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Massive Galaxies and Central Black Holes at $z = 6$ to $z = 8$

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Abstract

In a closed vacuum-dominated universe, the holographic principle implies that only a finite amount of information will ever be available to describe the distribution of matter in the sea of cosmic microwave background radiation. When $z = 6$ to $z = 8$, if information describing the distribution of matter in large scale structures is uniformly distributed in structures ranging in mass from that of the largest stars to the Jeans' mass, a holographic model for large scale structure in a closed universe can account for massive galaxies and central black holes observed at $z = 6$ to $z = 8$. In sharp contrast, the usual approach assuming only collapse of primordial overdensities into large scale structures has difficulty producing massive galaxies and central black holes at $z = 6$ to $z = 8$.

Keywords

Large Scale Structure, Holography, Early Galaxies, Early Supermassive Black Holes

1. Introduction

"Current theory predicts that galaxies begin their existence as tiny density fluctuations, with overdensities collapsing into virialized protogalaxies, and eventually assemble gas and dust into stars and black holes" [1]. Steinhardt *et al*. [1] summarized data indicating that the current approach had difficulty accounting for massive galaxies and their associated central black holes at redshifts $z = 6$ to $z = 8$.

To address the "impossibly early galaxy problem" of Steinhardt *et al*., this analysis treats our universe as a closed Friedmann universe, dominated by vacuum energy in the form of a cosmological constant, and so large that it is approximately flat. This is consistent with full mission 2015 *Planck* satellite observations [2] indicating that the universe is dominated by vacuum energy, spatially flat to a good approximation, with Hubble constant $H_0 = 67.8\ \text{km} \cdot \text{sec}^{-1} \cdot \text{Mpc}^{-1}$, total matter density $\Omega_m = 0.308$, and baryonic density $\Omega_b = 0.048$. Adler and

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Overduin [3] claimed "observation cannot distinguish—even in principle—between a perfectly flat universe and one that is sufficiently close to flat." However, analysis assuming a closed inflationary universe and accounting for important features of large scale structure may indicate that our universe is closed.

In the following, $\rho_r(z)$ is the cosmic microwave background (CMB) radiation density at redshift z, where $\rho_r(z) = (1+z)^4 \rho_r(0)$ and the mass equivalent of today's radiation energy density $\rho_r(0) = 4.4 \times 10^{-34}\ \text{g/cm}^3$ [4], the matter density at redshift z is $\rho_m(z) = (1+z)^3 \rho_m(0)$ where $\rho_m(0)$ is today's matter density, and $M_\odot = 2 \times 10^{33}\ \text{g}$ is the solar mass. With Hubble constant $H_0 = 67.8\ \text{km} \cdot \text{sec}^{-1} \cdot \text{Mpc}^{-1}$, the critical density $\rho_{crit} = \frac{3H_0^2}{8\pi G} = 8.64 \times 10^{-30}\ \text{g/cm}^3$, where $G = 6.67 \times 10^{-8}\ \text{cm}^3 \cdot \text{g}^{-1} \cdot \text{sec}^{-2}$ and $c = 3.00 \times 10^{10}\ \text{cm} \cdot \text{sec}^{-1}$. Since matter accounts for 30.8% of the energy in today's universe, $\rho_m(0) = 0.308 \rho_{crit} = 2.66 \times 10^{-30}\ \text{g/cm}^3$ and the vacuum energy density $\rho_v = (1-0.308)\rho_{crit} = 5.98 \times 10^{-30}\ \text{g/cm}^3$. The cosmological constant $\Lambda = \frac{8\pi G \rho_v}{c^2} = 1.12 \times 10^{-56}\ \text{cm}^{-2}$ and there is an event horizon in the universe at radius $R_H = \sqrt{\frac{3}{\Lambda}} = 1.64 \times 10^{28}\ \text{cm}$. According to the holographic principle [5], the number of bits of information available on the light sheets of any surface with area a is $\frac{a}{4\delta^2 \ln(2)}$, where $\delta = \sqrt{\frac{\hbar G}{c^3}}$ is the Planck length and $\hbar = 1.05 \times 10^{-27}\ \text{g} \cdot \text{cm}^2/\text{sec}$ is Planck's constant. So, only $N = \frac{\pi R_H^2}{\delta^2 \ln(2)} = 4.69 \times 10^{122}$ bits of information on the event horizon will ever be available to describe our universe.

