The First Stars and Quasars in the Universe

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Abstract.

The transition between the nearly smooth initial state of the Universe and its clumpy state today occurred during the epoch when the first stars and low-luminosity quasars formed. For Cold Dark Matter cosmologies, the radiation produced by the first baryonic objects is expected to ionize the Universe at \( z \approx 10^{-2} \) and consequently suppress by \( \sim 10\% \) the amplitude of microwave anisotropies on angular scales \( \lesssim 10^\circ \). Future microwave anisotropy satellites will be able to detect this signature. The production and mixing of metals by an early population of stars provides a natural explanation to the metallicity, \( \sim 1\% Z_\odot \), found in the intergalactic medium at redshifts \( z \lesssim 5 \). The Next Generation Space Telescope (NGST) will be able to image directly the “first light” from these stars. With its nJy sensitivity, NGST is expected to detect \( \sim 10^3 \) star clusters per square arcminute at \( z \gtrsim 10 \). The brightest sources, however, might be early quasars. The infrared flux from an Eddington luminosity, \( 10^6 M_\odot \), black hole at \( z = 10 \) is \( \sim 10 \) nJy at 1\( \mu \)m, easily detectable with NGST. The time it takes a black hole with a radiative efficiency of \( \sim 10\% \) to double its mass amounts to more than a tenth of the Hubble time at \( z = 10 \), and so a fair fraction of all systems which harbor a central black hole at this redshift would appear active. The redshift of all sources can be determined from the Lyman-limit break in their spectrum, which overlaps with the NGST wavelength regime, 1–3.5\( \mu \)m, for \( 10 < z < 35 \). Absorption spectra of the first generation of star clusters or quasars would reveal the reionization history of the Universe. The intergalactic medium might show a significant opacity to infrared sources at \( z \gtrsim 10 \) due to dust produced by the first supernovae.

1. Introduction

The cosmic microwave background (CMB) anisotropies detected by the COBE satellite (Bennet et al. 1996) confirmed the notion that the present structure in the Universe originated from small density fluctuations at early times. The gravitational collapse of overdense regions could explain the present-day abundance of bound objects, such as galaxies or X-ray clusters, under the appropriate extrapolation of the detected large-scale anisotropies to smaller scales (e.g., Baugh et al. 1997; Pen 1996). Recent deep observations with the Hubble Space Telescope (Steidel et al. 1996; Madau et al. 1996) and ground-based telescopes,
Figure 1. Collapse redshift for cold dark matter (dashed lines) and baryons (solid lines) in spheres of various masses and initial overdensities. The overdensities are in units of the rms amplitude of fluctuations $\sigma(M)$ for a standard CDM power-spectrum with $\sigma_{8h^{-1}} = 0.67$. The collapse of the baryons is delayed relative to the dark matter due to gas pressure. The curves were obtained by following the motion of the baryonic and dark matter shells with a spherically symmetric, Lagrangian hydrodynamics code (Haiman & Loeb 1997).

such as Keck (Lowenthal et al. 1996), have constrained considerably the evolution of galaxies and their stellar content at $z \lesssim 5$. However, in the bottom-up hierarchy of the popular Cold Dark Matter (CDM) cosmologies, galaxies were assembled out of building blocks of smaller mass. The elementary building blocks, i.e. the first gaseous objects to form, had a total mass of order the Jeans mass ($\sim 10^6 M_\odot$), below which gas pressure opposed gravity and prevented collapse (Haiman & Loeb 1997; Ostriker & Gnedin 1997). In the standard CDM cosmology, these basic building blocks formed at $z \sim 10–30$ (see Fig. 1).

