THE DAWN OF GALAXIES*

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The development of primordial inhomogeneities into the non-linear regime and
the formation of the first astrophysical objects within dark matter halos mark
the transition from a simple, neutral, cooling universe – described by just a few
parameters – to a messy ionized one – the realm of radiative, hydrodynamic, and
star formation processes. The recent measurement by the WMAP satellite of a
large optical depth to electron scattering implies that this transition must have
begun very early, and that the universe was reionized at redshift $z_{\text{ion}} = 17 \pm 5$. It
is an early generation of extremely metal-poor massive stars and/or ‘seed’ accreting
black holes in subgalactic halos that may have generated the ultraviolet radiation
and mechanical energy that reheated and reionized most of the hydrogen in the
cosmos. The detailed thermal, ionization, and chemical enrichment history of the
universe during the crucial formative stages around $z = 10 – 20$ depends on the
power-spectrum of density fluctuations on small scales, the stellar initial mass
function and star formation efficiency, a complex network of poorly understood
‘feedback’ mechanisms, and remains one of the crucial missing links in galaxy
formation and evolution studies.

1. Introduction

The last decade has witnessed great advances in our understanding of the
high redshift universe. The pace of observational cosmology and extra-
galactic astronomy has never been faster, and progress has been equally
significant on the theoretical side. The key idea of currently popular cos-
omological scenarios, that primordial density fluctuations grow by gravita-
tional instability driven by cold, collisionless dark matter (CDM), has
been elaborated upon and explored in detail through large-scale numerical
simulations on supercomputers, leading to a hierarchical (‘bottom-up’) sce-
nario of structure formation. In this model, the first objects to form are on

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subgalactic scales, and merge to make progressively bigger structures (‘hierarchical clustering’). Ordinary matter in the universe follows the dynamics dictated by the dark matter until radiative, hydrodynamic, and star formation processes take over. Perhaps the most remarkable success of this theory has been the prediction of anisotropies in the temperature of the cosmic microwave background (CMB) radiation at about the level subsequently measured by the COBE satellite and most recently by the BOOMERANG, MAXIMA, DASI, CBI, Archeops, and WMAP experiments.

In spite of some significant achievements in our understanding of the formation of cosmic structures, there are still many challenges facing hierarchical clustering theories, and many fundamental questions remain, at best, only partially answered. While quite successful in matching the observed large-scale density distribution (like, e.g., the properties of galaxy clusters, galaxy clustering, and the statistics of the Lyman-α forest), CDM simulations appear to produce halos that are too centrally concentrated compared to the mass distribution inferred from the rotation curves of (dark matter-dominated) dwarf galaxies, and to predict too many dark matter subhalos compared to the number of dwarf satellites observed within the Local Group.\(^{38,53,37,27}\) Another perceived problem (possibly connected with the ‘missing satellites’\(^8\)) is our inability to predict when, how, and to what temperature the universe was reheated and reionized, i.e. to understand the initial conditions of the galaxy formation process. While N-body+hydrodynamical simulations have convincingly shown that the intergalactic medium (IGM) – the main repository of baryons at high redshift – is expected to fragment into structures at early times in CDM cosmogonies, the same simulations are much less able to predict the efficiency with which the first gravitationally collapsed objects lit up the universe at the end of the ‘dark ages’. The crucial processes of star formation, preheating and feedback (e.g. the effect of the heat input from the first generation of sources on later ones), and assembly of massive black holes in the nuclei of galaxies are poorly understood.\(^{30}\) We know that at least some galaxies and quasars were already shining when the universe was less than 10^9 yr old. But when did the first luminous objects form, what was their nature, and what impact did they have on their environment and on the formation of more massive galaxies? While the excess H i absorption measured in the spectra of z \(\sim\) 6 quasars in the Sloan Digital Sky Survey (SDSS) has been interpreted as the signature of the trailing edge of the cosmic reionization epoch\(^{1,17,15}\), the recent detection by the Wilkinson Microwave Anisotropy Probe (WMAP) of a large optical depth to Thomson scatter-
ing, \( \tau_e = 0.17 \pm 0.04 \) suggests that the universe was reionized at higher redshifts, \( z_{\text{ion}} = 17 \pm 5 \).\(^{28,51} \) This is of course an indication of significant star-formation activity at very early times.

