THE PREMATURE FORMATION OF HIGH-REDSHIFT GALAXIES

FULVIO MELIA1

Department of Physics, The Applied Math Program, and Steward Observatory, The University of Arizona, Tucson AZ 85721, USA; fmelia@email.arizona.edu

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ABSTRACT

Observations with WFC3/IR on the Hubble Space Telescope and the use of gravitational lensing techniques have facilitated the discovery of galaxies as far back as \( z \sim 10–12 \), a truly remarkable achievement. However, this rapid emergence of high-\( z \) galaxies, barely \( \sim 200 \) Myr after the transition from Population III star formation to Population II, appears to be in conflict with the standard view of how the early universe evolved. This problem has much in common with the better known (and probably related) premature appearance of supermassive black holes at \( z \gtrsim 6 \). It is difficult to understand how \( \sim 10^9 M_\odot \) black holes could have appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, neither of which is seen in the local universe. In earlier work, we showed that the appearance of high-\( z \) quasars could instead be understood more reasonably in the context of the \( R_h = c t \) universe, which does not suffer from the same time compression issues as \( \Lambda \)CDM does at early epochs. Here, we build on that work by demonstrating that the evolutionary growth of primordial galaxies was consistent with the current view of how the first stars formed, but only with the timeline afforded by the \( R_h = c t \) cosmology. We also show that the growth of high-\( z \) quasars was mutually consistent with that of the earliest galaxies, though it is not yet clear whether the former grew from \( 5–20 M_\odot \) seeds created in Population III or Population II supernova explosions.

Key words: cosmology: observations – cosmology: theory – early universe – galaxies: general – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

The first stars and galaxies started forming toward the end of the cosmic “Dark Ages,” a period thought to have lasted \( \sim 400 \) Myr (in the context of \( \Lambda \)CDM) following hydrogen recombination at cosmic time \( t \sim 0.4 \) Myr. Over the past decade, many detailed simulations of this process have produced a comprehensive picture of how the universe transformed from a simple initial (dark) state to the complicated hierarchical system we see today, including galaxy clusters and the many components contained within them (see, e.g., Barkana & Loeb 2001; Miralda-Escudé 2003; Bromm & Larson 2004; Ciardi & Ferrara 2005; Glover 2005; Greif et al. 2007; Wise & Abel 2008; Salvaterra et al. 2011; Greif et al. 2012; Jaacks et al. 2012; for more recent reviews, see also Bromm et al. 2009, and Yoshida et al. 2012).

Interest in this cosmic dawn has been heightened recently with the dramatic discovery of faint galaxies at redshifts well beyond the end of the Epoch of Reionization (EoR), which observations show started at the end of the Dark Ages (\( z \sim 15 \), i.e., \( t \sim 400 \) Myr) and lasted until \( z \sim 6 \) (\( t \sim 900 \) Myr; see, e.g., Zaroubi 2012). Stretching the imaging capabilities of WFC3/IR on the Hubble Space Telescope (HST), and using gravitational lensing techniques, investigators have apparently uncovered the earliest galaxies emerging as far back as \( z \sim 10–12 \), a truly remarkable achievement (Bouwens et al. 2011, 2012, 2013; Zheng et al. 2012; Ellis et al. 2013; Coe et al. 2013; Oesch et al. 2013; Brammer et al. 2013). These nascent galaxies may have contributed to the re-ionization of the intergalactic medium, perhaps even dominated this process.

However, this rapid emergence of high-\( z \) galaxies so soon after the big bang may actually be in conflict with our current understanding of how they came to be. This problem is very reminiscent of the better known (and probably related) premature appearance of supermassive black holes at \( z \gtrsim 6 \). It is difficult to understand how \( \sim 10^9 M_\odot \) black holes could have appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, both of which are not seen in the local universe. Recent observations (e.g., Jiang et al. 2007; Kurk et al. 2009; Willott et al. 2010; Mortlock et al. 2011; De Rosa et al. 2011) have compounded this problem by demonstrating that most (if not all) of the high-\( z \) quasars appear to be accreting at their Eddington limit.

