Supermassive Black Holes in the Early Universe

F. Melia\textsuperscript{1} and T. M. McClintock\textsuperscript{2}

\textsuperscript{1}Department of Physics, The Applied Math Program, and Department of Astronomy, The University of Arizona, AZ 85721, USA
\textsuperscript{2}Department of Physics, The University of Arizona, AZ 85721, USA

The recent discovery of the ultraluminous quasar SDSS J010013.02+280225.8 at redshift 6.3 has exacerbated the time compression problem implied by the appearance of supermassive black holes only $\sim 900$ Myr after the big bang, and only $\sim 500$ Myr beyond the formation of Pop II and III stars. Aside from heralding the onset of cosmic reionization, these first and second generation stars could have reasonably produced the $\sim 5-20 M_{\odot}$ seeds that eventually grew into $z \approx 6-7$ quasars. But this process would have taken $\sim 900$ Myr, a timeline that appears to be at odds with the predictions of $\Lambda$CDM without an anomalously high accretion rate, or some exotic creation of $\sim 10^{5} M_{\odot}$ seeds. There is no evidence of either of these happening in the local universe. In this paper, we show that a much simpler, more elegant solution to the supermassive black hole anomaly is instead to view this process using the age-redshift relation predicted by $R_{b} = ct$ Universe, an FRW cosmology with zero active mass. In this context, cosmic reionization lasted from $t \sim 883$ Myr to $\sim 2$ Gyr ($6 \lesssim z \lesssim 15$), so $\sim 5-20 M_{\odot}$ black hole seeds formed shortly after reionization had begun, would have evolved into $\sim 10^{10} M_{\odot}$ quasars by $z \sim 6-7$ simply via the standard Eddington-limited accretion rate. The consistency of these observations with the age-redshift relationship predicted by $R_{b} = ct$ supports the existence of dark energy; but not in the form of a cosmological constant.

1. Introduction

The recent discovery of SDSS J010013.02+280225.8 (henceforth J0100+2802), an ultraluminous quasar at redshift $z = 6.30$, has accentuated the problem of supermassive black-hole growth and evolution in the
early Universe [1]. Each of the ~50 previously discovered quasars at redshifts z > 6 [2–9] contains a black hole with mass ~10^9 M⊙, challenging the standard model’s predicted timeline, which would have afforded them fewer than 900 Myr to grow after the big bang, but likely even fewer than ~500 Myr since the onset of Population II star formation. With an estimated mass of ~10 − 12 × 10^9 M⊙, ten times greater than the others, J0100+2802 significantly compounds this time-compression problem.

The early appearance of supermassive black holes is an enduring mystery in astronomy. Such large aggregates of mass could not have formed so quickly in ΛCDM without some anomalously high accretion rate [10] and/or the creation of unusually massive seeds [11], neither of which has actually ever been observed. In the local Universe, black-hole seeds are produced in supernova explosions, which sometimes leave behind ~5 − 20 M⊙ remnants, cores far from the ~10^9 M⊙ objects required to grow via Eddington-limited accretion into the billion solar-mass quasars seen at redshifts z ~ 6 – 7. Any attempt at circumventing this problem is severely challenged by the fact that no high-z quasar has ever been observed to accrete at more than ~1 − 2 times the Eddington rate (see, e.g., figure 5 in Ref. [12]).

In this paper, however, we demonstrate that such exotic processes are actually not necessary to address this apparent anomaly; although the timeline implied for the early Universe by the existence of J0100+2802 and its brethren may be problematic in ΛCDM, it is fully consistent with standard astrophysical processes in the R_h = ct Universe [13,14], an FRW cosmology with zero active mass [15]. Indeed, this tantalizing discovery comes on the heels of recent high-precision Baryon Acoustic Oscillation (BAO) measurements [16–18], that have apparently ruled out the concordance model in favor of R_h = ct at better than the 99.95% C.L. [19]. A resolution of the time-compression problem implied by J0100+2802 therefore provides important and timely observational confirmation of these critical BAO results.