In this talk I will summarize some recent developments in our understanding of the dawn of galaxies and the impact that some of the earliest cosmic structure may have had on the baryonic universe.

2. The dark ages

In the era of precision cosmology we know that, at a redshift \( z_{\text{dec}} = 1088 \pm 1 \), exactly \( t_{\text{dec}} = (372 \pm 14) \times 10^3 \) years after the big bang, the universe became optically thin to Thomson scattering\(^{51} \), and entered a ‘dark age’.\(^{42} \) At this epoch the electron fraction dropped below 13% (Figure 1), and the primordial radiation cooled below 3000 K, shifting first into the infrared and then into the radio. We understand the microphysics of the post-recombination universe well. The fractional ionization froze out to the value \( \sim 10^{-4.8} \Omega_M/(h\Omega_b) \): these residual electrons were enough to keep the matter in thermal equilibrium with the radiation via Compton scattering until a thermalization redshift \( z_t \simeq 800(\Omega_b h^2)^{2/5} \simeq 150 \), i.e. well after the universe became transparent.\(^{40} \) Thereafter, the matter temperature decreased as \((1+z)^2\) due to adiabatic expansion (Figure 2) until primordial inhomogeneities in the density field evolved into the non-linear

![Figure 1. Helium and hydrogen recombination for the WMAP parameters \((\Omega_M, \Omega_\Lambda, \Omega_b, h) = (0.29, 0.71, 0.045, 0.7)\).\(^{51} \) The step at earlier times in the left panel is due to the recombination of He \( ^{\text{II}} \) into He \( ^{\text{I}} \). We used the code RECFAST\(^{47} \) to compute the electron fraction.](image-url)
regime. The minimum mass scale for the gravitational aggregation of cold dark matter particles is negligibly small. One of the most popular CDM candidates is the neutralino: in neutralino CDM, collisional damping and free streaming smear out all power of primordial density inhomogeneities only below $\sim 10^{-7} \, M_\odot$. Baryons, however, respond to pressure gradients and do not fall into dark matter clumps below the cosmological Jeans mass (in linear theory this is the minimum mass-scale of a perturbation where gravity overcomes pressure),

$$M_J = \frac{4\pi\bar{\rho}}{3} \left( \frac{5\pi k_B T}{3G\bar{\rho} m_p \mu} \right)^{3/2} \approx 2.5 \times 10^5 \, h^{-1} \, M_\odot (aT/\mu)^{3/2} \Omega_M^{-1/2}. \quad (1)$$

Here $a = (1 + z)^{-1}$ is the scale factor, $\bar{\rho}$ the total mass density including dark matter, $\mu$ the mean molecular weight, and $T$ the gas temperature. The evolution of $M_J$ is shown in Figure 2. In the post-recombination universe, the baryon-electron gas is thermally coupled to the CMB, $T \propto a^{-1}$, and the Jeans mass is independent of redshift and comparable to the mass of globular clusters, $M_J \approx 10^6 \, M_\odot$. For $z < z_t$, the temperature of the baryons drops as $T \propto a^{-2}$, and the Jeans mass decreases with time, $M_J \propto a^{-3/2}$. This trend is reversed by the reheating of the IGM. The energy released by the first collapsed objects drives the Jeans mass up to galaxy scales (Figure 2): previously growing density perturbations decay as their

![Figure 2](image-url)

*Figure 2. Left: Evolution of the radiation (long-dashed line, labeled CMB) and gas (solid line, labeled IGM) temperatures after recombination. The universe is assumed to be reionized by ultraviolet radiation at $z \approx 20$. The short-dashed line is the extrapolated gas temperature in the absence of any reheating mechanism. Right: Cosmological (gas + dark matter) Jeans (solid line) and filtering (dot-dashed line) mass.*
mass drops below the new Jeans mass. In particular, photoionization by the ultraviolet radiation from the first stars and quasars would heat the IGM to temperatures of \( \approx 10^4 \) K (corresponding to a Jeans mass \( M_J \lesssim 10^{10} M_\odot \) at \( z \simeq 20 \)), suppressing gas infall into low mass halos and preventing new (dwarf) galaxies from forming.