In our recent assessment of the high-\( z \) quasar problem (Melia 2013a, 2014b), we considered the possibility that this conflict may be due to our use of an incorrect redshift–time relationship, i.e., an incorrect cosmological expansion, rather than to the astrophysics of black-hole formation and growth, which are increasingly constrained by the ever improving observations. We showed that the high-\( z \) quasar data may instead be interpreted more sensibly in the context of the \( R_h = c t \) universe (Melia 2007, 2013a; Melia & Shevchuk 2012), for which standard \( 5–20 M_\odot \) seeds forming after re-ionization had began at \( z \lesssim 15 \) could have easily grown into \( \gtrsim 10^9 M_\odot \) supermassive black holes by redshift \( z \gtrsim 6 \), merely by accreting at the observed Eddington rate. The principal difference between \( \Lambda \)CDM and \( R_h = c t \) that eases the tension between theory and observations is simply \( z(t) \). Specifically, in the \( R_h = c t \) cosmology, the EoR began at \( \sim 900 \) Myr (\( z \sim 15 \) in this cosmology) and ended at \( \sim 1.9 \) Gyr (\( z \sim 6 \)), placing the birth of supermassive black holes at \( \sim 1 \) Gyr (roughly \( z = 13 \)), right where one would have expected them to form via the supernova deaths of Population III and II stars that presumably started the EoR.

Now that the premature emergence of high redshift galaxies is creating comparable tension with established theory, it is necessary to consider whether their timing issues are similarly
resolved by the $R_h = ct$ universe, and whether one can find consistency between their evolutionary history and the growth of supermassive black holes at $z \gtrsim 6$. In Section 2 of this paper, we will briefly review the current thinking behind the formation of structure at $z \gtrsim 6$, and then in Section 3 compare this with what the most recent observations are telling us. In Section 4, we will discuss a re-interpretation of high-$z$ galaxy growth in the context of $R_h = ct$, and then present our conclusions in Section 5.

2. THE CURRENT THEORETICAL PICTURE

2.1. Background Physics

Simulations tracing the growth of initial perturbations in the expanding medium begin with a set of well-posed initial conditions, derived from the fluctuation power spectrum and elemental abundances of the plasma constrained by observations of the cosmic microwave background (CMB; Komatsu et al. 2009). These calculations show that the first stars (Population III) formed by redshift $z \sim 20$ at the core of dark matter minihalos of mass $M_{\text{halo}} \sim 10^6 M_\odot$ (Haiman et al. 1996; Tegmark et al. 1997; Abel et al. 2002; Bromm et al. 2002). In the concordance $\Lambda$CDM model with parameter values $\Omega_m = 0.27$, $\Omega = 1$, $w_\Lambda = -1$, and a Hubble constant $H_0 \approx 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, this redshift corresponds to a cosmic time $t \approx 200 \text{ Myr}$. Here, $\Omega \equiv \rho/\rho_c$ is the density $\rho$ scaled to the critical (or closure) density $\rho_c (\equiv 3c^2 H_0^2/8\pi G)$ in a flat universe, $\Omega_m$ is the correspondingly scaled (luminous and dark) matter density, and $w_\Lambda$ is the dark energy (assumed to be a cosmological constant $\Lambda$) equation-of-state parameter yielding the pressure in terms of $\rho_\Lambda$.

It is difficult to see how Population III stars could have formed any earlier than this, since primordial gas in the early universe could not cool radiatively. Only after molecular hydrogen started to accumulate could the plasma cool and eventually condense to make stars (Galli & Palla 1998). Once the density fluctuations had condensed to a minimum temperature of about 200 K, set by the internal rovibrational transitions of $H_2$ (Omukai & Nishi 1998), the gas cloud could become Jeans-unstable and collapse to form a protostar at the center of the halo. These objects, which would eventually become Population III stars, attained a mass of $\gtrsim 100 M_\odot$ once they reached the main sequence (Kroupa 2002; Chabrier 2003). Feedback from these first stars determined the fate of the surrounding primordial gas clouds, because the UV radiation from a single massive star could destroy all of the $H_2$ in the parent condensation. As such, probably only one Population III star could form in each minihalo (Yoshida et al. 2008). These early structures were not galaxies.

However, the enormous flux of ionizing radiation and $H_2$-dissociating Lyman–Werner radiation emitted by massive Population III stars had an impact on more than just their immediate surroundings (Bromm et al. 2001; Schaerer 2002); this radiation field apparently had a dramatic influence out to several kiloparsecs or more of the progenitor. In combination with strong outflows, which lowered the density in the mini-halos, this outpouring of radiative and mechanical energy delayed subsequent star formation considerably (Johnson et al. 2007).