2. Black Hole Growth in the Early Universe

In the standard picture, the Universe became transparent about 0.4 Myr after the big bang, descending into darkness as the thermal radiation field shifted towards longer wavelengths. The so-called Dark Ages ended several hundred Myr later, when density perturbations condensed into stars and early galaxies, producing ionizing radiation. Current constraints [20] place the epoch of re-ionization (EoR) at z ~ 6 − 15 which, in the context of ΛCDM, corresponds to a cosmic time t ~ 400 − 900 Myr (see figure 1).

The best probes of the re-ionization process are actually the high-z quasars themselves. The absence of structure bluewards of their Ly-α restframe emission observed by SDSS at z ≥ 6 suggests a decreasing ionizing fraction along the line-of-sight [22]. That the neutral fraction approaches ~1 by z ~ 15 is supported by the Wilkinson Microwave Anisotropy Probe (WMAP [23]) mission, whose measurements show that the Universe was ~50% neutral at z ≥ 10, with re-ionization starting before z ~ 14 [24].

| Source | Redshift | FWHM | F3000 | M_R_h=ct | M_ΛCDM | Δφ_R_h=ct | Δφ_ΛCDM | Ref. |
|--------|---------|------|-------|---------|---------|----------|---------|------|
| J0056-2616 | 5.35±0.11 | 3.43±0.70 | 3.04±0.64 | 3.06±0.64 | 3.09±0.64 | 3.12±0.64 | 3.13±0.64 | [1] |
| J0147-1365 | 5.59±0.09 | 2.85±0.06 | 2.86±0.06 | 2.87±0.06 | 2.87±0.06 | 2.88±0.06 | 2.88±0.06 | [2] |
| J0230-0842 | 5.37±0.09 | 2.89±0.05 | 2.90±0.05 | 2.90±0.05 | 2.91±0.05 | 2.92±0.05 | 2.92±0.05 | [3] |
| J0255-3150 | 5.50±0.09 | 2.85±0.04 | 2.86±0.04 | 2.87±0.04 | 2.87±0.04 | 2.88±0.04 | 2.88±0.04 | [4] |
| J0333-1547 | 5.60±0.09 | 2.84±0.03 | 2.85±0.03 | 2.86±0.03 | 2.87±0.03 | 2.88±0.03 | 2.88±0.03 | [5] |
| J0509-3407 | 5.74±0.09 | 2.80±0.02 | 2.81±0.02 | 2.82±0.02 | 2.83±0.02 | 2.84±0.02 | 2.84±0.02 | [6] |
| J2200-3754 | 5.86±0.09 | 2.75±0.01 | 2.76±0.01 | 2.77±0.01 | 2.78±0.01 | 2.79±0.01 | 2.79±0.01 | [7] |
Figure 1. Growth of quasars J0100+2802, P338+29, and J1120+0641, versus \( t \) in \( \Lambda \)CDM, with concordance parameter values: \( \Omega_m = 0.31, k = 0, w_\Lambda = -1 \) and \( H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1} \). The range in timelines corresponds to \( M_{\text{seed}} = 5 - 20 \, M_\odot \). The Dark Ages evolved into the EoR at \( t \sim 400 \, \text{Myr} \) \((z \sim 15)\), which lasted until \( \sim 900 \, \text{Myr} \) \((z \sim 6)\). For \( M_{\text{seed}} = 20 \, M_\odot \) and Eddington-limited accretion, these three black holes would have had masses \( 3.0 \times 10^6 \, M_\odot \), \( 3.1 \times 10^5 \, M_\odot \), and \( 5.4 \times 10^5 \, M_\odot \), respectively, at the start of the EoR. The seeds would have been created \( \sim 33 \, \text{ Myr} \), \( \sim 35 \, \text{ Myr} \), and \( \sim 59 \, \text{ Myr} \) prior to the big bang.