The first light from stars and quasars ended the “dark ages” of the universe and initiated a “renaissance of enlightenment” in the otherwise fading glow of the big bang. It is easy to see why the mere conversion of trace amounts of gas into stars or black holes at this early epoch could have had a dramatic effect on the ionization state and temperature of the rest of the gas in the Universe. Nuclear burning releases $5 \times 10^6$ eV per hydrogen atom, and thin-disk accretion onto a Schwarzschild black hole releases ten times more energy; however, the ionization of hydrogen requires only 13.6 eV. It is therefore sufficient to convert a minimum fraction of $\sim 10^{-5}$ of the baryonic mass into stars or black holes in order to ionize the rest of the Universe. (The actual required fraction is higher because some of the emitted photons are below 13.6 eV and because each hydrogen atom recombines multiple times at high redshifts). The free electrons produced in this process erase the microwave background anisotropies.
on angular scales below the size of the horizon at the reionization epoch ($\sim 10^\circ$),
by an amplitude comparable to their optical depth to Thomson scattering.

A variety of CDM models that are all consistent with both the COBE
anisotropies ($z \approx 10^3$) and the abundance of objects today ($z = 0$) differ appre-
ciably in their initial amplitude of density fluctuations on small scales. The
reionization history of the Universe is determined by the collapse redshift of the
smallest objects ($\sim 10^6-9M_\odot$) and is therefore ideally suited to discriminate
among these models.

We have not yet observed the first transition that the Universe made be-
tween its nearly smooth initial state and its clumpy present state. If I had been
asked to envision an instrument that would directly probe this transition epoch,
I would have probably sketched something like the Next Generation Space Tele-
scope (NGST). There are three reasons that make this choice natural: (i) At
$z \sim 10 - 50$, the rest frame optical–UV emission of star clusters or quasars is
redshifted to infrared wavelengths in the observer frame; (ii) The first sources
are faint because of their high redshift and low mass. Their detection, there-
fore, requires a sensitive infrared telescope with a large collecting area, in space.
The last requirement is necessary to avoid atmospheric background/opacity and
to reduce the zodiacal background through an extended solar orbit; and (iii)
High-redshift objects are likely to be denser and more compact than their low-
redshift counterparts. This simply follows from the increase in the mean density
of the Universe at early times. In the bottom-up hierarchy of structure forma-
tion, this tendency is also enhanced by the decrease of the nonlinear mass scale
with redshift. The physical size of an object of mass $M$ should scale roughly as
$\propto M^{1/3}/(1 + z_f)$, where $z_f$ is its formation redshift. High angular resolution is
therefore required for imaging star clusters at $z \gtrsim 10$.

The detection of the transition epoch could provide invaluable information
about the ionization and star formation history of the Universe. The study of
stars at high-redshift is also linked to the “archeology” of old stars in the Milky
Way halo. The metallicity-age trends which are identified in the Milky-Way
galaxy (McWilliam et al. 1996) should be related to the various epochs of star
formation in the early Universe.

So much for theoretical arguments. But is there direct evidence that struc-
ture started to form in the Universe long before galaxies were assembled? The
answer is, yes. By now, a number of observational clues constitute a “smoking
gun” for an early population of stars that had formed at $z \gtrsim 5$:

• Recent spectroscopic observations of the Ly$\alpha$ forest at $z \gtrsim 3$ show evidence
  for a metallicity $\sim 1\%Z_\odot$ in absorbers with HI column densities as low as
  $10^{15}\text{ cm}^{-2}$ (Cowie 1996; Songaila & Cowie 1996; Tytler et al. 1995). Nu-
  merical simulations identify such absorbers with mildly overdense regions in
  the intergalactic medium, out of which nonlinear objects such as galaxies
  condense (Hellstein et al. 1997, and references therein). Indeed, damped
  Ly$\alpha$ absorbers, which are thought to be the progenitors of present–day
  galaxies, show similar metallicities during the early phase of their forma-
  tion, at $3.5 \lesssim z \lesssim 4.5$ (Lu, Sargent, & Barlow 1996). The universality of
  this mean metal abundance in absorbers, spanning a range of six orders
  of magnitude in HI column density, indicates that an early phase of metal
  enrichment by stars occurred throughout the Universe at $z \gtrsim 5$.  


