Probing the End of the Dark Ages

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Abstract. In currently popular cosmological scenarios – all variants of the cold dark matter (CDM) cosmogony – some time beyond a redshift of 15, stars within the numerous small halos that condense with virial temperatures \( \sim 10^4 \) K created the first heavy elements; these protogalactic systems, together perhaps with an early population of mini-quasars, generated the ultraviolet radiation and mechanical energy that reheated and reionized the cosmos. The history of the Universe during and soon after these crucial formative stages is recorded in the thermal, ionization, and chemical state of the all-pervading intergalactic medium (IGM), which contains most of the ordinary baryonic material left over from the big bang. Throughout the epoch of structure formation, the IGM becomes clumpy under the influence of gravity, and acts as a source for the gas that gets accreted, cools, and forms stars within subgalactic fragments, and as a sink for the metal enriched material, energy, and radiation which they eject.

1. Introduction

At epochs corresponding to \( z \sim 1000 \) the intergalactic medium is expected to recombine and remain neutral until sources of radiation and heat develop that are capable of reionizing it. The detection of transmitted flux shortward of the \( \text{Ly}_\alpha \) wavelength in the spectra of sources at \( z \sim 6 \) implies that the hydrogen component of this IGM was ionized at even higher redshifts. It appears then that substantial sources of ultraviolet photons and mechanical energy were already present when the Universe was less than 6% of its current age, perhaps quasars and/or young star-forming galaxies: an episode of pregalactic star formation may provide a possible explanation for the widespread existence of heavy elements (like carbon, oxygen, and silicon) in the IGM, while the integrated radiation emitted from quasars is likely responsible for the reionization of intergalactic helium at later times.

Popular cosmological models predict that some time beyond a redshift of 15 the gas within halos with virial temperatures \( T_v \gtrsim 10^4 \) K [or, equivalently, with masses \( M \gtrsim 10^9 (1 + z)^{-3/2} h^{-1} \) M$_\odot$ comparable to present-day dwarf ellipticals] cooled rapidly due to the excitation of hydrogen Ly\( \alpha \) by the Maxwellian tail of the electron distribution, and fragmented. Massive stars formed with some initial mass function (IMF), synthesized heavy elements, and exploded as Type II supernovae (SNe) after a few \( \times 10^7 \) yr, enriching and heating the surrounding
medium. Whilst collisional excitation of molecular hydrogen may have allowed the gas in even smaller systems [virial temperatures of only a few hundred K, corresponding to masses around \(10^7 \times (1 + z)^{-3/2} M_\odot\)] to cool and form stars at earlier times (Abel, Ciardi, and Ferrara, this volume), \(H_2\) molecules are efficiently photo-dissociated by stellar UV radiation, and such negative ‘feedback’ is likely to have suppressed molecular cooling and further star formation inside very small halos. One should note that while numerical N-body+hydrodynamical simulations have convincingly shown that the IGM is expected to fragment into structures at early times in CDM cosmogonies (e.g. Cen et al. 1994; Zhang et al. 1995), 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 age’.

2. ‘Minihalos’, Metal Enrichment, and Reionization

The reionization scenario that has been the subject of the most theoretical study is one in which intergalactic hydrogen is photoionized by the UV radiation emitted either by quasars or by stars with masses \(\gtrsim 10 M_\odot\), rather than ionized by collisions with electrons heated up by, e.g., supernova-driven winds from early pregalactic objects. In the former case a high degree of ionization requires about \(13.6 \times (1 + t/t_{\text{rec}})\) eV per hydrogen atom, where \(t_{\text{rec}}\) is the volume-averaged hydrogen recombination timescale, the ratio \(t/t_{\text{rec}}\) being much greater than unity already at \(z \sim 10\) (Haiman and Gnedin, this volume). Collisional ionization to a neutral fraction of only few parts in \(10^5\) requires a comparable energy input, i.e. an IGM temperature close to \(10^5\) K or about 25 eV per atom.