Standard astrophysical principles suggest that ionizing radiation was produced by Pop II and III stars. More exotic physics, invoking the decay of dark-matter particles or cosmic strings, is poorly known and, anyway, appears to be too tightly constrained to account for the EoR on its own [25]. Almost certainly, high-\( z \) quasars became more important towards the end of the EoR, though they probably could not have been the dominant source of ionizing radiation for the whole EoR [26].

Our view of how the Universe evolved through the dark ages and into the EoR is informed by many detailed simulations that have been carried out in recent years [27–36]. (For recent reviews, see Refs. [37,38].) According to these calculations, the first (Pop III) stars formed by redshift \( \sim 20 \) at the core of mini halos with mass \( \sim 10^6 \, M_\odot \) [39–42]. In the concordance \( \Lambda \)CDM model with parameter values \( \Omega_m = 0.31, k = 0, w_\Lambda = -1 \) and Hubble constant \( H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1} \), this redshift corresponds to a cosmic time \( t \sim 200 \, \text{Myr} \).

Based on the astrophysics we know today, specifically the rate of cooling in the primordial gas, it is difficult to see how Pop III stars could have formed earlier than this. The subsequent transition to Pop II star formation incurred additional delays because the gas expelled by the first generation of Pop III stars had to cool and re-collapse. Detailed calculations of this process show that the gas re-incorporation time was at least \( \sim 100 \, \text{Myr} \) [43,44].

So the formation of structure could not have begun in earnest until at least \( \sim 300 \, \text{Myr} \) after the big bang, and the start of the EoR presumably overlapped with the ramp up in Pop II star formation and evolution. Standard astrophysical principles would suggest that this was also
the time when $\sim 5 - 20 M_\odot$ black-hole seeds were created, presumably following the supernova explosion of evolved Pop II (and possibly Pop III) stars. In other words, unless we introduce new, exotic physics for the formation of these seeds, it is difficult to see how they could have emerged any earlier than the start of the EoR, and certainly no sooner than the transition from Pop III to Pop II star formation.

Without invoking anomalously high accretion rates, these seeds would have grown at a rate set by the Eddington limit, defined to be the maximum luminosity attainable from the outward radiation pressure on ionized material under the influence of gravity. For hydrogen plasma, this power is given as $L_{\text{Edd}} \approx 1.3 \times 10^{38} (M/M_\odot) \text{ ergs s}^{-1}$, in terms of the black-hole mass $M$. The mass accretion rate $\dot{M}$ is inferred from $L_{\text{Edd}}$ with the inclusion of an efficiency $\epsilon$ for converting rest-mass energy into radiation. A minimum of $\sim 6\%$ is expected for $\epsilon$ in a Schwarzschild black hole, but other factors (such as a black-hole spin) may enhance $\epsilon$ above this value. To allow for such variations, one typically adopts the fiducial value $\epsilon = 0.1$.

Conventional astrophysics would then suggest that early black-hole growth was driven by an accretion rate $\dot{M} = L_{\text{Edd}}/\epsilon c^2$, and solving for the mass as a function of time one then arrives at the so-called Salpeter relation,

$$M(t) = M_{\text{seed}} \exp \left( \frac{t - t_{\text{seed}}}{45 \text{ Myr}} \right), \quad (2.1)$$

where $M_{\text{seed}} (\sim 5 - 20 M_\odot)$ is the seed mass produced at time $t_{\text{seed}}$. It is now straightforward to see why the discovery of J0100+2802 at redshift 6.3 presents such a big problem for the standard model. With an inferred mass of $\sim 10 - 12 \times 10^9 M_\odot$, the minimal growth time implied by the Salpeter relation is $t - t_{\text{seed}} \sim 910 \text{ Myr}$ (assuming conservatively that $M_{\text{seed}} = 20 M_\odot$). And since in the standard model $t(z = 6.3) \sim 880 \text{ Myr}$, not only is this quasar inconsistent with what is known about the transition from the Dark Ages to the EoR, but it would have had to start growing before the big bang, an obviously non-sensical interpretation.