3. Linear theory

When the Jeans mass itself varies with time, linear gas fluctuations tend to be smoothed on a (filtering) scale that depends on the full thermal history of the gas instead of the instantaneous value of the sound speed. From linear perturbation analysis, and for a flat universe at high redshift, the growth of density fluctuations in the gas is suppressed for comoving wavenumbers \( k > k_F \), where the filtering scale \( k_F \) is related to the Jeans wavenumber \( k_J \) by

\[
\frac{1}{k_F^2(a)} = \frac{3}{a} \int_0^a \frac{d a'}{k_J^2(a')} [1 - (a'/a)^{1/2}].
\]  

(2)

Here \( k_J \equiv (a/c_s)\sqrt{4\pi G \bar{\rho}} \), and \( c_s \) is the sound speed. This expression for \( k_F \) accounts for an arbitrary thermal evolution of the IGM through \( k_J(a) \). Corresponding to the critical wavenumber \( k_F \) there is a critical (filtering) mass \( M_F \), defined as the mass enclosed in the sphere with comoving radius equal to \( k_F \),

\[
M_F = \frac{(4\pi/3)\bar{\rho}(2\pi a/k_F)^3}{3}.
\]  

(3)

The Jeans mass \( M_J \) is defined analogously in terms of \( k_J \). It is the filtering mass that is central to calculations of the effects of reheating and reionization on galaxy formation. The filtering mass for a toy model with early photoionization is shown in Figure 2: after reheating, the filtering scale is actually smaller than the Jeans scale. Numerical simulations of cosmological reionization confirm that the characteristic suppression mass is typically lower than the linear-theory Jeans mass.

4. The emergence of cosmic structure

As mentioned in the introduction, some shortcomings on galactic and sub-galactic scales of the currently favored model of hierarchical galaxy formation in a universe dominated by CDM have recently appeared. The significance of these discrepancies is still debated, and ‘gastrophysical’ solutions involving feedback mechanisms may offer a possible way out. Other models
have attempted to solve the apparent small-scale problems of CDM at a more fundamental level, i.e. by reducing small-scale power. Although the ‘standard’ ΛCDM model for structure formation assumes a scale-invariant initial power spectrum of density fluctuations, \( P(k) \propto k^n \) with \( n = 1 \), the recent WMAP data favor (but don’t require) a slowly varying spectral index, \( dn/d\ln k = -0.031^{+0.016}_{-0.018} \), i.e. a model in which the spectral index varies as a function of wavenumber \( k \). This running spectral index model predicts a significantly lower amplitude of fluctuations on small scales than standard ΛCDM. The suppression of small-scale power has the advantage of reducing the amount of substructure in galactic halos and makes small halos form later (when the universe was less dense) hence less concentrated, relieving some of the problems of ΛCDM. But it makes early reionization a challenge.

Figure 3 shows the linearly extrapolated (to \( z = 0 \) ) variance of the

![Figure 3](image)

Figure 3. The variance of the matter-density field vs. mass \( M \), for different power spectra. All models assume a ‘concordance’ cosmology with parameters \((\Omega_M, \Omega_X, \Omega_b, h) = (0.29, 0.71, 0.045, 0.7)\). Solid curve: standard ΛCDM with no tilt, cluster normalized. Dotted curve: AWDM with a particle mass \( m_X = 2 \) keV, cluster normalized, no tilt. Dashed curve: tilted WMAP model, WMAP data only. Dash-dotted curve: tilted WMAP model, including 2dFGRS and Lyman-\( \alpha \) data. Dash-triple dotted curve: running spectral index WMAP model, including 2dFGRS and Lyman-\( \alpha \) data. Here \( n \) refers to the spectral index at \( k = 0.05 \) Mpc\(^{-1} \). The horizontal line at the top of the figure shows the value of the extrapolated collapse overdensity \( \delta_c(z) \) at \( z = 20 \).
mass-density field smoothed on a scale of comoving radius $R$,

