

First Galaxies: Exploring the Reionization Epoch

Rychard J. Bouwens, Garth D. Illingworth

Executive Summary: Studies of the nature of the first galaxies, and of the processes that led to their assembly and buildup, are of compelling importance. Not only did the first generation of galaxies likely reionize the universe, but they also were the seeds for the diverse population of today’s galaxies and the massive black holes that reside in them. Star formation in the first galaxies was likely very different than at later times, with different feedback processes dominating and early galaxies hosting an early generation of primordial stars. The challenges of characterizing the fascinating physical processes at work during the first hundreds of millions of years to $z \sim 6-7$ are considerable. Characterizing these galaxies in detail with observations is difficult due to their small sizes, extreme faintness and the need for sophisticated IR instruments for detection and measurement. Yet such observations are needed if our models are to be realistic. With a 30-m class GSMT, we should have the necessary spatial and spectral resolution to push to the low luminosities needed to characterize their contribution to reionization and to do detailed studies of their sizes, structure and morphologies (Figure 1). The synergies of GSMT with ALMA and JWST would enhance this field greatly.

1 The First Galaxies

The first generation of stars – and eventually galaxies – formed from the inevitable gravitational collapse of hydrogen clouds and dark matter onto slight overdensities in the matter distribution. The first stars were thought to be hundreds of times more massive than our sun, extremely short-lived, metal-free, and had properties very different from successive generations of stars. Ultraviolet radiation from the first few generations of stars and galaxies is thought to have eventually ionized hydrogen in the IGM.

In terms of sources for study, the frontier for exploration is at redshift $z \sim 7 - 15$, corresponding to when the Universe was about 3-800 million years old.

1.1 What Role Did High-Redshift Galaxies Play in Reionizing the Universe?

The reionization of neutral hydrogen at $z \sim 6 - 20$ represented a fundamental phase transition in the universe, but there is much uncertainty surrounding how, when, or even the duration over which it occurred. The Thompson optical depth measured by WMAP $\tau = 0.087 \pm 0.017$ indicates that the universe was largely reionized at least as early as $z = 11$, although reionization probably commenced much earlier (Dunkley et al. . 2009). Meanwhile, reionization appears to have been completed by $z \sim 6$ due

to the lack of a Gunn Peterson trough at $z < 6$ in the spectra of most $z \sim 6$ QSOs (Fan et al. 2002).

How might reionization have proceeded? To answer this question, it seems quite reasonable to search for energetic (and likely abundant) star-forming galaxies at high redshift. However, it is not known if reionization was an instantaneous or protracted event or what types of galaxies may have contributed the most significant number of reionizing photons. While it seems likely that luminous QSOs at $z \geq 5$ do not contribute substantially to this process, some cosmologists suspect there may be contributions from black holes or decaying particles. Only by locating and carefully studying star-forming galaxies at very high redshifts can these important questions be answered.

Studies of $z \sim 4 - 6$ galaxies potentially provide us with a clue as to the luminosity of the galaxies that are likely to produce the bulk of the ionizing radiation at high redshifts. The important result is the very steep faint end slopes found for the LFs at $z \sim 4 - 6$ (Figure 2: Bouwens et al. 2006, 2007; Yan & Windhorst 2004; Beckwith et al. 2006; Oesch et al. 2007; Reddy et al. 2008). These studies indicate that very low luminosity galaxies provide a substantial contribution to the overall luminosity density in the *UV* and therefore to the overall ionizing background. Of course, expectations are that lower luminosity galaxies will be an even more dominant population before or during reionization than they are after, given the effect of the ionizing background in suppressing star formation in lower mass halos.

1.2 Which Physical Processes Governed Star Formation in the Highest Redshift Galaxies?

Star formation in galaxies is complex and can depend upon a number of physical processes, including gas cooling, supernovae feedback, and AGN feedback. At lower luminosities, star formation is thought to be governed by supernovae feedback, while at higher luminosities, feedback from AGN is thought to be dominant. As a result, star formation in galaxies is expected to be most efficient in some intermediate mass (luminosity) regime.