Of course, these are the reasons some workers have been driven to find non-standard physics to account for the discrepancy between this implied timeline and the predictions of the standard model. But given that no evidence has been seen for such proposals, the only viable explanation within the context of $\Lambda$CDM appears to be the possible role played by mergers in the early Universe [45–47]. However, even this mechanism could only work if the black-hole seeds formed well before the EoR, and their creation would have had to end by $z \sim 20 - 30$ to avoid over-producing the low-mass end of the distribution. In other words, the black-hole seeds would have had to be produced by unknown, exotic processes unrelated to the Pop II and Pop III star formation rate. Also, a more recent consideration of possible mergers [48] suggests that such events could not have been common in the early Universe. Simulations now show that Pop III stars needed very large halos to form, which would have decreased the halo abundance by orders of magnitude. In addition, the associated build-up of Lyman-Werner background radiation would have accelerated the dissociation of H$\text{}_2$, which was necessary for the star-formation process. Both of these trends point to a reduction in the Pop III star formation rate, and therefore a reduction in the possible number of seed black holes. All in all, the mysterious appearance of billion-solar mass quasars at $z \sim 6 - 7$ therefore constitutes significant tension with the standard ($\Lambda$CDM) model.

### 3. A Cosmological Solution

The purpose of this paper is to demonstrate that a resolution of the time-compression problem revealed by supermassive quasars at high redshifts may be found more reasonably in the cosmology itself, rather than the physics of black-hole birth and evolution. Recent observations have pointed to a growing inconsistency with $\Lambda$CDM [19], so it would not be surprising to find that its predicted age-redshift relation is also at odds with the quasar measurements. Table 1 lists the highest redshift quasars discovered to date, including the most massive (J0100) among them. The growth histories of three representative members of this group calculated using the Salpeter...
relation (equation (1) are illustrated in figure 1, which also shows the duration of the Dark Ages and EoR. The inferred black-hole mass \( M \) in this table is calculated from the simultaneous measurement of the quasar’s luminosity and the velocity of its line-emitting gas via the observation of its Doppler-broadened Mg II line \([49]\). This is made possible by reverberation mapping, which produces a tight relationship between the distance of the line-emitting gas from the central ionizing source, and the optical/UV luminosity \([50]\). When high-quality line and continuum measurements are available, one can infer the black-hole mass from the relation \([51]\)

\[
\log M = 6.86 + 2 \log \frac{\text{FWHM}(\text{MgII})}{1,000 \text{ km s}^{-1}} + 0.5 \log \frac{L_{\text{3000}}}{10^{44} \text{ erg s}^{-1}},
\]

where, for ease of comparison between the two models, we use the same value \( H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1} \) in both cases. In this model, the dark ages therefore ended—and the EoR began—at approximately 883 Myr (i.e., \( z \sim 15 \)), and reionization was completed by about 2 Gyr (\( z \sim 6 \)). By comparison, the EoR lasted from ~400 Myr to ~900 Myr in \( \Lambda \)CDM. Insofar as the EoR is concerned, what we do know fairly well from observations is its redshift range, but the corresponding ages are less reliably known. However, there are several indications that the time compression problem associated with supermassive black holes occurs more generally. For example, the early appearance of galaxies at \( z \sim 10 - 12 \) may be an even bigger problem than that for quasars \([57]\) because, whereas a single event could have created a quasar, galaxies had to form gradually through the assembly of more than \( 10^9 \) stars. This does not appear to be feasible in such a short time following the transition from Pop III to Pop II stars with the \( 2 - 4 M_\odot \text{ yr}^{-1} \) star-formation rate predicted in the standard model.
Figure 2. Same as figure 1, but now for the $R_h = ct$ cosmology, which has only one free parameter: $H_0$, whose value is assumed to be the same as in $\Lambda$CDM for ease of comparison. Here, the EoR lasted from $\sim 883$ Myr to $\sim 2.0$ Gyr ($6 \lesssim z \lesssim 15$), and the $20M_\odot$ seeds would have formed at $t \sim 1.09$ Gyr (J0100+2802), $\sim 1.06$ Gyr (P338+29), and $\sim 990$ Myr (J1120+0641), shortly after the start of the EoR.