$$\sigma^2_M = \langle (\delta M/M)^2 \rangle = \frac{1}{2\pi^2} \int_0^\infty dk k^2 P(k) T^2(k) W^2(kR),$$  \hspace{1cm} (4)

for different power spectra. Here $M = H_0^2 \Omega_M R^3/2G$ is the mass inside $R$, $T(k)$ is the transfer function for the matter density field (which accounts for all modifications of the primordial power-law spectrum due to the effects of pressure and dissipative processes), and $W(kR)$ is the Fourier transform of the spherical top-hat window function, $W(x) = (3/x^2)(\sin x/x - \cos x)$. The value of the rms mass fluctuation in a $8\, h^{-1}\text{Mpc}$ sphere, $\sigma_8 \equiv \sigma(z = 0, R = 8\, h^{-1}\text{Mpc})$, has been fixed for the $n = 1$ models to $\sigma_8 = 0.74$, consistent with recent normalization by the $z = 0$ X-ray cluster abundance constraint.$^{43}$

In the CDM paradigm, structure formation proceeds ‘bottom-up’, i.e., the smallest objects collapse first, and subsequently merge together to form larger objects. It then follows that the loss of small-scale power modifies structure formation most severely at the highest redshifts, significantly reducing the number of self-gravitating objects then. This, of course, will make it more difficult to reionize the universe early enough. It has been argued, for example, that one popular modification of the CDM paradigm, warm dark matter (WDM), has so little structure at high redshift that it is unable to explain the WMAP observations of an early epoch of reionization.$^{51,2}$ And yet the WMAP running-index model may suffer

Figure 4. Mass fraction in all collapsed halos above the filtering mass $M_F$ as a function of redshift, for different power spectra. Curves are the same as in Figure 3. **Left panel:** filtering mass $M_F$ has been computed in the absence of reionization. **Right panel:** $M_F$ computed assuming the universe is reionized by ultraviolet radiation at $z \approx 20$. 


from a similar problem. A look at Figure 3 shows that $10^9$ M$_\odot$ halos will collapse at $z = 20$ from 2.9 $\sigma$ fluctuations in a tilted ΛCDM model with $n = 0.99$ and $\sigma_8 = 0.9$, from 4.6 $\sigma$ fluctuations in a running-index model, and from 5.7 $\sigma$ fluctuations in a WDM cosmology. The problem is that scenarios with increasingly rarer halos at early times require even more extreme assumptions (i.e. higher star formation efficiencies and UV photon production rates) in order to be able to reionize the universe by $z \sim 17$ as favored by WMAP. Figure 4 depicts the mass fraction in all collapsed halos with masses above the filtering mass for a case without reionization and one with reionization occurring at $z \sim 20$. At early epochs this quantity appears to vary by orders of magnitude in different models!

5. The epoch of reionization

Since hierarchical clustering theories provide a well-defined framework in which the history of baryonic material can be tracked through cosmic time, probing the reionization epoch may then help constrain competing models for the formation of cosmic structures. Quite apart from uncertainties in the primordial power spectrum on small scales, however, it is the astrophysics of baryons that makes us unable to predict when reionization actually occurred. Consider the following illustrative example:

Hydrogen photoionization requires more than one photon above 13.6 eV per hydrogen atom: of order $t/\bar{t}_{\text{rec}} \sim 10$ (where $\bar{t}_{\text{rec}}$ is the volume-averaged hydrogen recombination timescale) extra photons appear to be needed to keep the gas in overdense regions and filaments ionized against radiative recombinations. A ‘typical’ stellar population produces during its lifetime about 4000 Lyman continuum (ionizing) photons per stellar baryon. A fraction $f \sim 0.25\%$ of cosmic baryons must then condense into stars to supply the requisite ultraviolet flux. This estimate assumes a standard (Salpeter) initial mass function (IMF), which determines the relative abundances of hot, high mass stars versus cold, low mass ones.