In a closed universe, there is no source or sink for information outside the universe, so the total amount of information available to describe the universe remains constant. Also, after the first few seconds of the life of the universe, energy exchange between matter and radiation is negligible compared to the total energy of matter and radiation separately [6]. Therefore, in a closed universe, the total quantity of matter in the universe is conserved; there is only a fixed amount of information available; and the average mass per bit of information is constant. In a closed, isotropic, and homogeneous Friedmann universe, the constant mass per bit of information (the mass $M_H = \frac{4}{3}\pi R_H^3 \rho_0(0) = 4.92 \times 10^{55}\ \text{g}$ within the event horizon today divided by the number of bits of information within the event horizon) is $(4.92 \times 10^{55}\ \text{g})/(4.69 \times 10^{122}) = 1.05 \times 10^{-67}\ \text{g}$. So, the total mass within the event horizon today relates to the square of the event horizon radius by $M_H = fR_H^2$, where $f = 0.183\ \text{g/cm}^2$, giving the relation between mass within the event horizon and radius of a holographic screen just enclosing that mass.

2. Galaxies at $z = 6$ to $z = 8$

At $z < 6$, a hierarchical model of large scale structure can be developed using the holographic principle [7], but the hierarchical model is not applicable at $z \geq 6$. So, the following analysis extends the ideas in Refs. [7] to consider large scale structure at $z \geq 6$.

When the matter density $\rho_m(z)$ is much greater than the radiation density $\rho_r(z)$, the speed of pressure waves affecting matter density is $c_s(z) = c\sqrt{\frac{4(1+z)^4 \rho_r(0)}{9\rho_m(z)}}$ [8], and the Jeans' length is $L_J(z) = c_s(z)\sqrt{\frac{\pi}{G(1+z)^3 \rho_m(0)}}$ [8]. The Jeans' mass, the mass of matter within a radius one quarter of the Jeans' wavelength, is $M_J(z) = \frac{4\pi}{3}\left(\frac{L_J(z)}{4}\right)^3 \rho_m(z)$, where $L_J(z) = \frac{(1+z)^2}{\rho_m(z)} \frac{2c}{3} \sqrt{\frac{\pi \rho_r(0)}{G}} = \frac{B}{(1+z)\rho_m(0)}$. Since $B = \frac{2c}{3}\sqrt{\frac{\pi \rho_r(0)}{G}}$ is independent of z, the Jeans' mass $M_J = 2.24 \times 10^{50}\ \text{g} = 1.13 \times 10^{17} M_\odot$ is independent of z, and there are $\frac{M_H}{M_J} = \frac{4.92 \times 10^{55}}{2.24 \times 10^{50}} = 2.20 \times 10^5$ Jean's masses within the event horizon.

In this holographic model for large scale structure at $z \geq 6$, visible structures inhabit spherical isothermal halos of dark matter with masses ranging from that of the largest star to the Jeans' mass, holographic radii $R = \sqrt{\frac{M}{0.183}}$ cm, the number $\mathrm{d}n$ of halos in mass bin $\mathrm{d}m$ given by $\frac{\mathrm{d}n}{\mathrm{d}m} = \frac{K}{m}$, and the number of bits of information in any mass bin (proportional to $\frac{K}{m} m$) the same in all mass bins. Following Ref. [7], this analysis uses a maximum stellar mass of $M_{\max *} = 300 M_\odot$ [9] coinciding with the estimated minimum stellar mass at $z \approx 64$ and consistent with indications that the first stars formed at $z \approx 65$ [10]. The mass within the event horizon relates to the aggregate of halo masses by $M_H = \int_{M_{\max *}}^{M_J} m \left(\frac{K}{m} \right) \mathrm{d}m \approx K M_J$. So, $K = \frac{M_H}{M_J} = 2.2 \times 10^5$, the number of halos within the event horizon is $n = \int_{M_{\max *}}^{M_J} \left(\frac{K}{m} \right) \mathrm{d}m = \ln \left(\frac{M_J}{M_{\max *}} \right) K = 33.6K = 7.37 \times 10^6$ and the average halo mass is $\frac{M_H}{n} = \frac{M_J}{33.6} = 6.7 \times 10^{48}$ g.

While recognizing the difficulties and intricacies involved in estimating halo masses at large redshift, Steinhardt *et al.* [1] present their estimates for the number of halos in a volume $1 (\mathrm{Mpc/h})^3 = 9.43 \times 10^{73}$ cm^3 in their Figure 1. For comparison with those data, consider mass bins with width $10^{11} M_\odot$. Then, within the volume now enclosed by the event horizon, the number of halos with mass between $0.5 \times 10^{11} M_\odot$ and $1.5 \times 10^{11} M_\odot$ is $n_{10^{11} M_\odot} = \int_{0.5 \times 10^{11} M_\odot}^{1.5 \times 10^{11} M_\odot} \left(\frac{K}{m} \right) \mathrm{d}m = \ln(3) K = 2.4 \times 10^5$. Correspondingly, the number of halos with mass between $0.95 \times 10^{12} M_\odot$ and $1.05 \times 10^{12} M_\odot$ is $n_{10^{12} M_\odot} = 2.4 \times 10^4$ and the number of halos with mass between $0.995 \times 10^{13} M_\odot$ and $1.005 \times 10^{13} M_\odot$ is $n_{10^{13} M_\odot} = 2.4 \times 10^3$.