is viewed in the context of $R_h = ct$, the extended timeline reduces the required escape fraction to a value much closer to $\sim 5\%$ [38].

A comparison between the quasar timelines in figures 1 and 2 highlights the significant differences between these two models when it comes to how and when these supermassive black holes were formed. In $R_h = ct$, all of the quasars seen at $z \sim 6 - 7$ could have easily grown to their measured size via Eddington-limited accretion within the EoR. Crucially, all of the required $\sim 5 - 20M_\odot$ seeds would have formed after the end of the Dark Ages, presumably from the supernova explosion of evolved Pop II and/or III stars. The birth and growth of these high-z quasars is therefore entirely consistent with standard astrophysical processes and our current understanding ($\S$ II) of how the first stars formed and evolved into nascent structure in the early Universe.

4. Conclusions

Irrespective of whether or not mergers played a role in building up the black-hole mass distribution, black-hole seeds in $\Lambda$CDM would have had to form very early in the Universe’s history, well before the onset of re-ionization at $z \sim 15$. Unless some unknown exotic mechanism was responsible for their creation, they would almost certainly have been produced by Pop III stars shortly after the big bang. However, no evidence of re-ionization has yet been found prior to the redshift ($z \sim 20 - 30$) where seed creation must have stopped in order to avoid overproducing lower mass black holes. Reconciling these opposing trends may not be feasible.
In this paper we have assumed that the high-z quasars accreted steadily at the Eddington rate. Their duty cycle is unknown, however, so it’s possible that, on average, their rate of growth was less than Eddington. This would lengthen the Salpeter time (∼45 Myr) even further, thereby exacerbating the time compression problem for $\Lambda$CDM. On the other hand, circumstantial evidence does suggest that when they were turned on, high-z quasars did accrete close to Eddington. This is based on the maximum black-hole mass observed in the local Universe [59]. No more than a couple of $10^{10} M_\odot$ black hole masses have thus far been detected, even after the peak quasar activity at $1 \lesssim z \lesssim 3$ [60]. Yet high-z quasars would have had to be more massive than $10^{10} M_\odot$ in order to produce their fluxes measured at Earth if they were accreting below the Eddington limit.

Perhaps the solution to the time-compression problem in $\Lambda$CDM is simply that the high-z quasars accreted steadily at super-Eddington rates from the time their seeds formed all the way to when we see them at ∼900 Myr. But one can see from Equation (2.1) that in order to grow to $\sim 10^{10} M_\odot$ in ∼400 – 500 Myr, they would have had to accrete at ∼2 – 3 times the Eddington rate throughout that epoch. One cannot yet completely discount such a possibility, but we should then be able to find at least some members of this super-Eddington class at $z \gtrsim 6$. However, all the current observations appear to have ruled out the existence of such sources. The latest measurements [61–63] indicate that the most distant quasars are accreting at no more than the standard Eddington value, and their accretion rate is decreasing at smaller redshifts.

When all the facets of the time-compression problem are considered together, the simplest and most elegant solution to the early appearance of supermassive black holes appears to be a change in the cosmology itself. In the $R_h = ct$ Universe, the birth, growth and evolution of high-z quasars are fully consistent with the principal timescales associated with Pop II and III star formation, and the ensuing epoch of reionization. This picture supports the view that supermassive black holes probably did not contribute significantly to the ionizing radiation early on, but may have become more prominent contributors towards the end of the EoR. Indeed, it may turn out that the rapid ramp up in black-hole mass towards $z \sim 6$ (see figure 2) may have been responsible for completely ionizing the intergalactic medium, thereby bringing an end to the EoR around $z \sim 6$.