At higher redshift, it is still very uncertain which physical processes govern star formation in galaxies. It seems clear that gas cooling and star formation would likely proceed very rapidly, unless modulated by supernovae feedback. However, how this feedback would operate in high redshift galaxies seems very unclear. There has been speculation based upon numerous observations at both low and high redshift that there is a fundamental panochromatic surface brightness limit that starbursts do not exceed (Meurer et al. 1997; Hathi et al. 2008). It has been speculated that the change in the maximum star formation rate of galaxies to high redshift – i.e., the observed evolution in L^* (Bouwens et al. 2007, 2008) – is simply the result of this limiting surface brightness combined with the size evolution of halos (Mo et al. 1998; Ferguson et al. 2004; Bouwens et al. 2004).

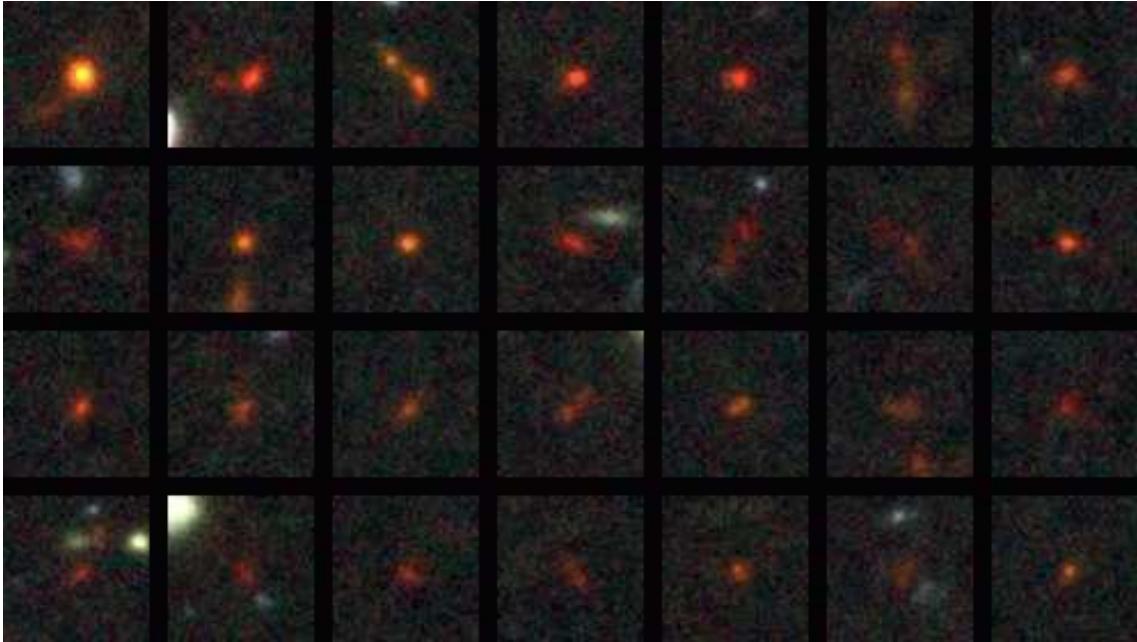


Figure 1: Postage stamps ($V_{606}i_{775}z_{850}$ color images) of the brightest 24 $z \sim 6$ i -dropouts from the HUDF. Objects are ordered in terms of their z_{850} -band magnitude. Each postage stamp is $3.0''$ on a side. With JWST, we would expect substantially higher S/N than present here, but not much better resolution – particularly at 2μ . The improved resolution expected as a result of the larger aperture with JWST would be mostly offset by the fact that observations of high redshift ($z > 7$) galaxies would need to be conducted at longer wavelengths ($> 1.6\mu$). However, with a 30-m telescope with diffraction-limited imaging in the near-IR, we could obtain a spatial resolution $\sim 5\times$ greater than shown here. Resolving star-forming regions in high redshift galaxies is important for determining the impact of feedback in regulating star formation at early times.