The scale factor $a(z)$ relates to today's scale factor $a(0)$ by $a(z) = \frac{a(0)}{1+z}$. The volume within the event horizon today, $V_H = \frac{4}{3} \pi R_H^3 = 1.85 \times 10^{85}$ cm^3, occupied a volume of 5.39×10^{82} cm^3 at $z = 6$ and a volume of 2.54×10^{82} cm^3 at $z = 8$. So, the volume within the event horizon today was $5.7 \times 10^8 (\mathrm{Mpc/h})^3$ at $z = 6$, and $2.7 \times 10^8 (\mathrm{Mpc/h})^3$ at $z = 8$. Considering mass bins with width $10^{11} M_\odot$, the number of halos per $(\mathrm{Mpc/h})^3$ and the logarithm of that density expected from this holographic model for $z = 6$ and $z = 8$ are shown below.

Halo mass $(M_\odot)$	Redshift z	Density = number/(Mpc/h^3)	Log$_{10}$ (density)
10^{11}	6	4.2×10^{-4}	−3.4
10^{11}	8	9.0×10^{-4}	−3.0
10^{12}	6	4.2×10^{-5}	−4.4
10^{12}	8	9.0×10^{-5}	−4.0
10^{13}	6	4.2×10^{-6}	−5.4
10^{13}	8	9.0×10^{-6}	−5.0

Compared to the cloud of data points in Figure 1 of Steinhardt *et al.* [1] showing their estimated halo densities, the above results are slightly below the cloud at $10^{11} M_\odot$, just below the lower edge of the cloud at $10^{12} M_\odot$, and at the upper edge of the cloud at $10^{13} M_\odot$. So, halo densities similar to those estimated from observations at $z = 6$ to $z = 8$ are an inevitable consequence of the holographic anlysis outlined above.

3. Black Holes at z = 6 to z = 8

As in Ref. [7], it is assumed an isothermal spherical halo of dark matter with mass M_S is enclosed by a holographic screen with radius $R_S = \sqrt{\frac{M_S}{0.183}}$ cm. The isothermal halo matter density distribution is $\rho(r) = \frac{a}{r^2}$, where r is the distance from the center of the halo and a is constant. The mass M_s within the holographic radius R_s in an isothermal density distribution is $M_s = 4\pi\int_0^{R_s} \frac{a}{r^2} r^2 \mathrm{d}r = 4\pi a R_s$, requiring $a = \frac{M_s}{4\pi R_s}$. The mass within radius R from the center of a halo is $M_R = 4\pi\int_0^{R} \frac{a}{r^2} r^2 \mathrm{d}r = \frac{R}{R_s} M_s$.

If the mass of the central supermassive black hole (SMBH) is at the center of a core volume with radius R_c equal to the holographic radius of stars with the maximum stellar mass, stars of all masses can orbit the center of the structure just outside the core without their holographic screens encountering the central black hole so they would be disrupted and drawn into the central black hole. The resulting SMBH mass estimate is $M_{\mathrm{SMBH}} = \sqrt{M_h M_{\max*}}$, where M_h is the total halo mass and $M_{\max*} = 300 M_\odot$ is the maximum stellar mass.

Mortlock *et al*. [11] found a black hole with mass $2\times10^9 M_\odot$ at $z \approx 7.1$ in the quasar ULAS J1120+ 0641. Pacucci, Volonteri, and Ferrara [12], noting evidence for supermassive black holes in the $10^9 M_\odot$ to $10^{10} M_\odot$ range only 10^9 years after the Big Bang, recognize this "evidence contrasts with the standard theory of black hole growth." In comparison, the average halo mass at z = 6 to z = 8 in this holographic model is $3.4\times10^{15} M_\odot$ and the corresponding central black hole mass is $10^9 M_\odot$, similar to the mass of the black hole in ULAS J1120 + 0641.

4. Conclusion

Caltech's Professor Steinhardt and colleagues [1] discussed the "impossibly early galaxy problem," reviewing data showing that the conventional approach to formation of large scale structure cannot adequately account for presence of the massive galaxies and associated central black holes observed at redshifts z = 6 to z = 8. In sharp contrast, the holographic analysis outlined above *requires* supermassive black holes with mass on the order of $10^9 M_\odot$ at z = 6 to z = 8. This is consistent with the observations of Trakhtenbrot *et al*. [13] indicating the presence of a black hole with mass $6.9\times10^9 M_\odot$ in the AGN (active galactic nucleus) CID-947 at $z = 3.328$.

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