The gas expelled by this first generation of Population III stars would have been too hot and diffuse to permit further star formation until it had time to cool and reach high densities again. But cooling and re-collapse take a long time. Analytic models (Yoshida et al. 2004), confirmed by detailed numerical simulations (Johnson et al. 2007), show that the gas re-incorporation time was roughly 100 Myr, essentially the dynamical time for a first-galaxy halo to assemble itself. The critical mass for hosting the formation of the first galaxies is not yet known with high precision, though it is thought that these would have probably been atomic cooling halos, i.e., condensations with mass $\sim 10^8 M_\odot$ and virial temperatures $\gtrsim 10^4 \text{ K}$, so that atomic line cooling could have been possible (Wise & Abel 2007). This mass scale is supported by simulations of the energetics, feedback, and chemical enrichment associated with the first (Population III) supernova explosions (Greif et al. 2007). The supernova remnant propagates for a Hubble time at $z \sim 20$ to a final mass-weighted mean shock radius of 2.5 kpc, sweeping up a total gas mass of $2.5 \times 10^5 M_\odot$ in the process. A dark matter halo of at least $10^8 M_\odot$ must be assembled to recollect and mix all components of the shocked gas.

At $t \sim 300 \text{ Myr}$, with $z \sim 15$ toward the end of the Dark Ages, the formation of structure would have begun in earnest. But this is where a potential conflict emerges between theoretical expectations and the recent observation of high-$z$ galaxies because, in $\Lambda$CDM, there simply was not sufficient time for these galaxies to form by $z \sim 10–12$, a mere $\sim 200 \text{ Myr}$ later. We will demonstrate this quantitatively in the next section, but first, let us see what the simulations predict.

2.2. A Brief Survey of the Simulations

The results of simulations by independent workers essentially confirm each other’s conclusions, chiefly because their calculations incorporate the same set of physical principles described above. We will summarize the key features of two of these simulations, by Jaacks et al. (2012) and Salvaterra et al. (2013), who use different metrics to characterize their results, though with very similar outcomes.

Starting their simulation at $z = 100$, Salvaterra et al. (2013) follow the growth of structure all the way out to $z = 2.5$ and find that by redshift $z \sim 6–10$, most of the early galaxies had a mass $\sim 10^5–10^6 M_\odot$, with a few percent as high as $\sim 10^7 M_\odot$. These structures had a specific (i.e., per solar-mass) star-formation rate (sSFR) $\sim 3–10 \text{ Gyr}^{-1}$. The $10^8–10^9 M_\odot$ galaxies were therefore forming stars at a rate SFR $\sim 0.3–10 M_\odot \text{ yr}^{-1}$, in line with SFRs observed over a remarkably broad range of redshifts ($z \sim 2–7$). In this redshift range, observations indicate that galaxies of this size formed $2–3 M_\odot$ per year per $10^7 M_\odot$ of total stellar mass (Stark et al. 2009; Gonzalez et al. 2010; McLure et al. 2011). As we shall see in the next section, the recent discoveries appear to be tracing the high end of this mass and SFR distribution (see Table 1).

The key result of this work most relevant to our discussion in this paper is that the ratio between the doubling time $t_{\text{inh}}$ (i.e., the inverse of the sSFR) and the corresponding cosmic time seems to be universally equal to $\sim 0.1–0.3$, independently of redshift. Let us conservatively take the smaller value, which minimizes the growth time. Then, a galaxy with mass $M_s = 10^6 M_\odot$ at $z = 6$ (corresponding to $t_s \sim 900 \text{ Myr in } \Lambda$CDM), would have started its condensation at cosmic time $t_{\text{init}} \sim 0.99 t_s$, where $n \equiv [\log(M_s/M_\text{init})]/\log 2$ is the number of doublings since the galaxy started growing with a mass $M_\text{init}$ at $t_{\text{init}}$. Conservatively putting $M_\text{init} = 10^5 M_\odot$, this gives $t_{\text{init}} \approx 230 \text{ Myr}$, roughly where the arguments concerning the transition from Population III to Population II stars would placed it.