Massive stars will deposit both radiative and mechanical energy into the interstellar medium of subgalactic fragments. A complex network of ‘feedback’ mechanisms is likely at work in these systems, as the gas in shallow potential is more easily blown away thereby quenching further star formation, and the blastwaves produced by supernova explosions reheat the surrounding intergalactic gas and enrich it with newly formed heavy elements and dust. It is therefore unclear at this stage whether an early input of mechanical energy will actually play a major role in determining the thermal and ionization state of the IGM on large scales (Tegmark et al. 1993). What can be easily shown is that, during the evolution of a a ‘typical’ stellar population, more energy is lost in ultraviolet radiation than in mechanical form. This is because in nuclear burning from zero to solar metallicity \((Z_\odot = 0.02)\), the energy radiated per baryon is \(0.02 \times 0.007 \times m_{\text{H}} c^2\); about one third of it goes into H-ionizing photons. The same massive stars that dominate the UV light also explode as SNe, returning most of the metals to the interstellar medium and injecting about \(10^{51}\) ergs per event in kinetic energy. For a Salpeter IMF, one has about one SN every \(150 M_\odot\) of baryons that forms stars. The mass fraction in mechanical energy is then approximately \(4 \times 10^{-6}\), ten times lower than the fraction released in photons above 1 ryd.

The relative importance of photoionization versus shock ionization will depend, however, on the efficiency with which radiation and mechanical energy actually escape into the IGM. Consider, in particular, the case of an early generation of halos with circular speed \(v_c = 25 \text{ km s}^{-1}\), corresponding in top-hat
spherical collapse to a virial temperature \( T_v = 0.5\mu m_p v^2_c/k \approx 10^{4.3} \text{K} \) and halo mass \( M = 0.1v^3_c/GH \approx 10^8[(1+z)/10]^{-3/2}h^{-1}M_\odot \). In these systems rapid cooling by atomic hydrogen can take place and a significant fraction, \( f\Omega_B \), of their total mass may be converted into stars over a dynamical timescale (here \( \Omega_B \) is the baryon density parameter). In a flat cosmology with \( \Omega_M = 1 \), \( h = 0.5 \), and rms mass fluctuation normalized at present to \( \sigma_8 = 0.63 \) on spheres of \( 8h^{-1}\text{Mpc} \), halos with \( M = 10^8h^{-1}M_\odot \) would be collapsing at \( z = 9 \) from \( 2\sigma \) fluctuations. At this epoch more massive halos with \( M = 10^{10}h^{-1}M_\odot \), while able to cool rapidly, would be collapsing from \( 3\sigma \) peaks and be too rare to produce significant amounts of heavy elements and UV radiation (in a gaussian theory the \( 3\sigma \) peaks contain only 5% as much mass as the \( 2\sigma \) peaks at a given epoch), unless they were able somehow to form stars more efficiently than lower-mass objects. Halos from \( 1\sigma \) fluctuations would be more numerous and contain most of the mass, but with virial temperatures of only a few hundred degrees they would most likely be unable to cool via \( \text{H}_2 \) before reionization actually occurs at \( z = z_{\text{rei}} \).

For \( f = 0.1 \), \( \Omega_B h^2 = 0.019 \), and \( h = 0.5 \), the explosive output of 10,000 SNe would inject a total energy \( E_0 \approx 10^{55} \text{ergs} \). Correlated multi-SN explosions will create large holes in the ISM of these pregalactic halos, perhaps enlarging by far pre-existing ones due to winds from their progenitors stars. The energy from SNe will impart enough momentum to the interstellar medium that large portions of it will become unbound and leave the parent halo, taking the metal-enriched stellar debris along (MacLow & Ferrara 1999). A large fraction – perhaps as much as 90% – of the energy injected in these SN-driven bubbles could be lost to radiation in the halo before the bubbles expand out into the surrounding IGM (Madau et al. 2000). Eventually the hot gas will escape its host, shock the IGM, and form a cosmological blast wave. If the explosion occurs at cosmic time \( t = 4 \times 10^8 \text{yr} \) (corresponding in the adopted cosmology to \( z = 9 \)), at time \( \Delta t = 0.2t \) after the event we can use the standard Sedov-Taylor self-similar (adiabatic) solution to give a rough estimate of the proper radius of the shock,

\[
R_s \approx \left[ \frac{12\pi G(0.1E_0)}{\Omega_B} \right]^{1/5} t^{2/5} \Delta t^{2/5} \approx 10\text{kpc}. \tag{1}
\]