• The lack of complete absorption shortward of the Ly\(\alpha\) resonance (the so-called “Gunn-Peterson effect”; Gunn & Peterson 1965) in quasar spectra at \(z \sim 5\) implies that the intergalactic gas was highly photoionized before that time. On the other hand, the bright quasar population has been observed to decline at \(z \gtrsim 3\), and so stellar sources might be necessary to keep the intergalactic gas in its inferred high-ionization state (Shapiro & Giroux 1987; Miralda-Escudé & Ostriker 1990).

• Microlensing surveys argue that \(\sim 50^{+30}_{-20}\%\) (instead of the previously known range of 0–100%!) of the mass of the halo of the Milky Way galaxy might be in the form of Massive Compact Halo Objects (MACHOs) with a mass \(\sim 0.5^{+0.3}_{-0.2}M_\odot\) (Alcock et al. 1996). It remains to be seen whether future microlensing studies confirm these early reports. A stellar population that forms before galaxies are assembled, would behave as collisionless matter and populate the halos of galaxies like Cold Dark Matter (CDM) particles do.

In this review I will describe the properties of the first stars and quasars and their effect on the ionization history of the Universe. Much of the quantitative details of this sketch can be found in a series of papers that I wrote in collaboration with my student, Zoltan Haiman. The underlying theme of these papers was to calibrate the net fraction of gas that is converted into stars based on the measured C/H ratio in the Ly\(\alpha\) forest. This calibration fixes the reionization history for a given stellar Initial Mass Function (IMF) and a particular CDM cosmology.

2. Properties of the First Star Clusters

The various stages in the reionization history of the Universe are illustrated in Figure 2. This sequence follows the collapse redshift history of baryonic objects shown in Figure 1, which was calculated with a spherically-symmetric code for gas and dark matter (Haiman, Thoul, & Loeb 1996). For objects with baryonic masses \(\gtrsim 3 \times 10^4M_\odot\), gravity dominates and results in the characteristic bottom-up hierarchy of CDM cosmologies. At lower masses, gas pressure delays the collapse and results in a top-down hierarchy, reminiscent of hot dark matter cosmologies. The first objects to collapse are located at the “knee” that separates these regimes. Such objects reach virial temperatures of several hundred degrees and could fragment into stars only through cooling by molecular hydrogen [see Haiman et al. (1996) or Tegmark et al. (1997), for details regarding the chemistry network leading to the formation of H\(_2\) in a primordial gas].

However, H\(_2\) is fragile and could easily be photo-dissociated by photons with energies of 11.2–13.6eV, to which the Universe is transparent even before it gets ionized. Haiman, Rees, & Loeb (1996) showed that a UV flux of \(\lesssim 1\) erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) sr\(^{-1}\) is capable of dissociating H\(_2\) throughout the collapsed environments in the Universe. This flux is lower by \(\gtrsim 2\) orders of magnitude than the minimum flux necessary to ionize the Universe, which amounts to one UV photon per baryon. The inevitable conclusion is that soon after the first stars form, the formation of more stars due to H\(_2\) cooling is suppressed. Further
STAGES OF STELLAR REIONIZATION OF THE UNIVERSE

Figure 2.

Fragmentation is possible only through atomic line cooling, which is effective in objects with high virial temperatures, \( T_{\text{vir}} \gtrsim 10^4 \text{K} \). Such objects correspond to a total mass \( \gtrsim 10^8 M_\odot ([1 + z]/10)^{-3/2} \). Figure 2 illustrates this sequence of events by describing two classes of objects: those with \( T_{\text{vir}} < 10^4 \text{K} \) (small dots) and those with \( T_{\text{vir}} > 10^4 \text{K} \) (large dots). In the first stage (top panel), some low-mass objects collapse, form stars, and create ionized hydrogen (HII) bubbles around them. Once the UV background between 11.2–13.6eV reaches some critical level, \( \text{H}_2 \) is photo-dissociated throughout the Universe and the formation of new stars is delayed until objects with \( T_{\text{vir}} \gtrsim 10^4 \text{K} \) collapse. Each massive source creates an HII region which expands into the intergalactic medium. Initially the volume of the Universe is dominated by neutral hydrogen (HI). But as new sources appear exponentially fast (due to the Gaussian nature of the perturbations), numerous HII bubbles add up, overlap, and transform all the remaining HI into HII over a short period of time. This process resembles a first-order phase transition. Since the characteristic separation between sources is eventually very much smaller than the Hubble distance, the transition completes over a period of time which is much shorter than the Hubble time, and can be regarded as sudden.