In other words, these simulations appear to be consistent with the growth implied by $10^7 M_\odot$ galaxies at $z = 6$. But let us now consider whether this same type of growth rate would allow a similar galaxy to have formed by $z = 10$ (i.e., $t_s \sim 550 \text{ Myr in } \Lambda$CDM). Such a galaxy would have begun
Table 1 High-\(z\) Galaxies

| Name            | \(z\) | \(M\) \((10^8 M_\odot)\) | SFR \((M_\odot\,\text{yr}^{-1})\) | References |
|-----------------|-------|---------------------------|-------------------------------|-----------|
| UDFj-39546284\* | 11.8  | \(\sim 10\)               | \(\sim 4\)                   | (1) (2) (6) (7) |
| MACS0647-JD     | 10.7  | 1–10                      | 1–4                           | (3)       |
| MACS1149-JD     | 9.7   | \(\sim 1.5\)              | \(\sim 1.2\)                 | (4) (5)   |
| UDF12-4106-7304 | 9.5   | \(\sim 10\)               | \(\sim 3\)                   | (6)       |
| UDF12-4265-7049 | 9.5   | \(\sim 10\)               | \(\sim 3\)                   | (6)       |
| MACS1115-JD1    | 9.2   | \(\sim 4\)                | \(\sim 1\)                   | (5)       |
| MACS1720-JD1    | 9.0   | \(\sim 4\)                | \(\sim 1\)                   | (5)       |
| UDF12-3921-6322 | 8.8   | \(\sim 10\)               | \(\sim 3\)                   | (6)       |
| UDF12-4344-6547 | 8.8   | \(\sim 10\)               | \(\sim 3\)                   | (6)       |
| UDF12-3985-7114 | 8.6  | \(\sim 10\)               | \(\sim 3\)                   | (6)       |
| UDF12-3947-8076 | 8.6  | \(\sim 10\)               | \(\sim 3\)                   | (6)       |

Notes. \* This source may instead be an evolved galaxy at \(z \approx 2.4\), though both interpretations are problematic.

References. (1) Bouwens et al. 2011; (2) Oesch et al. 2013; (3) Coe et al. 2013; (4) Zheng et al. 2012; (5) Bouwens et al. 2012; (6) Ellis et al. 2013; (7) Brammer et al. 2013.

its growth with \(M_{\text{init}} = 10^4 M_\odot\) at \(t_{\text{init}} \approx 140\) Myr, well before even the Population III stars would have had sufficient time to develop and explode, producing the conditions necessary to initiate the subsequent growth of galactic structure. A \(10^9 M_\odot\) galaxy observed at \(z \approx 10.7\), corresponding to a cosmic time \(t_* \approx 490\) Myr, would have started at \(t_{\text{init}} \approx 82\) Myr, which appears to be completely untenable, given what we now believe occurred at the dawn of cosmic structure formation.

Jaacks et al. (2012) took a different approach and examined the duty cycle and history of the SFR for high-redshift galaxies at \(z \gtrsim 6\), and found that, though individual galaxies have “bursty” SFRs, the averaged SFR between \(z \approx 15\) and \(z \approx 6\) can be characterized well by an exponentially increasing functional form with characteristic timescales \(t_c = 70–200\) Myr, for galaxies with stellar mass \(M_* \sim 10^8 M_\odot\) to \(\sim 10^{10} M_\odot\), respectively.

From their hydrodynamic simulations, one may therefore infer that stellar mass grew at a rate

\[
\frac{dM}{dt} = K \exp \left( \frac{t - t_*}{t_c} \right),
\]

using the definition that a galaxy has mass \(M_*\) at cosmic time \(t_*\). In these calculations, galaxies begin with a mass \(M \ll M_*\) at \(t \approx 400\) Myr and, for \(M_* = 10^8 M_\odot\) at \(t_* = 900\) Myr (i.e., \(z = 6\), \(t_c = 100\) Myr. Therefore, \(K \approx 1 M_\odot\,\text{yr}^{-1}\) in Equation (1). Placing a comparable \(M = 10^9 M_\odot\) galaxy at \(z \approx 10\), where \(t \approx 550\) Myr, would then mean that its mass at \(t = 300\) Myr would have begun \(\approx 8 \times 10^6 M_\odot\), which is inconsistent with the transition from Population III to Population II stars described above.

Both of these calculations therefore suggest that, whereas \(10^9 M_\odot\) galaxies would have had no problem forming by redshift 6 with the timeline predicted by CDM, similar galaxies at \(z \approx 10\) could not have grown to this mass during the short time elapsed since the emergence of Population III and II stars. We are not aware of any other simulations published thus far that produce an outcome contrary to this result.

In the next section, we will summarize the observational status of these high-\(z\) galaxies, including a discussion of the actual, measured SFR as a function of redshift. The empirically derived expression for SFR(t) for galaxies at \(z \lesssim 8\) matches the theoretical predictions quite well. Therefore, when we use these relations to trace comparably massive galaxies at larger redshifts, the results reinforce the view that \(\sim 10^8–10^9 M_\odot\) galaxies probably could not have had sufficient time to form by \(z \sim 10–12\) in ΛCDM.

