8. Early Appearance of Supermassive Black Holes and Galaxies

A Candid Assessmet of Standard Cosmology, Fulvio Melia

The Early appearance of quasars in the ΛCDM Universe (Melia 2018) , such as ULAS J134208.10 + 092838.61 (henceforth **J1342 + 0928**, an ultraluminous supermassive black hole at **redshift z = 7.54**. This object has an inferred mass of $M = 7.8\ 10^8$ M and (as we shall see shortly) should have **taken more than 820 Myr** to grow via standard Eddington-limited accretion. **But its redshift suggests we're seeing it only several hundred Myr after Population II and III Supernovae could have created the (presumably) ~ 5 – 25 M_e seed that started its growth to the gargantuan object we see today.**

The growth of black hole seeds (massive or otherwise) is constrained by the maximum luminosity attainable due to the outward radiation pressure on ionized matter under the influence of gravity. The limiting power in hydrogen-rich plasma is known as the Eddington limit, $L_{Edd} \approx 1.3 \times 10^{38}$ (M/M_e) ergs s^{-1} . With an assumed effiicency, ε, for converting rest-mass energy into radiation, one then infers an accretion rate $M = L_{bol}\, c^2$, in terms of the bolometric luminosity, L_{bol}. One typically adopts a fiducial value ε = 0.1 to cover the possible variations in basic accretion-disk theory, to arrive at the expression

$$\frac{dM}{dt} = \frac{1.3 \times 10^{38}\ \mathrm{erg\ s^{-1}}}{\epsilon c^2 M_\odot} M$$

(Salpeter 1964; Melia 2013b) , whose solution is known as the Salpeter relation, where M_{seed} (~ 5 – 25 Me) is the seed created at t_{seed}.

$M_{seed} := 5 M_\odot$

$$M_{Salpeter}(t) := M_{seed}\cdot exp\left[\left[\frac{(t - 820)\cdot Myr}{45 Myr}\right]\right] \qquad M_{Salpeter}(820) = 5\cdot M_\odot$$

Conventional astrophysics thus predicts that **J1342 + 0928** should have **taken approximately 820 Myr to grow from an initial black hole mass of 10** $M_\odot$ Although mergers in the early Universe (Lippai et al. 2009; Tanaka & Haiman 2009; Hirschmann et al. 2010) might have shortened this growth time, there are limitations to how this mechanism could have worked. Simulations show that the black hole distribution always converges toward a Gaussian, irrespective of how one chooses the initial seed profile. But to comply with the observational constraints, ~ 100 $M_\odot$seeds must have started forming no later than z ~ 40 (Tanaka & Haiman 2009) , well before the EoR. In addition, seeds must not have formed after z ~ 20 – 30, for then there would be an overproduction of black holes at ~ $10^5 M_\odot$ to ~ 10^7 $M_\odot$) compared to the data (see, e.g., Figures 5 and 6 in Tanaka & Haiman 2009) . Without this cutoff, the lower mass black holes would be over-represented by a factor ~ 100 – 1000.

The suggestion that early mergers might have critically impacted the formation of supermassive black holes at high-z is therefore inconsistent with our view of how and when Population III stars were born. **The onset of the EoR at t ~ 400 Myr is set by the cooling time to form the first generation of stars, corresponding to z ~ 15** — much later than z ~ 40. And there is no explanation for why these stars then stopped forming below z ~ 20 – 30, even before the EoR started. **One would be forced to hypothesize that some mechanism other than Population III supernovae must have created the massive seeds well before the EoR, requiring new, unknown physics.**

But we simply have no observational evidence for such events occurring prior to z ~15.