Because the potential wells of the first clusters are relatively shallow (\(~10 \text{ km s}^{-1}\)), supernova–driven winds are likely to have expelled the metal–rich gas out of these systems and mixed it with the intergalactic medium. Incomplete mixing could have led to the observed order-of-magnitude scatter in the C/H ratio along lines-of-sight to different quasars (Rauch, Haehnelt, & Steinmetz 1996; Hellsten et al. 1997). It is an interesting coincidence that the supernova energy output associated with a metal enrichment of \(~ 1\% Z_\odot \) corresponds to \(~ 10 \text{ eV} \) per hydrogen atom, which is just above the binding energy of these early star clusters. Supernova feedback in these objects could have therefore dictated
Figure 3. The different panels show: (i) the collapsed fraction of baryons; (ii) the average metallicity of the IGM; (iii) the volume filling factor of ionized hydrogen; (iv) the optical depth to cosmological microlensing; (v) the optical depth to electron scattering; and (vi) the net damping factor for the power-spectrum decomposition of microwave anisotropies as a function of the spherical harmonic index $l$. The different curves show the sensitivity of the results to changes in the normalization $\sigma_{8h^{-1}}$ or the primordial index $n$ of the CDM power-spectrum.

the average metallicity observed in the Ly$\alpha$ forest. Direct observations of these supernovae might be feasible in the future (Miralda-Escudé & Rees 1997).

The measured C/H ratio can be used to calibrate the net fraction of gas that is converted into stars by a redshift $z \approx 3$. For a Scalo (1986) IMF of stars, this corresponds to converting $\sim 3\%$ of all the gas into stars. Haiman & Loeb (1997) have used this fraction and an extension of the Press–Schechter formalism to calculate the early star formation history in a variety of CDM cosmologies. We combined the collapse redshift information in Figure 1 with the Press-Schechter theory and assumed that each object converts a fixed fraction of its gas into stars in a single starburst. We then used the spectral atlases of Kurucz (1993) and the stellar evolutionary tracks of Schaller et al. (1992) to find the emission spectrum of the stars as a function of redshift. The ionizing radiation from each star cluster was absorbed in part by the gas in it (assumed to be distributed as a singular isothermal sphere at the virial temperature) and then propagated into

1There is a remaining uncertainty of whether 3% of the gas in each object formed stars or whether a small fraction of all objects formed stars with a higher efficiency. We assume that supernova feedback limits star formation to a single starburst and sets the efficiency of star formation to 3% in all objects. In the alternative scenario, NGST should see fewer but brighter sources.
Figure 4. **Top panel:** optical depth to absorption and scattering by intergalactic dust at $z \geq 3$, as a function of observed wavelength. The vertical scale is proportional to the mass of dust produced per supernova in units of $0.3M_\odot$. The source is located at redshifts $z_s=10$, 20, or 100. **Bottom panel:** the expected flux with (lower curve) and without (upper curve) intervening dust, from star-clusters at $z_s=10$ and 20, containing $10^7$ $M_\odot$ and $2.4 \times 10^7$ $M_\odot$ in stars. The stars are distributed on the main sequence according to a Scalo IMF. The break in the spectra at the redshifted Lyman limit wavelength includes only the absorption by neutral hydrogen in the stellar atmospheres.

A smooth intergalactic medium (IGM), using the radiative transfer equations in an expanding universe.