Our conclusion adds some support to the possibility, already suggested by other kinds of observation—such as the latest high-precision Baryon Acoustic Oscillation data [16,17,19]—that $\Lambda$CDM does not account for high-precision cosmological measurements as well as $R_h = ct$ does. The latter is itself an FRW cosmology, though restricted by the zero active mass condition (i.e., $\rho + 3p = 0$), which is lacking in $\Lambda$CDM [15]. With this constraint, however, dark energy cannot be a cosmological constant. Its density must evolve dynamically, suggesting an origin in particle physics beyond the standard model. The analysis we have reported in this paper therefore has significant implications because, unlike many other kinds of cosmological measurements, the early appearance of quasars hinges on the time-redshift relationship rather than on integrated distances. It has the potential of opening up a new perspective on the expansion histories in different models in that crucial early period (∼1 – 2 Gyr) when the dynamics differed significantly from one cosmology to the next.

Acknowledgments

FM is grateful to Purple Mountain Observatory in Nanjing, China, where some of this work was carried out. He acknowledges partial support from the Chinese Academy of Sciences President’s International Fellowship Initiative, under Grant No. 2012T1J0011.

Ethics Statement. This research poses no ethical considerations.

Data Accessibility Statement. All data used in this paper were previously published, as indicated in Table 1.
Competing Interests Statement. We have no competing interests.

Authors’ contributions. FM conceived the project and wrote the paper. TMM carried out the simulations. All authors gave final approval for publication.

Funding. The Chinese Academy of Sciences President’s International Fellowship Initiative, Grant No. 2012T1J0011.