The very first generation of stars (‘Population III’) must have formed, however, out of unmagnetized metal-free gas: numerical simulations of the fragmentation of pure H and He molecular clouds have shown that these characteristics likely led to a ‘top-heavy’ IMF biased towards very massive stars (VMSs, i.e. stars a few hundred times more massive than the Sun), quite different from the present-day Galactic case. Metal-free VMSs emit about $10^5$ Lyman continuum photons per stellar baryon, approximately 25 times more than a standard stellar population. A corresponding
smaller fraction of cosmic baryons would have to collapse then into VMSs to reionize the universe, \( f \sim 10^{-4} \). There are of course further complications. Since, at zero metallicity, mass loss through radiatively-driven stellar winds is expected to be negligible\(^{29}\), Population III stars may actually die losing only a small fraction of their mass. If they retain their large mass until death, VMSs with masses \( 100 \lesssim m \lesssim 250 \, M_\odot \) will encounter the electron-positron pair instability and disappear in a giant nuclear-powered explosion\(^{18}\), leaving no compact remnants and polluting the universe with the first heavy elements. In still heavier stars, however, oxygen and silicon burning is unable to drive an explosion, and complete collapse to a black hole will occur instead.\(^5\) Thin disk accretion onto a Schwarzschild black hole releases about \( 50 \, \text{MeV} \) per baryon. The conversion of a trace amount of the total baryonic mass into early black holes, \( f \sim 3 \times 10^{-6} \), would then suffice to reionize the universe.

6. **Preheating and galaxy formation**

Even if the IMF at early times were known, we still would remain uncertain about the fraction of cold gas that gets retained in protogalaxies after the formation of the first stars (this quantity affects the global efficiency of star formation at these epochs) and whether – in addition to ultraviolet radiation – an early input of mechanical energy may also play a role in determining the thermal and ionization state of the IGM on large scales. The same massive stars that emit ultraviolet light also explode as supernovae (SNe), returning most of the metals to the interstellar medium of pregalactic systems and injecting about \( 10^{51} \, \text{ergs} \) per event in kinetic energy. A complex network of feedback mechanisms is likely at work in these systems, as the gas in shallow potential is more easily blown away,\(^{13}\) thereby quenching star formation. Furthermore, as the blastwaves produced by supernova explosions – and possibly also by winds from ‘miniquasars’ – sweep the surrounding intergalactic gas, they may inhibit the formation of nearby low-mass galaxies due to ‘baryonic stripping’\(^{45}\), and drive vast portions of the IGM to a significantly higher temperature than expected from photoionization,\(^{54,31,32,52,10}\) so as to ‘choke off’ the collapse of further galaxy-scale systems. Note that this type of global feedback is fundamentally different from the ‘in situ’ heat deposition commonly adopted in galaxy formation models, in which hot gas is produced by supernovae within the parent galaxy. We refer here to this global early energy input as ‘preheating’.\(^4\) Note that a large scale feedback mechanism may also be
operating in the intracluster medium: studies of X-ray emitting gas in clusters show evidence for some form of non-gravitational entropy input. The energy required there is at a level of $\sim 1\text{ keV}$ per particle, and must be injected either in a more localized fashion or at late epochs in order not to violate observational constraints on the temperature of the Lyman-$\alpha$ forest at $z \sim 3$. The thermal and ionization history of a preheated universe may be very different from one where hydrogen is photoionized. The gas will be heated up to a higher adiabat, and collisions with hot electrons will be the dominant ionization mechanism. The higher energies associated with preheating may doubly ionize helium at high-$z$, well before the ‘quasar epoch’ at $z \sim 3$. Galaxy formation and evolution will also be different, as preheating will drive the filtering mass above $10^{10} - 10^{11}\text{ M}_\odot$ and will tend to flatten the faint-end slope of the present-epoch galaxy luminosity function, in excellent agreement with the data and without the need for SN feedback at late times.