For a wide range of models and a Scalo IMF, we have found that the Universe is reionized by a redshift $z = 10–20$, and that the resulting optical depth to electron scattering is $\sim 10\%$ (cf. Fig. 3). This result changes qualitatively only if the IMF is tilted by a power-law index $\geq 1$ relative to the Scalo shape (a bias towards high mass stars is likely due to the lack of cooling by metals and the associated increase in the Jeans mass). The sensitivity to model parameters other than the IMF is only logarithmic because of the exponential dependence of the collapsed baryonic fraction on redshift for Gaussian fluctuations. However, the formation time of CDM halos has a very weak dependence on mass scale at low masses, and it is not obvious whether the Press-Schechter approach is accurate in this limit. Three-dimensional simulations (Gnedin & Ostriker 1997) find reionization somewhat later, at $z \approx 7$, based on a significantly different star formation history than the our semi-analytic approach predicts. Future microwave anisotropy satellites, such as the Microwave Anisotropy Probe (MAP) or the Planck Surveyor, could detect a reionization optical depth as low as 2% or 0.5% respectively after processing their polarization data (Zaldarriaga, Spergel, & Seljak 1997), and will therefore test these predictions.

Deep imaging with future infrared telescopes, such as the Space Infrared Telescope Facility (SIRTF) or the Next Generation Space Telescope (NGST), would be able to image pre-galactic star clusters. For standard CDM with
\( \sigma_{8h^{-1}} = 0.67 \) and a Scalo IMF, Haiman & Loeb (1997) predict that NGST should find \( \gtrsim 10^4 \) star clusters per square arcminute at \( z > 10 \), given its planned detection threshold of 1 nJy in the wavelength range of 1–3.5 \( \mu \)m (Mather & Stockman 1996). The characteristic separation between such sources is a few arcseconds, much larger than their typical size of \( \lesssim 0.1'' \).

The early epoch of star formation and metal enrichment is inevitably accompanied by the formation of dust in Type II supernova shells. This dust has two important observational signatures. First, the absorption of starlight energy and its re-emission at long wavelengths distorts the spectrum of the cosmic microwave background (CMB) radiation (Wright et al. 1994, and references therein). Second, the opacity of the intergalactic medium to infrared sources at redshifts \( z \gtrsim 10 \) could be significant. For these redshifts, infrared in the observer frame corresponds to UV in the source frame—a spectral regime in which dust absorption peaks. Dust obscuration must therefore be considered when predicting the performance of future infrared telescopes such as NGST.

Loeb & Haiman (1997a) find that for a Scalo IMF and a uniform mix of metals and dust with the intergalactic gas, the dust distorts the microwave background spectrum by a \( y \)-parameter in the range \((0.02–2) \times 10^{-5}(M_{\text{SN}}/0.3M_\odot)\), where \( M_{\text{SN}} \) is the average mass of dust produced per supernova. Note that this range is not far below the current COBE limit of \( 1.5 \times 10^{-5} \) (Fixsen et al. 1996). The opacity of intergalactic dust to infrared sources at redshifts \( z \gtrsim 10 \) is significant, \( \tau_{\text{dust}} = (0.1–1) \times (M_{\text{SN}}/0.3M_\odot) \), and could be detected with NGST. Although dust suppresses the Ly\( \alpha \) emission from early sources, the redshifts of star clusters at \( z = 10–35 \) can be easily inferred from the Lyman-limit break in their infrared spectrum between 1–3.5\( \mu \)m (see Fig. 4).

### 3. When Did the MACHOs Form?

As mentioned before, recent microlensing searches (Alcock et al. 1996) suggest that \( \sim 50^{+30}_{-20} \% \) of the mass of the Milky-Way halo might be in the form of Massive Compact Halo Objects (MACHOs) with a mass \( \sim 0.5^{+0.3}_{-0.2} M_\odot \). A substantial MACHO population of dim stars would naturally be linked to the early universe. Pre-galactic stars which originate in abundant low-mass systems are expected to behave as collisionless particles and populate the halos of galaxies, just as elementary CDM particles do. Only stars which are born in massive rare (high-\( \sigma \)) peaks are more likely to end up concentrated in galactic bulges due to the strong dynamical friction which acts on their parent systems. In general, dim stars could constitute the dark matter in galaxy clusters only if \( \Omega_b \sim 0.2 \) and the efficiency of converting gas into these stars is of order 80%.