Of course, it is also possible that the observed evolution of the LF may simply be the result of the evolution expected in the halo mass function and evolution in dynamical time of galaxies (as proposed by Bouwens et al. 2008; Stark et al. 2007; Wyithe & Loeb 2006), and that the evolution in the LF has little to do with this maximum efficiency of star formation discussed by Meurer et al. (1997). However, determining which of these is the case requires that we observe high redshift galaxies at sufficiently high resolution to examine the distribution of surface brightnesses within galaxies and to know whether individual star-forming regions are running up against this limit or not.

1.3 How Were Primordial Stars Distributed Within High-Redshift Galaxies?

The earliest galaxies will contain massive stars formed from primordial gas. As these stars evolve and eject processed material from their eventual supernovae, newly-formed stars containing heavy elements will become more common. Simulations con-

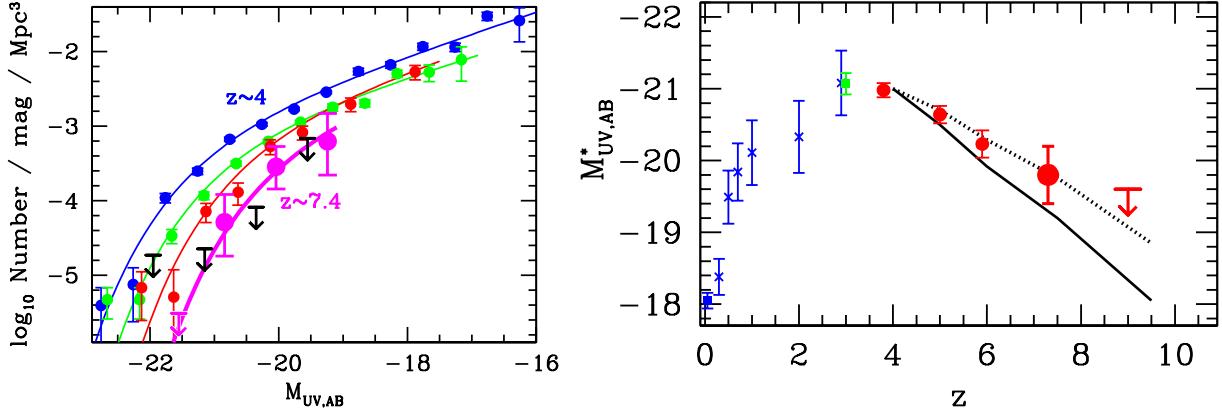


Figure 2: (left) The rest-frame UV LF determined at $z \sim 4$ (blue), $z \sim 5$ (green), $z \sim 6$ (red), and $z \sim 7$ (magenta) from HST B , V , i , and z dropout selections. The 1σ upper limits on the LF at $z \sim 9$ are shown. (right) The characteristic luminosity of galaxies observed as a function of redshift versus that expected from the halo mass function assuming a mass-to-light ratio that evolves as $(1+z)^0$ (solid) and $(1+z)^{-1}$ (dotted). It seems likely that feedback processes are important for regulating star formation in very high-redshift galaxies.

sistent with the WMAP polarization results (Ciardi et al. 2006) suggest primordial (so-called Population III) stars may lie in the redshift range 7 to 20. Verifying their presence and determining the redshift distribution of galaxies containing these early populations would represent a major new constraint on early galaxy evolution.

As massive hot sources, Population III stars are expected to generate radiation fields intense enough to ionize the primordial helium gas. The characteristic emission lines produced by this gas, particularly He II at 1640\AA , can thus serve as a marker for a primordial system. Model atmosphere calculations by Schaerer (2002) suggest this helium line could be detected and measured since it has a strength of up to $\sim 10\%$ of that of the hydrogen Lyman alpha line in these systems (Figure 3).