3. HIGH-REDSHIFT GALAXIES AND THEIR EVOLUTIONARY HISTORY

3.1. The High-\(z\) Galaxy Sample

Observations by Spitzer of the assembled stellar mass at \(z \approx 5–6\) suggest that star formation must have started well beyond \(z \approx 8\) (Stark et al. 2007; Gonzalez et al. 2010), though only recently have attempts succeeded in finding the earliest galaxies. Various groups have utilized an assortment of techniques, some based on gravitational lensing by foreground clusters of galaxies, others relying on spectral energy distribution fitting techniques on objects selected from a deep multi-band near-infrared stack. The Cluster Lensing and Supernova survey with Hubble (CLASH; Postman et al. 2012) has discovered several \(z > 8.5\) candidates, three at \(z \approx 9–10\) (Zheng et al. 2012; Bouwens et al. 2012) and a multiply-imaged source at \(z = 10.7\) (Coe et al. 2013).

The deepest search to date for star-forming galaxies beyond a redshift \(z \approx 8.5\) utilizing a new sequence of the WFC3/IR images of the Hubble Ultra Deep Field (UDF12) was just completed in 2012 September (Ellis et al. 2013). This search has thus far yielded 7 promising \(z > 8.5\) candidates, including the recovery of UDFj-39546284 (previously proposed at \(z = 10.3\), though now suspected of lying at \(z = 11.8\)). It is not entirely clear whether this object is really a young galaxy at such a high redshift, or is perhaps an intense emission line galaxy at \(z \approx 2.4\). Both interpretations are problematic (see Bouwens et al. 2011, 2013; Brammer et al. 2013).

The highest redshift galaxies discovered so far are shown in Table 1, together with best estimates of their SFRs and current masses. Galaxies observed with deep-exposure imaging are too faint to yield masses directly. In these cases, their mass is inferred by comparing their SFR with the specific star formation rate (sSFR \(\approx 2–3\,\text{Gyr}^{-1}\)) observed on average for galaxies over a broad range of redshifts (\(z \approx 2–7\); see, e.g., Stark et al. 2009; Gonzalez et al. 2010; McLure et al. 2011).

Other than the candidate UDFj-39546284 which may not even be a high-\(z\) galaxy, the most distant galaxy reliably known to date, with a photometric redshift of \(z \approx 10.7\), is MACS0647-JD (Coe et al. 2013). Estimates of its mass are based on the aforementioned sSFR measured at lower redshifts, but also on the fact that the average stellar mass \((\sim 10^9 M_\odot)\) of galaxies at \(z \approx 7–8\) rose to a few times \(10^{10} M_\odot\) by \(z \approx 2\) (Gonzalez et al. 2010). Based on this trend, one might expect the average stellar mass of galaxies at \(z \approx 11\) to be \(\lesssim 10^9 M_\odot\). If this holds true for MACS0647-JD, its stellar mass would be on the order of \(10^8–10^9 M_\odot\). In CDM, this redshift corresponds to a cosmic time \(t \approx 427\) Myr. Therefore, almost a billion solar masses had to assemble inside this galaxy in only \(\sim 130\) Myr.

However, the high-\(z\) galaxy with the best measured properties appears to be MACS1149-JD, a gravitationally lensed source at redshift \(z \approx 9.7\) (Zheng et al. 2012). The availability of both Hubble and Spitzer data has made it possible to produce a broad spectrum in the object’s rest frame which, when combined with state-of-the-art models of synthetic stellar populations, yields reliable estimates for several key parameters.
This analysis suggests a stellar mass of \(1.5 \times 10^8 M_{\odot}\) and an SFR of \(\sim 1.2 M_{\odot} \text{yr}^{-1}\). It is comforting to note that the estimates of \(M\) and SFR for the other high-\(z\) galaxies in Table 1 are consistent with these measurements.

### 3.2. Inferred Evolutionary History in \(\Lambda CDM\)

The comparison between theory and observations shows that the calculations can account quite well for the empirically derived average SFR based on a comprehensive analysis of \(z \lesssim 8\) galaxies using the ultra-deep WFC3/IR data (Oesch et al. 2013). These data sets exploit all of the WFC3/IR observations from HUDF09, HUDF12, as well as wider area WFC3/IR imaging over GOODS-South. (This compilation also produced three samples centered around \(z \sim 9, 10, 11\), with seven \(z \sim 9\) galaxy candidates, and one each at \(z \sim 10\) and \(z \sim 11\).)