References

1. Wu X-B et al. 2015. An ultraluminous quasar with a twelve-billion-solar-mass black hole at redshift 6.30. Nature 518 512.
2. Fan X et al. 2003. A Survey of z>5.7 Quasars in the Sloan Digital Sky Survey. II. Discovery of Three Additional Quasars at z>6. Astron. J. 125 1649.
3. Jiang L et al. 2007. Gemini Near-Infrared Spectroscopy of Luminous z 6 Quasars: Chemical Abundances, Black Hole Masses, and Mg II Absorption. Astron. J. 134 1150.
4. Willott CJ et al. 2007. Four Quasars above Redshift 6 Discovered by the Canada-France High-z Quasar Survey. Astron. J. 134 2435.
5. Jiang L et al. 2008. A Survey of z 6 Quasars in the Sloan Digital Sky Survey Deep Stripe. I. A Flux-Limited Sample at zAB < 21. Astron. J. 135 1057.
6. Willott CJ et al. 2010. The Canada-France High-z Quasar Survey: Nine New Quasars and the Luminosity Function at Redshift 6. Astron. J. 139 906.
7. Mortlock DJ et al. 2011. A luminous quasar at a redshift of z = 7.085. Nature 474 616.
8. Venemans EP et al. 2013. Discovery of Three z > 6.5 Quasars in the VISTA Kilo-Degree Infrared Galaxy (VIKING) Survey. Astrophys. J. 779 24.
9. Banados E et al. 2014. Discovery of Eight z 6 Quasars from Pan-STARRS1. Astron. J. 148 14.
10. Volonteri M and Rees MJ. 2005. Rapid Growth of High-Redshift Black Holes. Astrophys. J. 633 624.
11. Yoo J and Miralda-Escudé J. 2004. Formation of the Black Holes in the Highest Redshift Quasars. Astrophys. J. Let. 614 L25.
12. Willott CJ et al. 2010. Eddington-limited Accretion and the Black Hole Mass Function at Redshift 6. Astron. J. 140 546.
13. Melia F. 2007. The Cosmic Horizon. MNRAS 382 1917.
14. Melia F and Shevchuk ASH. 2012. The R0 = ct Universe. MNRAS 419 2579.
15. Melia F. 2015. A Physical Basis for the Symmetries in FRW. Ann. Phys. (Berlin) submitted.
16. Anderson L et al. 2014. The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: baryon acoustic oscillations in the Data Releases 10 and 11 Galaxy samples. MNRAS 441 24.
17. Delubac T et al. 2015. Baryon acoustic oscillations in the Lyalpha forest of BOSS DR11 quasars. Astron. Astrophys. 574 59.
18. Font-Ribera A et al. 2014. Quasar-Lyman alpha forest cross-correlation from BOSS DR11: Baryon Acoustic Oscillations. JCAP 5 id27.
19. Melia F and López-Corredoira M. 2015. Alcock-Paczynski Test with Model-independent BAO Data. Astrophys. J. submitted [arXiv:1503.05052].
20. Zaroubi, S. 2012 The First Galaxies–Theoretical Predictions and Observational Clues. Eds. Wiklind T, Mobasher B and Bromm V. Springer, New York.
21. Venemans EP et al. 2015. The Identification of Z-dropouts in Pan-STARRS1: Three Quasars at 6.5< z < 6.7. Astrophys. J. Let. 801 11.
22. Fan X et al. 2006. A Survey of z>5.7 Quasars in the Sloan Digital Sky Survey. IV. Discovery of Seven Additional Quasars. Astron. J. 131 1203.
23. Bennett C et al. 2003. The Microwave Anisotropy Probe Mission. Astrophys. J. 583 1.
24. Page L et al. 2007. Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Polarization Analysis. Astrophys. J. Sup. 170 335.
25. Ripamonti E Mapelli M and Ferrara A. 2007. The impact of dark matter decays and annihilations on the formation of the first structures. MNRAS 375 1399.
26. Jiang L et al. 2006. Probing the Evolution of Infrared Properties of z 6 Quasars: Spitzer Observations. Astron. J. 132 2127.
27. Barkana E and Loeb A. 2001. In the beginning: the first sources of light and the reionization of the universe. *Phys. Rep.* **349** 125.
28. Miralda-Escudé J. 2003. The Dark Age of the Universe. *Science* **300** 1904.
29. Bromm V and Larson RB. 2004. The First Stars. *ARA&A* **42** 79.
30. Ciardi B and Ferrara A. 2005. The First Cosmic Structures and Their Effects. *Space Sci. Rev.* **116** 625.
31. Glover S. 2005. The Formation Of The First Stars In The Universe. *Phys. Rep.* **349** 125.
32. Miralda-Escudé J. 2003. The Dark Age of the Universe. *Science* **300** 1904.
33. Wise JH and Abel T. 2008. Resolving the Formation of Protogalaxies. III. Feedback from the First Stars. *Astrophys. J.* **685** 40.