1.4 Intergalactic Medium beyond $z = 7$

A useful probe of the metallicity in the diffuse intergalactic medium is provided by the CIV 1550 doublet and is observed through absorption in very bright high-redshift sources – typically QSOs but also GRBs. The density of this ion in the intergalactic medium is almost constant to $z \sim 5$ (Songaila 2001), but decreases at $z \sim 6$ suggesting a substantial fall-off in the SFR density at $z > 6$ (e.g., Becker et al. 2009). The abundance of this ion provides one of the most fundamental constraints on the total metal production and therefore integrated star formation in the early universe.

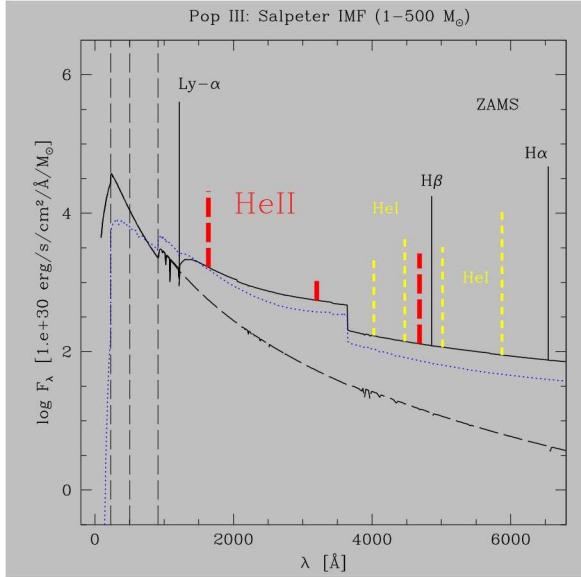


Figure 3: Predicted spectrum of first luminous objects. Spectrum of a Pop III ZAMS burst (from Schaerer 2002) based on non-LTE model atmospheres including H and He recombination lines. The dashed line shows the pure stellar continuum (neglecting nebular emission). Note the prominent line of He II 1640 (thick dashed line) and the importance of nebular continuous emission. Simulations indicate the He II line, which decays rapidly within 2 Myr, is a valuable tracer of metal-free stellar populations.

2 Future Prospects: Need for a 30-m class telescope

Quantifying the role of galaxies in reionizing the universe: To accurately quantify the role that galaxies play in reionizing the universe, we need a reliable census of galaxies over the entire redshift range where reionization is taking place – which means we ideally want to reach back as early as $z \sim 11$. Extrapolating the best-fit LFs measured at $z \sim 4 - 8$ to $z \sim 10$ would place M^* at $z \sim 10$ at ~ 29.5 . Given the steep faint-end slope of the LF, obtaining an accurate census of the ionizing photons from $z \sim 11$ requires that we reach at least 3 mag below L^* which indicates that we reach 32.5 AB mag. This will be impossible to reach in even the deepest fields with JWST – which are slated to have a depth of ~ 31 AB mag. Such depths however could well be achievable with a 30 m near-IR ground-based telescope with adaptive optics, due to the much significantly higher ability of such a telescope to resolve the very small sources (~ 30 milli-arcsecs) expected to be found at such magnitudes. Even if this depth proves to be too challenging, the depth reached with a 30-m GSMT will likely exceed JWST in the near-IR.

A particularly exciting prospect is targeting ionized bubbles in the IGM (identified by 21 cm facilities) with IFUs on a 30-m telescope to better understand the relationship between the ionizing sources and the IGM.

Ascertaining the physical processes that drove galaxy formation at $z > 6$: With the exception of the most luminous galaxies at $z \geq 8$, the majority of galaxies are expected to have relatively small sizes, i.e., $\sim 60\text{-}100$ milliarcseconds and therefore to be just barely resolved at $1.6\text{--}2.0\mu$ with JWST (Figure 4). The higher resolutions possible with diffraction-limited AO-imaging with a 30-m telescope would make it possible to view these sources at $5\times$ the resolution possible with JWST, to accurately quantify their morphologies (see Figure 1), and therefore better determine what processes drive the evolution of the LF at high redshift (e.g., see discussion in §1.2 above).