At least in this redshift range, the simulations thus appear to be handling the galaxy evolution rather well. It is therefore problematic that none of the calculations completed thus far have shown the possibility of forming \(10^8–10^9 M_{\odot}\) galaxies prior to redshift \(\sim 10\). To better understand why the basic physical principles summarized in Section 2.1 produce this outcome, we will take the following approach. We will assume that a galaxy of mass \(M \sim 10^9 M_{\odot}\) at \(z \sim 10\) would have followed a growth history similar to a comparably massive galaxy at \(z \lesssim 8\), though with an appropriate translation in cosmic time \(t\). This seems reasonable because \(t\) also functions as the proper time in the local co-moving frame, so that locally (at least) the growth rate would not be overly affected by the universal expansion rate, i.e., by the functional form of \(z(t)\). (This cannot be completely true, however, since the expansion history does affect the rate at which a local condensation of mass—energy can accrete from larger volumes. Our analysis here should therefore be viewed as preliminary, with the need of a more comprehensive simulation to follow before our conclusions can be made definitive.)

Let us now consider the evolutionary growth of the galaxies in Table 1 as a function of cosmic time. Figure 1 shows the history of three representative members of this set, calculated using the analytic (exponential) form of the time-dependent SFR from Jaacks et al. (2012), though with the time \(t\) shifted to coincide with the measured redshift. We include the candidate UDFJ-39546284, though there are concerns about whether this source is truly a galaxy at redshift \(z \sim 11\) (see Melia 2013a). The galaxy growth rate is based primarily on the observed SFR at \(z \sim 9–12\) (Oesch et al. 2013), supported by the theoretical simulations discussed in Section 2. For the sake of clarity, only three representative galaxies from the compilation in Table 1 are shown here. The others have very similar evolutionary histories.

(A color version of this figure is available in the online journal.)

![Figure 1. Growth of high-\(z\) galaxies observed at \(z \sim 9–11\), as a function of cosmic time \(t\), in \(\Lambda CDM\). The principal epochs are (a) the “Dark Ages” (\(t \sim 0.4–400\) Myr), (b) the period of reionization (\(t \sim 400–900\) Myr), (c) the transition from Population III to Population II star formation (at \(\sim 300\) Myr), and (d) the era (\(t \sim 0–240\) Myr) during which 5–20 \(M_{\odot}\) seed black holes would have had to form in order to grow (via Eddington-limited accretion) into the high-\(z\) quasars observed at \(z \sim 6–7\) (see Melia 2013a). The galaxy growth rate is based primarily on the observed SFR at \(z \sim 9–12\) (Oesch et al. 2013), supported by the theoretical simulations discussed in Section 2. For the sake of clarity, only three representative galaxies from the compilation in Table 1 are shown here. The others have very similar evolutionary histories.](https://example.com/figure1)

3.3. Inferred Evolutionary History in the \(R_h = ct\) Universe

The tension between theory and observations disappears in the \(R_h = ct\) universe. The \(R_h = ct\) universe is an FRW cosmology whose basic principles follow directly from a strict adherence to the Cosmological Principle and Weyl’s postulate (Melia 2007; Melia & Shevchuk 2012; see also Melia 2012a for a pedagogical treatment). Over the past several years, the predictions of \(R_h = ct\) have been compared with those of \(\Lambda CDM\) and with the available observations, both at low and high redshifts. These include cosmic chronometer data, which appear to favor the expansion history in the former (Melia & Maier 2013), and the gamma-ray burst Hubble diagram, which confirms that \(R_h = ct\) is more likely to be correct than \(\Lambda CDM\) (Wei et al. 2013). A short summary of the current status of this cosmology appears in Melia (2012b, 2013b, 2014a).

Insofar as accounting for the high-\(z\) quasars and galaxies is concerned, the essential feature of the \(R_h = ct\) universe that distinguishes it from \(\Lambda CDM\) is its expansion factor, \(a(t) \propto t\). In this cosmology, the redshift is given as

\[
1 + z = \frac{t_0}{t},
\]

where \(t_0\) is the current age of the universe and \(t\) is the cosmic time at which the light with redshift \(z\) was emitted. In addition,
Figure 2. Same as Figure 1, except here for the $R_0 = ct$ universe. In this case, the EoR corresponds to $t \sim 800–1,900$ Myr, and the Dark Ages extend up to $\sim 800$ Myr. The black-hole seed formation period is now $t \sim 800–1,200$ Myr, well within the EoR. Note, in particular, that all of the high-$z$ galaxies observed thus far would have started their growth after the transition from Population III to Population II star formation at $\sim 300$ Myr.