34. Salvaterra R Ferrara A and Dayal P. 2011. Simulating high-redshift galaxies. *MNRAS* **414** 847.
35. Greif TH et al. 2012. Formation and evolution of primordial protostellar systems. *MNRAS* **424** 399.
36. Jaacks J Nagamine K and Choi J-H. 2012. Duty cycle and the increasing star formation history of z >= 6 galaxies. *MNRAS* **427** 403.
37. Bromm V Yoshida N Hernquist L and McKee CF. 2009. The formation of the first stars and galaxies. *Nature* **459** 49.
38. Yoshida N Hosokawa T and Omukai K. 2012. Formation of the first stars in the universe. *Prog. Theor. Exp. Phys.* **2012** id.01A305.
39. Haiman Z Thoul AA and Loeb A. 1996. Cosmological Formation of Low-Mass Objects. *Astrophys. J.* **464** 523.
40. Tegmark M et al. 1997. How Small Were the First Cosmological Objects? *Astrophys. J.* **474** 1.
41. Abel T Bryan GL and Norman ML. 2002. The Formation of the First Star in the Universe. *Science* **295** 93.
42. Bromm V Coppi PS and Larson RB. 2002. The Formation of the First Stars. I. The Primordial Star-forming Cloud. *Astrophys. J.* **564** 23.
43. Yoshida N Bromm V and Hernquist L. 2004. The Era of Massive Population III Stars: Cosmological Implications and Self-Termination. *Astrophys. J.* **605** 579.
44. Johnson JL Greif TH and Bromm V. 2007. Local Radiative Feedback in the Formation of the First Protogalaxies. *Astrophys. J.* **665** 85.
45. Tanaka T and Haiman Z. 2009. The Assembly of Supermassive Black Holes at High Redshifts. *Astrophys. J.* **696** 1798.
46. Lippai Z Frei Z and Haiman Z. 2009. On the Occupation Fraction of Seed Black Holes in High-redshift Dark Matter Halos. *Astrophys. J.* **701** 360.
47. Hirschmann M et al. 2010. On the evolution of the intrinsic scatter in black hole versus galaxy mass relations. *MNRAS* **407** 1016.
48. Johnson JL et al. 2013. The First Billion Years project: the impact of stellar radiation on the co-evolution of Populations II and III. *MNRAS* **428** 1857.
49. Wandel A et al. 1999. Central Masses and Broad-Line Region Sizes of Active Galactic Nuclei. I. Comparing the Photoionization and Reverberation Techniques. *Astrophys. J.* **526** 579.
50. Blandford RD and McKee CF. 1982. Reverberation mapping of the emission line regions of Seyfert galaxies and quasars. *Astrophys. J.* **255** 419.
51. Vestergaard M and Osmer PO. 2009. Mass Functions of the Active Black Holes in Distant Quasars from the Large Bright Quasar Survey, the Bright Quasar Survey, and the Color-selected Sample of the SDSS Fall Equatorial Stripe. *Astrophys. J.* **699** 800.
52. Melia F. 2014. The high-z quasar Hubble Diagram. *JCAP JCAP01(2014)027*.
53. Richards GT et al. 2006. Spectral Energy Distributions and Multiwavelength Selection of Type 1 Quasars. *Astrophys. J. Sup.* **166** 470.
54. Schneider D et al. 2005. The Sloan Digital Sky Survey Quasar Catalog. III. Third Data Release. *AJ* **130** 367.
55. Melia F. 2014. The High-z Quasar Hubble Diagram. *JCAP JCAP01(2014)027*.
56. Melia F. 2015. The Cosmic Equation of State. *Astrophys. Space Sc.* **356** 393.
57. Melia F. 2014. The Premature Formation of High-redshift Galaxies. *AJ* **147** 120.
58. Melia F and Fatuzzo M. 2015. The Epoch of Reionization in the R = ct Universe. *MNRAS* submitted.
59. Shankar F et al. 2009. Self-Consistent Models of the AGN and Black Hole Populations: Duty Cycles, Accretion Rates, and the Mean Radiative Efficiency. *Astrophys. J.* **690** 20.
60. McConnell NJ et al. 2012. Dynamical Measurements of Black Hole Masses in Four Brightest Cluster Galaxies at 100 Mpc. *Astrophys. J.* 756 179.
61. Mortlock DJ Warren SJ Venemans BP et al. 2011. A Luminous Quasar at a Redshift of $z = 7.085$. *Nature* 474 616.
62. De Rosa G DeCarli R Walter F Fan X Jiang L Kurk J Pasquali A and Rix H-W. 2011. Evidence for Non-evolving Fe II/Mg II Ratios in Rapidly Accreting $z \approx 6$ QSOs. *ApJ* 739 id.56.
63. Willott CJ et al. 2010. Eddington-limited Accretion and the Black Hole Mass Function at Redshift 6. *AJ* 140 546.