Recent observations of the star formation history at \( z \lesssim 4 \) might account for most of the luminous stellar population in galaxies today (Madau 1996). However, it is important to remember that this population amounts only to a density parameter \( \Omega_* \sim 6 \times 10^{-3} \) (Woods & Loeb 1997). Therefore, if stellar MACHOs make the dark matter with \( \Omega \sim 0.2 \), then we have not observed yet \( \sim 97\% \) of the star formation history in the Universe.

NGST could easily detect stellar MACHOs during their earlier history when they were still bright due to hydrogen burning. For example, Chabrier et al. (1996) and Adams & Laughlin (1996) have argued that an old population of
white dwarfs could account for the microlensing data and still be consistent with metallicity, star counts, and infrared background constraints, as long as their IMF was highly peaked around $\sim 2M_\odot$. But a $2M_\odot$ star has a lifetime $\sim 1$ Gyr during which it is more than an order of magnitude brighter than the Sun. Even if these stars formed at arbitrarily early times, the age of the Universe is only $\sim 1$ Gyr at $z = 4$. Therefore, the halos of galaxies at $z \approx 4$ should be glowing in the infrared if dim white dwarfs constitute the dark matter in the present universe. Existing Hubble Deep Field observations (Guzmán et al. 1997) already place constraints on the extent of luminous halos around galaxies (Loeb & Pinsonneault 1997). However, optical observations probe the rest-frame UV and do not see the bulk of the stellar population. Infrared observations with NGST would improve dramatically our ability to set constraints on unusual stellar populations in the halos of galaxies.

4. The Next Frontier: Star Formation at High Redshifts

Most of the current theoretical modeling of star formation was developed to explain the complex properties of star forming regions in the interstellar medium (ISM) of our Galaxy. The reason for this bias is obvious: these are the environments for which data exists! The situation resembles a search for a needle in a haystack, just because the haystack happens to be nearby. An alternative strategy is to invest (NASA) money in a long-range mission and search for the needle in simpler environments.

I would like to argue that the formation process of the first generation of stars in the early Universe should be easier to model than that of stars in the local ISM. This follows from the fact that the initial conditions in cosmology are simpler and better-defined: (i) The Universe started from a smooth initial state and a specified spectrum of fluctuations on top of it; many details of this spectrum will be determined by forthcoming microwave anisotropy experiments; (ii) the composition of the gas is well defined by standard Big-Bang nucleosynthesis (Schramm & Turner 1996), and the chemistry and cooling rates are simplified by the lack of heavy elements, dust, or cosmic rays; and (iii) Magnetic fields were probably negligible before stars formed; most cosmological scenarios result in small field amplitudes (Sigl et al. 1997, and references therein).

Due solely to lack of data, theoretical studies of the formation of the first stars are sparse in the literature. Direct imaging and spectroscopy of the first stars by NGST could stimulate theoretical work on the simplest environment for star formation, namely the early Universe. The era of classical cosmology will end if the MAP and Planck satellites determine the basic cosmological parameters to a reasonable accuracy. Since much of observational cosmology relies on starlight, cosmologists might then find it appropriate to shift their attention to the fundamental problem of star formation; and there is no better place to start dealing with it than the early universe.

5. The First Quasars

Extrapolation of the quasar luminosity function (Pei 1995) to redshifts $z \gtrsim 5$ predicts a noticeable tail of faint sources that could be detected with NGST
out to the reionization epoch (Loeb & Haiman 1997b). If these sources are brighter than the first star clusters, it would be easier to measure their absorption spectra and use them to determine the reionization redshift beyond which the Gunn-Peterson effect appears. Bearing in mind that quasars can account for a considerable fraction of the UV background at lower redshifts (Meiksin & Madau 1993), it is quite possible that early low-luminosity quasars were in fact responsible for the reionization of the Universe. Quasars could be more effective than stars in ionizing the Universe because: (i) their emission spectrum is harder; (ii) the radiative efficiency of accretion flows could be more than an order of magnitude higher than that of a star; (iii) quasars are brighter, and for a given recombination rate in their host system, the escape fraction of their ionizing photons is higher than for stars.