(A color version of this figure is available in the online journal.)

Figure 3. Same as Figures 1 and 2, except here highlighting the dependence of our results on the uncertainty in the inferred galaxy mass $M$. The shaded regions correspond to a mass range $10^8–10^9 M_\odot$, the largest uncertainty quoted in Table 1 (and references cited therein), for two representative objects from this sample. The transition from Population III to Population II star formation would have occurred at $\sim 300$ Myr in both cosmologies, but the time interval corresponding to the redshift range of the EoR is different, so we do not show it here.

(A color version of this figure is available in the online journal.)

the gravitational horizon $R_0$ is equivalent to the Hubble radius $c/H(t)$, and therefore one has $t_0 = 1/H_0$. With these equations, we can produce a diagram like that shown in Figure 1, except this time for the $R_0 = ct$ universe, and this is illustrated in Figure 2. The EoR redshift range $z \sim 6–15$ here corresponds to the cosmic time $t \sim 830–1,890$ Myr, so the Dark Ages did not end until $\sim 830$ Myr after the big bang. Note also that in this cosmology, $5–20 M_\odot$ black-hole seeds formed during the period $t \sim 830–1,200$ Myr, at the beginning of the EoR, would have grown via Eddington-limited accretion into the $\sim 10^9 M_\odot$ quasars seen at $z \sim 6–7$.

Our examination of the evolutionary history of high-$z$ galaxies confirms and reinforces the view that $R_0 = ct$ may be better than ΛCDM in accounting for the timing and duration of various important epochs in the early universe. From Figure 2, we see that in $R_0 = ct$, not only did all the high-$z$ galaxies have time to grow into $\sim 10^9 M_\odot$ structures by redshift $z \sim 10–11$, but all of them (including UDFj-39546284) would have done so after the transition from Population III to Population II star formation at $t \sim 300$ Myr. This would appear to be a minimal requirement in any successful cosmological theory, given that the assembly of primordial galaxies could not have started until after the clouds that would make Population II stars had begun their condensation.

But how accurately do we know the masses of these galaxies, and is it possible that our current estimates of $M$ are simply greatly overestimated? To gauge the possibility that the timing problem in ΛCDM may be due to such uncertainties, we show in Figure 3 the impact of changing $M$ by a factor 10 in two representative galaxies from the sample listed in Table 1. These two objects span the range of redshifts covered in this group, other than UDFj-39546284 which, as we have already noted, may simply be a mis-identification. The shaded regions in this figure show the possible evolutionary trajectories of these galaxies in both ΛCDM and $R_0 = ct$, when we allow for an order-of-magnitude uncertainty in the mass. It is quite straightforward to see that the problem still persists. In order to alleviate the negative impact of the time compression in the standard model, the inferred masses for these objects would have to be wrong by at least 4 or 5 orders of magnitude. Even with the range of masses used in this figure, none of the galaxies in this sample could have grown to their observed size following the transition from Population III to Population II stars, and at least one member of this set would have had to start growing before the big bang.

Finally, one of our stated goals at the beginning of this discussion was to see if the creation of $5–20 M_\odot$ black-hole seeds could be made compatible with the evolutionary growth of structure in the early universe. Figure 2 suggests that the answer is yes. If the high-$z$ quasars grew at an Eddington-limited accretion rate, they would have started as black holes created in Population III (and possibly Population II) stars near the beginning of the EoR. In fact, this diagram even allows for the possibility that their growth was slower than the standard Eddington rate, since Population III stellar explosions could have occurred up to $\sim 500$ Myr earlier. According to this figure, most of the primordial galaxy growth also took place within a period of roughly 600 Myr, starting near the end of the Dark Ages, and extending into the middle of the EoR. Quite tellingly, most of this growth also would have coincided with the formation of the $5–20 M_\odot$ black-hole seeds.