It is interesting to set some general constraints on the early star-formation episode and stellar populations that may be responsible for an early preheating of the IGM at the levels consistent with the temperature of intergalactic gas inferred at $z \approx 3$. Let us characterize the energy input due to preheating by the energy per baryon, $E_p$, deposited in the IGM at redshift $z_p$. We examine a homogenous energy deposition since the filling factor of pregalactic outflows is expected to be large. Let $\Omega_*$ be the mass density of stars formed at $z_p$ in units of the critical density, $E_{\text{SN}}$ the mechanical energy injected per SN event, and $f_w$ the fraction of that energy that is eventually deposited into the IGM. Denoting with $\eta$ the number of SN explosions per mass of stars formed, one can write

$$\frac{\Omega_*}{\Omega_b} = \frac{E_p}{f_w \eta E_{\text{SN}} m_p},$$

where $m_p$ is the proton mass. For a Salpeter IMF between 0.1 and 100 M$_\odot$, the number of Type II SN explosions per mass of stars formed is $\eta = 0.0074$ M$_\odot^{-1}$, assuming all stars above 8 M$_\odot$ result in SNe II. Numerical simulations of the dynamics of SN-driven bubbles from subgalactic halos have shown that up to 40% of the available SN mechanical luminosity can be converted into kinetic energy of the blown away material, $f_w \approx 0.4$, the remainder being radiated away. With $E_{\text{SN}} = 1.2 \times 10^{51}\text{ ergs}$, equation (5) then implies

$$\left(\frac{\Omega_*}{\Omega_b}\right)_{\text{sp}} = 0.05 \left(\frac{E_p}{0.1\text{ keV}}\right).$$
SN-driven pregalactic outflows efficiently carry metals into intergalactic space. For a normal IMF, the total amount of metals expelled in winds and final ejecta (in SNe or planetary nebulae) is about 1% of the input mass. Assuming a large fraction, \( f_Z = 0.5 \), of the metal-rich SN ejecta escape the shallow potential wells of subgalactic systems, the star-formation episode responsible for early preheating will enrich the IGM to a mean level

\[
\langle Z \rangle_{sp} = \frac{0.01 \Omega_* f_Z}{\Omega_b} = 0.014 Z_\odot \left( E_p/0.1 \text{ keV} \right).
\]

The weak C IV absorption lines observed in the Lyman-\( \alpha \) forest at \( z = 3 - 3.5 \) imply a minimum universal metallicity relative to solar in the range \([-3.2]\) to \([-2.5]\). Preheating energies in excess of 0.1 keV appear then to require values of \( \Omega_* \) and \( \langle Z \rangle \) that are too high, comparable to the total mass fraction in stars seen today and in excess of the enrichment of the IGM inferred at intermediate redshifts, respectively.

The astrophysics of first light may not be as simple, however. The metal constraint assumes that metals escaping from protogalaxies are evenly mixed into the IGM and the Lyman-\( \alpha \) clouds. Inefficient mixing could instead produce a large variance in intergalactic metallicities. The metal abundances of the Lyman-\( \alpha \)-clouds may underestimate the average metallicity of the IGM if there existed a significant warm-hot gas phase component with a higher level of enrichment, as detected for example in O VI. Today, the metallicity of the IGM may be closer to \( \sim 1/3 \) of solar if the metal productivity of galaxies within clusters is to be taken as representative of the universe as a whole. Uncertainties in the early IMF make other preheating scenarios possible and perhaps even more likely. Population III stars with main-sequence masses of approximately 140 – 260 M\( \odot \) will encounter the electron-positron pair instability and be completely disrupted by a giant nuclear-powered explosion. A fiducial 200 M\( \odot \) Population III star will explode with a kinetic energy at infinity of \( E_{SN} = 4 \times 10^{52} \) ergs, injecting about 90 M\( \odot \) of metals. For a very ‘top-heavy’ IMF with \( \eta = 0.005 M_{\odot}^{-1} \), equation (5) now yields

\[
\left( \frac{\Omega_*}{\Omega_b} \right)_{III} = 0.001 \left( E_p/0.1 \text{ keV} \right),
\]

and a mean IGM metallicity

\[
\langle Z \rangle_{III} = \frac{0.45 \Omega_* f_Z}{\Omega_b} = 0.02 Z_\odot \left( E_p/0.1 \text{ keV} \right)
\]