First, let us address the black hole formation process. To form a black hole inside a given dark matter halo, the baryons must cool. For most objects, this is possible only due to atomic line cooling (see §2), at virial temperatures, $T_{\text{vir}} \gtrsim 10^4 \text{K}$, and baryonic masses $\gtrsim 10^7 M_{\odot} (1+z)/10^{3/2}$. After losing their thermal pressure, the cold baryons collapse to a thin disk on a dynamical time (Loeb & Rasio 1994). The basic question is then: which fraction of the cold baryons are able to sink to the very center of the potential well and form a massive black hole? The main barrier to this process is angular momentum. The centrifugal force opposes radial infall and keeps the gas in typical disks at a distance which is 6-8 orders of magnitude larger than the Schwarzschild radius of the system. However, Eisenstein & Loeb (1995) have demonstrated that a small fraction of all objects have a sufficiently low angular momentum so that the gas in them inevitably forms a compact semi-relativistic disk that evolves to a black hole on a short viscous time. These low-spin systems are born in special cosmological environments that exert unusually small tidal torques on them during their cosmological collapse. As long as the initial cooling time of the gas is short and its star formation efficiency is low, the gas would form this compact disk on a free-fall time. In typical systems the baryons dominate gravity inside the scale length of the disk. Therefore, if the baryons in a low-spin system acquire a specific angular momentum $j$ which is only a tenth of the typical value, then the size of the resulting disk ($r \propto j^2$) will be smaller by a factor of $\sim 10^2$ than average, and the rotation velocity of the disk will be a factor of $\sim 10$ larger than the velocity dispersion of the dark matter halo. For $T_{\text{vir}} \sim 10^4 \text{K}$, the dark matter halo has a velocity dispersion of $\sim 10 \text{ km s}^{-1}$, and the low-spin disk would have a characteristic rotation velocity of $\sim 100 \text{ km s}^{-1}$ (sufficient to retain the gas against supernova-driven winds), a size $\lesssim \text{pc}$, and a viscous evolution time shorter than the Hubble time. If a low-spin object of this type is embedded inside an overdense region that will eventually become a galactic bulge, the black hole progenitor would eventually sink to the center of the bulge by dynamical friction and seed quasar activity. Based on the phase-space volume accessible to low-spin systems ($\propto j^3$), one would expect a fraction $\sim 10^{-3}$ of all the mass in the Universe to be included in such systems (Eisenstein & Loeb 1995). However, this is a conservative estimate. Additional angular momentum loss due to dynamical friction of gaseous clumps in dark matter halos (Navarro, Frenk, & White 1995) or bar instabilities in self-gravitating disks (Shlosman, Begelman, & Frank 1990) could only make the black hole formation process
more prominent. The popular paradigm that all galaxies harbor black holes at their center (Haehnelt & Rees 1993) simply postulates that in all massive systems, a small fraction of the gas ends up as a black hole, but does not explain quantitatively why this fraction obtains its particular small value.

Observations of galactic nuclei in the local Universe imply black hole masses which are typically a fraction \( \sim 2 \times 10^{-3} \) of the total baryonic mass of their host (see summary of dynamical estimates in Fig. 5 of Kormendy et al. 1997; and the maximum ratio between a quasar luminosity and its host mass found by McLeod 1997). This ratio is somewhat higher in low-mass galaxies, such as the compact ellipticals M32 and NGC 4486B. In particular, van der Marel et al. (1997) infer a black hole mass of \( \sim 3.4 \times 10^6 M_\odot \) in M32, which is a fraction \( \sim 8 \times 10^{-3} \) of the stellar mass of the galaxy, \( \sim 4 \times 10^8 M_\odot \), for the central mass-to-light ratio of \( \gamma_V = 2 \); while Kormendy et al. (1997) infer a black hole mass of \( 6 \times 10^8 M_\odot \) in NGC 4486B which is a fraction \( \sim 9\% \) of the stellar mass.