However, it is still too early to tell whether the black hole seeds formed during Population III supernovae, or later, from the explosions of Population II stars. Perhaps the answer is both. Even if a Population III supernova would have produced the seed, the fact that the explosion expelled most of the material, forcing a delay by another $\sim 100$ Myr before gravitational collapse could have replenished the gaseous medium surrounding the black hole, would have significantly slowed down the rate at which the quasar could have grown initially. It is likely that...
regardless of whether the black hole seeds formed at \( \sim 300-400 \) Myr, or later within primordial galaxies (at \( t \sim 1 \) Gyr), their rapid growth into \( \sim 10^9 M_\odot \) supermassive black holes would have been delayed until \( t \sim 1-1.9 \) Gyr. However, this kind of timing flexibility is only available in \( R_h = ct \). It is not possible in \( \Lambda CDM \).

4. CONCLUSIONS

The problem with the premature formation of supermassive black holes at \( z \gtrsim 6 \) has been with us for several years. In order to get around the limited time available in \( \Lambda CDM \) to form such enormous objects in only \( \sim 500 \) Myr, various “fixes” have been proposed and studied, though the latest observations suggest that even these modifications may not be consistent with the data. For example, the possibility that black holes might have grown at greatly super-Eddington rates seems to have been ruled out by the latest measurements (e.g., Mortlock et al. 2011; De Rosa et al. 2011; Willott et al. 2010), which indicate that the most distant quasars are accreting at no more than the standard Eddington value. The possibility that their seeds may have been much more massive than is typically seen (\( 5-20 M_\odot \)) in supernova explosions appears to be remote, at best, given that we simply do not see these forming in the local universe. At the very least, new physics would have to be devised in order to account for such exotic events. All in all, our ever improving capability to constrain the high-z quasar properties appears to be arguing against the viability of \( \Lambda CDM \) to account for the expansion of the early universe.

The dramatic recent discovery of high-z galaxies has created renewed interest in this timing problem, because these structures appear to have formed too quickly following the end of the Dark Ages. In some instances, \( \sim 10^9 M_\odot \) of stellar material would have necessarily assembled in only \( \sim 200 \) Myr. This is inconsistent with the broad range of detailed simulations carried out to date. The premature emergence of high-z galaxies confirms and reinforces the difficulty faced by \( \Lambda CDM \) in properly accounting for the formation of structure during the cosmic dawn.

In this paper, we have explored the possibility that the evolutionary growth of high-z quasars and galaxies might instead be better explained in the context of the early universe. At the very least, new physics would have necessarily assembled in only \( \sim 10^9 M_\odot \) in supernova explosions appears to be remote, at best, given that we simply do not see these forming in the local universe. At the very least, new physics would have to be devised in order to account for such exotic events. All in all, our ever improving capability to constrain the high-z quasar properties appears to be arguing against the viability of \( \Lambda CDM \) to account for the expansion of the early universe.

In this paper, we have explored the possibility that the evolutionary growth of high-z quasars and galaxies might instead be better explained in the context of the \( R_h = ct \) universe. We have found that not only would it have been possible for these structures to grow since the big bang consistent with standard physical principles, but that their evolution would have been mutually consistent with each other, and with what we currently believe was the history of early star formation.

Having said this, there are at least two important caveats to this conclusion. The first clearly has to do with how accurately we know the mass of these high-redshift galaxies. This question was partially addressed in Figure 3, which showed that even a factor 10 uncertainty in \( M \) is insufficient to alleviate the timing problem in \( \Lambda CDM \). We estimate that in order to remove the problem completely, the real mass of these objects would have to be at least 4 orders of magnitude smaller than currently measured. Whether this is feasible remains to be seen. The second caveat is that although none of the simulations carried out to date within the context of \( \Lambda CDM \) can adequately account for these early galaxies, it may be possible that a critical physical ingredient has been overlooked. With the high-z quasars, proposals to fix the problem have invoked new physics to generate massive seeds, or unusual circumstances to permit super-Eddington accretion. It would be more difficult to generate such ideas for the early formation of galaxies, which are aggregates of many stars, not single objects and, at least as far as we know today, could not have started forming until Population III stars gave way to Population II. Perhaps the initial cooling that led to the formation of Population III stars was not due to the condensation of molecular hydrogen; maybe some other process permitted the gas to cool much faster than the currently believed several hundred million year time frame. No doubt, future simulations will probe such ideas and new physics, and perhaps a solution may be found to work with the timeline afforded by \( \Lambda CDM \). However, with what we know today, our results demonstrate that the formation of high-redshift galaxies could be consistent with \( R_h = ct \), but probably not with \( \Lambda CDM \).

Our understanding of this important early period in the universe’s life will improve quite rapidly in the coming years as primordial galaxies are observed with increasing numbers and greater sensitivity, and as simulations incorporate more detailed physics and new ideas.

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