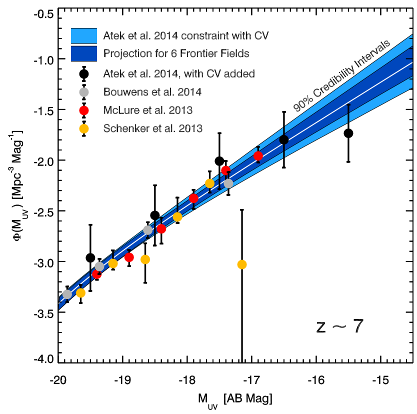


Fig. 6. **Left:** The distribution of lensing magnifications deduced for high redshift galaxies in the HST CLASH survey of foreground clusters.[46] Most sources are only modestly magnified but there are rare sources magnified by factor as large as $\times$10-20. **Right:** Using gravitational lensing in the HST Frontier Field program to extend the $z \simeq$7 luminosity function fainter than was possible in the UDF. Using the available data for one cluster,[53] a projection is made for all 6 clusters.[54]

given all the familiar rest-frame optical lines ([O II], [O III], Hα, [N II]) used locally and at intermediate redshifts as well-calibrated metallicity indicators, are shifted beyond 2μm where ground-based spectroscopy of faint objects is impractical. However, there are valuable sub-mm lines accessible with ALMA at high redshift which may give information on both the metallicity and dust content of early galaxies. Although the currently-held view is that the blue UV colors of most of the $z > 7$ galaxies implies little or no dust, strong ALMA upper limits on far-infrared continua would provide a more convincing argument.

The [CII] 158 μm line has traditionally been one of the most valuable tracers of star formation in energetic sources and a correlation is often claimed between the [C II] luminosity and the star formation rate estimated from the far infrared flux although its interpretation remains unclear[55] . Early ALMA studies of luminous $z \simeq 5-7$ dusty starbursts recovered prominent [CII] emission[56,57] consistent with this correlation. However, an intense Lyα emitter, dubbed 'Himiko' at z=6.595 (see Figure 5) with a high star formation rate ($\simeq 100 M_{\odot}$ yr^{-1}) reveals no far infrared or [CII] emission[58] , and thus deviates significantly from the normal relation. As the Lyα emission is particularly extended and the source is unusually luminous compared to its cohorts, conceivably it is being observed during a special moment in its history e,g. an energetic burst of early activity in a very low metallicity system. Such studies with ALMA may shed light on metal formation in the most luminous early systems ahead of the launch of JWST.

Ultimately one might hope to identify systems with minimal pollution from metals. Such 'Population III' sources initially represented something of a 'Holy Grail' for the next generation facilities - specifically, the charge to find a star-forming galaxy or stellar system devoid of metals. More recent numerical simulations[59] indicate the self-enrichment of halos from early supernovae is surprisingly rapid (<100 Myr) and so such primordial 'first generation' stellar systems may be very rare.

5. Outstanding Issues

Although there a gaps in our quantitative knowledge of the reionization history and the role of galaxies, it has perhaps become commonplace to regard sketched histories such as Figures 3 and 4b as the correct framework within which future facilities can fill in the details. In this concluding section I want to highlight some outstanding issues and puzzles that will serve to focus our collective research in the near future.

The extent of star formation beyond $z \simeq$10: The Ultra Deep Field 2012 campaign argued for a near-continuous decline in the cosmic star formation rate density over $4 < z < 10$ (Ref [60]) and Robertson et al[30] used this continuity plus the mature ages of the $z \simeq$7-8 galaxies[42] , as indirect evidence that the star formation history beyond $z \simeq$10. However, recent work exploiting the wider, but shallower CANDELS data[61] together with several analyses exploiting early Frontier Field lens data[62] point to a discontinuity in this decline at $z \simeq$8. Such a downturn would be hard to reconcile with the stellar mass density evolution[52,63] and, if correct, would seriously increase the UV photon budget shortfall. A key issue here, given the paucity of data beyond $z \simeq$8, is uncertainties arising from cosmic variance[54] . Hopefully with further data from the Frontier Fields and more Spitzer age measures of individual galaxies at $z \simeq$7-8, the situation will be clarified ahead of the launch of JWST.