Figure 1 implies that 2\( \sigma \) peaks with a baryonic mass \( \sim 10^9 M_\odot \) and a velocity dispersion \( \sim 100 \text{ km s}^{-1} \), similar to M32 or NGC 4486B, collapse at \( z \sim 10 \) in standard CDM. With a 3\% star formation efficiency, such objects are \( \sim 10 \text{nJy} \) star clusters for NGST. We assume that each such object forms a black hole with an efficiency\(^2\) of \( 10^{-3} \), i.e. the black hole mass is \( M_{\text{bh}} \sim 10^6 M_\odot \). If the black hole shines at a fraction \( \tilde{L} \) of the Eddington limit with a characteristic quasar spectrum, then its infrared flux at \( z \sim 10 \) would be \( \sim 10 (M_{\text{bh}}/10^6 M_\odot) \tilde{L} \text{nJy} \). Such a flux is comparable to the emission from the host star cluster and would easily be detected with NGST.

Among local galaxies, a fraction \( \sim 1–10\% \) of all galactic nuclei appear highly active (Huchra & Burg 1992; Maiolino & Rieke 1995; Ho, Fillipenko, & Sargent 1997; Köhler et al. 1997). This fraction can be explained in terms of the ratio between the Eddington time and the current Hubble time. A black hole which shines at a luminosity \( \tilde{L} \) in Eddington units would double its mass on a timescale,

\[
t_{\text{Edd}} = \frac{M_{\text{bh}}}{\dot{M}_{\text{bh}}} = 4 \times 10^7 \text{ yr } \frac{\epsilon_{0.1}}{\tilde{L}},
\]

where \( \epsilon_{0.1} \) is the radiative efficiency of the black hole in units of 10\%. Since the black hole mass, \( M_{\text{bh}} \propto \exp\{t/t_{\text{Edd}}\} \), grows exponentially with the Eddington e-folding time, the characteristic lifetime of the quasar activity is several times \( t_{\text{Edd}} \), namely \( \sim 1\% \epsilon_{0.1} \) of the current Hubble time. But notice that for a fixed radiative efficiency, the quasar lifetime is independent of redshift while the Hubble time is shorter at high redshift. For a flat universe, the ratio between \( t_{\text{Edd}} \) and the Hubble time \( H^{-1} \) is, \( \sim 10\% [(1+z)/10]^{3/2} \epsilon_{0.1} \tilde{L}^{-1} \). Therefore several tenths of all star clusters might show nuclear activity at \( z \sim 10 \). Based on

\(^2\)On a given galaxy mass scale, the efficiency of black hole formation could only increase with increasing formation redshift \( z_f \), since the central density of the host galaxy grows as \( \propto (1+z_f)^3 \) while its spin parameter has a negligible dependence on redshift.

\(^3\)Note that although quasars might be brighter than star clusters and supernovae, they are not necessarily the brightest sources in the early Universe. The optical afterglow of \( \gamma \)-ray bursts could reach much higher luminosities in the first month \( \times (1+z) \) of the burst (Groot et al. 1997; Sahu et al. 1997); however, in the local Universe such events are rarer by \( \sim 4 \) orders of magnitude than supernovae.
Figure 5. Summary: the zoo of different objects that populate the high-redshift universe. Listed below each entry are related instruments or observational programs. The Sloan Digital Sky Survey (SDSS; see [http://www.astro.princeton.edu/BBOOK]), will catalog $\sim 10^5$ quasars, an order of magnitude more than the number in current surveys.

these numbers we infer that quasars would dominate the UV background during reionization if the fraction of gas converted to black holes is $\gtrsim 10^{-3} \epsilon_{-1}^{-1}$.

We have suggested that the formation efficiency of black holes in low-mass galaxies at $z \sim 10$ is similar to that found in galaxies in the local Universe. It is however possible that the efficiency of black hole formation is substantially reduced in the shallow potential wells of the early population of sub-galactic halos (Haehnelt & Rees 1993). Observations with NGST will determine whether this is the case or whether quasars indeed pre-dated massive galaxies (Loeb 1995).

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