An additional problem with the merger scenario is that the halo abundance now appears to have been smaller than previously thought by at least an order of magnitude. Large (4 Mpc^3) high-resolution simulations (Johnson et al. 2013) show that Population III and II star formation overlapped and evolved down to z ~ 6. The enhanced metal enrichment and the feedback radiation — including molecule-dissociating Lyman –Werner photons that destroyed the coolants H_2 and HD required for the condensation of early matter — would have significantly altered the halo and Population III star formation rates. Indeed, both the halo and Population III star formation rates would have been reduced by an order of magnitude at z >= 10 compared to previous, less sophisticated simulations. This net shift reduced the volume density of Population III supernovae, and the density of black hole seeds they produced, at the redshift (z >= 10) when the frequency of mergers among these objects would have mattered most.

The Premature Formation of Galaxies

Interest in the cosmic dawn has also been generated by the recent dramatic discovery of faint galaxies at redshifts well before the end of the EoR. By stretching the imaging capabilities of WFC3/IR on the Hubble Space Telescope (HST), and introducing gravitational lensing techniques, several teams appear to have uncovered galaxies emerging at $z \sim 10 – 12$, a highly surprising result.
It now appears that these primordial galaxies contributed to the re-ionization of the cosmic fluid, and may even have dominated this process. These initial detections by HST have been characterized as an "impossibly early" galaxy problem, but the more recent discovery by the James Webb Space Telescope (JWST), of well-formed (~ 10^9 $M_\odot$) galaxies at redshifts extending out to ~ 17, with some confirming ALMA observations have greatly exacerbated this apparent conflict with the standard model. As of this writing, the JWST discoveries are still considered to be primarily candidates, though their photometrically identified redshifts appear to be quite reliable, and follow-up observations will be conducted very shortly. As we shall see, if these turn out to be real, as is highly expected, their implied formation would have begun (and been largely completed) even before Population II and III stars are supposed to have emerged.

Just as we found for the supermassive black holes, **this rapid emergence of high-z galaxies so quickly after the big bang therefore appears to be in conflict with our current understanding of how they evolved.** These two problems are probably not independent of each other. Not surprisingly, one can easily show that the same time-compression problem is responsible for the tension seen between theory and the premature formation of both the early quasars and galaxies.

One can already see from this brief summary, however, that **the rate of growth versus redshift does not appear to be quite right.** Probing more deeply, one infers from the results that the ratio of the doubling time t_{db} (essentially the inverse of the sSFR) to the corresponding cosmic time falls within the range ~ 0.1 – 0.3, independently of redshift. For the sake of illustration, let us take the smaller value, which minimizes the growth time. Then, a galaxy with mass $M_* =$ 10^8 $M_\odot$ at $z = 6$ (i.e., $t_* \sim 900$ Myr in ΛCDM) must have started its assembly at $t_{init} \sim (0.9)^n\ t_*$ where $n = M_*/M_{init})$ log2 is the number of doublings from an initial mass M_{init} at t_{init}. One therefore infers that such galaxies seen at $z = 6$ could have started forming during the transition from Population III to Population II stars (i.e., $t_{init} \sim 230$ Myr) if one conservatively assumes that $M_{init} = 10^4 M_\odot$.
But the timeline breaks down completely if one instead considers the same type of growth rate for a similar galaxy seen at $z = 10$ (i.e., $t_* \sim 550$ Myr in ΛCDM). Such a galaxy must have started growing from an initial condensation of $M_{init} = 10^4$ $M_\odot \sim 140$ Myr, well before Population III stars had suffcient time to evolve and explode as supernovae, initiating the subsequent growth of galactic structure. As a specific illustrative example, consider that a 10^9 $M_\odot$ galaxy seen at $z \sim 10.^7$ (i.e., $t_* \sim 490$ Myr), must have started growing at $t \sim 82$ Myr, a situation that simply cannot be reconciled with what must have happened at the dawn of cosmic structure formation. Comparing the time compression problem for quasars with that of galaxies, one draws the interesting conclusion that **stretching the time elapsed per unit of redshift by a factor 2 beyond z ~ 6 would be sufficient to eliminate the tension in both cases.**

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