(in both expressions above we have assumed \( f_w = f_Z = 1 \)). This scenario can yield large preheating energies by converting only a small fraction of
the comic baryons into Population III stars, but tends to produce too many 
metals for $E_p \gtrsim 0.1 \text{keV}$. The metallicity constraint, of course, does not 
bound preheating from winds produced by an early, numerous population 
of faint ‘miniquasars’.\textsuperscript{a} Accretion onto black holes releases 50 MeV per 
baryon, and if a fraction $f_w$ of this energy is used to drive an outflow and is 
ultimately deposited into the IGM, the accretion of a trace amount of 
the total baryonic mass onto early black holes,

\[
\frac{\Omega_{\text{BH}}}{\Omega_b} = \frac{E_p}{f_w 50 \text{MeV}} = 2 \times 10^{-6} f_w^{-1} (E_p/0.1 \text{keV}),
\]  

(10)

may then suffice to preheat the whole universe. Note that this value is about 
50 $f_w$ times smaller than the density parameter of the supermassive variety 
found today in the nuclei of most nearby galaxies, $\Omega_{\text{SMBH}} \approx 2 \times 10^{-6} h^{-1}$.\textsuperscript{35}

7. Conclusions

The above discussion should make it clear that, despite much recent 
progress in our understanding of the formation of early cosmic structure 
and the high-redshift universe, the astrophysics of first light remains one 
of the missing links in galaxy formation and evolution studies. We are 
left very uncertain about the whole era from $10^8$ to $10^9$ yr – the epoch 
of the first galaxies, stars, supernovae, and massive black holes. Some of 
the issues discussed above are likely to remain a topic of lively controversy 
until the launch of the James Webb Space Telescope (JWST), ideally suited 
to image the earliest generation of stars in the universe. If the first massive 
black holes form in pregalactic systems at very high redshifts, they 
will be incorporated through a series of mergers into larger and larger halos, 
sink to the center owing to dynamical friction, accrete a fraction of 
the gas in the merger remnant to become supermassive, and form binary 
systems.\textsuperscript{55} Their coalescence would be signalled by the emission of low-
frequency gravitational waves detectable by the planned Laser Interferometer Space Antenna (LISA). An alternative way to probe the end of the dark 
ages and discriminate between different reionization histories is through 21 cm tomography.\textsuperscript{34} Prior to the epoch of full reionization, 21 cm spectral features 
will display angular structure as well as structure in redshift space due

\textsuperscript{a}Because the number density of bright quasi-stellar objects at $z > 3$ is low\textsuperscript{16}, the thermal 
and kinetic energy they expel into intergalactic space must be very large to have a global 
effect, i.e., for their blastwaves to fill and preheat the universe as a whole. The energy 
density needed for rare, luminous quasars to shock-heat the entire IGM would in this 
case violate the COBE limit on $y$-distortion.\textsuperscript{54}
to inhomogeneities in the gas density field, hydrogen ionized fraction, and spin temperature. Radio maps will show a patchwork (both in angle and in frequency) of emission signals from H I zones modulated by H II regions where no signal is detectable against the CMB. The search at 21 cm for the epoch of first light has become one of the main science drivers of the \textit{LOw Frequency Array (LOFAR)}. While remaining an extremely challenging project due to foreground contamination from unresolved extragalactic radio sources and free-free emission from the same halos that reionize the universe, the detection and imaging of large-scale structure prior to reionization breakthrough remains a tantalizing possibility within range of the next generation of radio arrays.

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