Determining the location of HeII emission in early galaxies: Given the very small sizes of the youngest galaxies likely to include HeII emission and the probable segregation of HeII emission in the extremeties of those galaxies that would show such emission, we really want to have a telescope with as high of spatial resolution as possible to detect this emission over an extremely small area.

Determining the redshifts of the lowest luminosity high-redshift galaxies: Measuring the redshifts of the lowest luminosity sources at high redshift will be important for quantifying their properties. While this may be difficult with JWST, it seems likely we will be able to obtain high S/N spectra on these sources by taking advantage of the superb resolution possible with a diffraction-limited 30-m telescope operating with AO (see Figure 4).

Determining the metal abundances in the IGM at $z > 7$: With a 30-m telescope, we can extend this measurement to the highest redshifts at which quasars or GRB targets can be found. The b-values of the CIV lines are about 8 km s^{-1} , typically, and are best mapped with resolutions at or above $R = 30,000$. Mapping the weakest absorption features in the CIV forest requires a $\text{SNR} > 100$ which can be achieved on $J \sim 20$ quasars in 5 hours.

Summary: The reionization epoch is one of the most exciting and fascinating periods for astrophysics in terms of the scientific richness and the challenges it poses for our theoretical and modeling capability. A 30-m GSMT remains a key component of developing an observational understanding of this epoch, and plays a crucial complementary role to ALMA and JWST and obtaining the optimal returns on our huge investment in those observatories.

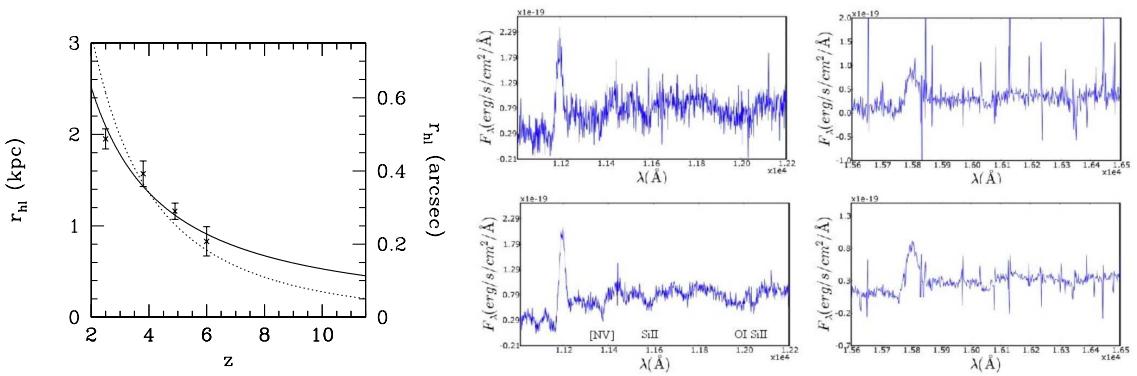


Figure 4: (left) The half-light radii of $L_{z=3}^*$ galaxies (in kpc) measured at $z \sim 2 - 6$ (crosses: Bouwens et al. 2004). The half-light radii appear to become smaller as $(1+z)^{-1}$ (solid line) for galaxies of a constant L^* luminosity. The dotted line corrects for the fact that higher redshift galaxies will have fainter characteristic luminosities (assuming $r \propto L^{1/3}$). The right axis shows the angular size that would be relevant for physical sizes at $z = 10$. The typical L^* galaxy at $z \sim 10$ would have a radius of 50 milliarcseconds, which would just barely be resolved at JWST resolution. A 30-m telescope with adaptive optics would be able to image such systems at $5\times$ higher spatial resolution than JWST. (right) Simulated spectra of three high redshift star forming regions with Ly- α luminosities of 7×10^{42} , 1×10^{42} , and 5×10^{41} erg/s, respectively, at $z = 8.2$ (left panels) and $z = 12$ (right panels). The top panels show 1 hour observations with a 30-m telescope while the bottom panels show 8 hour observations. Input data is an actual STIS spectrum of Haro 2 (Mas-Hesse, private communication).

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