Missing star-forming galaxies: The high redshift galaxies discussed in this review have almost exclusively been located by their ultraviolet emission, either via continuum colors or through Lyα emission. In addition to assuming there are yet fainter galaxies further down the luminosity function beyond HST's limits, is it conceivable there are additional sources perhaps dusty or those not selected via the current methods? An unresolved puzzle is the anomalously high rate of long duration gamma ray bursts seen beyond $z \simeq$5 compared to that expected using a GRB rate normalized to the star formation rate observed at lower redshift[64] (Figure 7a). This discrepancy may be telling us more about the evolving production rate of GRBs in low metallicity environment rather than something fundamental about the cosmic star formation history. Nonetheless, it acts as a warning that some aspects of early massive star formation may not be understood.

The escape fraction of ionizing photons: The largest uncertainty in addressing the role of galaxies in completing the reionization process is the average fraction of ionizing photons that can escape a typical low-luminosity galaxy. Even with a fraction $f_{esc} \simeq$, 20% there is significant tension in the ionizing budget and in reproducing the optical depth τ of electron scattering by the CMB (Figure 4b). Most likely the escape fraction varies significantly from galaxy to galaxy according to the geometric viewing angle, kinematic state, star formation rate and physical

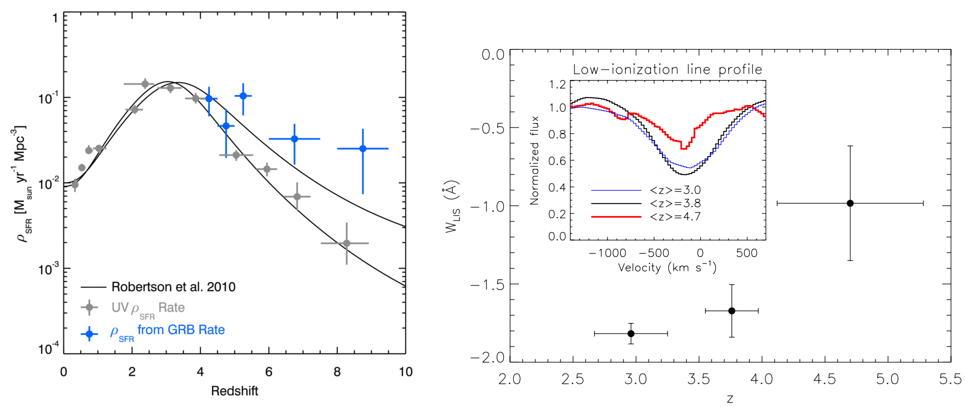


Fig. 7. **Left:** The star formation history beyond a redshift 4 as inferred from the rate of gamma ray bursts (GRBs)[64] . The number of GRBs is converted into a volume-averaged star formation by matching their cumulative redshift distribution over $0 < z < 4$ with the cosmic star formation history. There is a worrying excess in the number of high z GRBs compared to expectations based on the rate at lower redshift. **Right:** The equivalent width of low ionization gaseous absorption lines from Keck spectra of Lyman break galaxies stacked at various redshifts. The inset shows the stacked absorption line profiles whose depth becomes shallower as the redshift increases. Such data suggests that the covering fraction of neutral gas is less at high redshift and hence the escape fraction increases[65] .

size of each galaxy. Even at redshifts $z \simeq$2-3, determining f_{esc} has been a challenging endeavor although the consensus points to the range 0-5%[40,41] . At high redshift, the only practical route is to examine the *covering fraction*, f_{cov}, of neutral or low ionization gas on the assumption that, typically, $f_{esc} = 1 - f_{cov}$. Even so, measuring f_{cov} requires high signal/noise absorption line spectroscopy which is only practical for stacks of galaxies[65] or strongly-lensed examples[66] . Such data to $z \simeq$4-5 shows some evidence for a rising escape fraction with increased redshift (Figure 7b) but the method needs to be extended to larger samples at yet higher redshifts.

When did the Universe produce dust? To these more immediate issues of observational interpretation should be added the question of whether dust is present beyond $z \simeq 7$. Its presence would seriously confuse interpretations of the UV colors (e.g. Figure 4a) as well as raise the question of obscured star formation. An example has recently been found of a convincing ALMA continuum detection for a star-forming galaxy at z=7.58 (Watson et al in prep) which raises very interesting consequences. This early result highlights the key role that ALMA can play in complementing studies of high redshift galaxies with HST and Spitzer.

Summary

Although many puzzles remain as indicated above, the pace of observational discovery is truly impressive and will continue as we see the first convincing results from 21cm interferometry in the next 1-2 years, launch JWST in 2018 and commission the next generations telescopes in the early 2020's. The observational promise is evident and I encourage our theoretical colleagues to get ready for the next revolution in observational data at the redshift frontier!

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