At this instant the shock velocity relative to the Hubble flow is

\[
v_s \approx 2R_s/5\Delta t \approx 50 \text{ km s}^{-1}, \tag{2}
\]

down the escape velocity from the halo. The gas temperature just behind the shock front is \( T_s = 3\mu m_p v^2_s/16k \approx 10^5 \text{K} \), more than enough to efficiently ionize all the incoming hydrogen. At these redshifts, it is the onset of Compton cooling off cosmic microwave background photons that ends the adiabatic stage of blast wave propagation. According to the Press-Schechter formalism, the comoving abundance of collapsed halos with mass \( M = 10^8h^{-1}M_\odot \) at \( z = 9 \) is \( dn/d\ln M \sim 30h^3 \text{Mpc}^{-3} \), corresponding to a mean proper distance between neighboring halos of \( \sim 20h^{-1} \text{kpc} \), and to a total mass density parameter of order 0.01. With the assumed star formation efficiency only a small fraction, about one percent, of the stars seen today would form at these early epochs. Still, our simplistic analysis (see Madau et al. 2000 for a more detailed treatment) conveys
the interesting idea that the blast waves from such a population of pregalactic objects may actually fill a significant fraction of the Hubble volume, and drive the intergalactic medium at early epochs to a higher adiabat, \( T \sim 10^5 \) K, than expected from photoionization, so as to inhibit the formation of further protogalaxies by raising the Jeans mass. This effect could perhaps be responsible for providing a global negative feedback to self-regulate the early stellar birthrate, effectively causing a pause in the cosmic history of star formation. After this epoch of pregalactic outflows, the IGM would be polluted to a mean metallicity \( \langle Z \rangle = \Omega_Z/\Omega_b \sim 0.001 Z_\odot \) (Madau et al. 2000). A lower density of sources – which would therefore have to originate from higher amplitude peaks – would suffice if the typical efficiency of star formation were larger than assumed here.

3. Cosmological H II regions

In this section we will focus our attention to the photoionization of the IGM, i.e. we will assume that UV photons from an early generation of stars and/or quasars are the main source of energy for the reionization and reheating of the Universe, and that star formation and quasar activity occurs in collapsed galaxy halos. The process then begins as individual sources start to generate expanding H II regions in the surrounding IGM; throughout an H II region, H is ionized and He is either singly or doubly ionized. As more and more sources of ultraviolet radiation switch on, the ionized volume grows in size while the neutral phase shrinks. Reionization is completed when the H II regions overlap, and every point in the intergalactic space gets exposed for the first time to a nearly uniform Lyman-continuum (Lyc) background.

In the presence of a population of ionizing sources, the transition from a neutral IGM to one that is almost fully ionized can be statistically described by the evolution with redshift of the volume filling factor (or porosity) \( Q \) of H II, He II, and He III regions. The radiation emitted by spatially clustered stellar-like and quasar-like sources – the number densities and luminosities of which may change rapidly as a function of redshift – coupled with absorption processes in a medium that becomes more and more clumpy owing to the non-linear collapse of structures (Figure 1), all determine the complex topology of neutral and ionized zones in the Universe (Gnedin, this volume; Ciardi et al. 2000; Abel et al. 1999). When \( Q \ll 1 \) and the radiation sources are randomly distributed, the ionized regions are spatially isolated, every UV photon is absorbed somewhere in the IGM, and the UV radiation field is highly inhomogeneous. As \( Q \) grows, the crossing of ionization fronts becomes more and more common, until percolation occurs at \( Q = 1 \).

Since the mean free path of Lyc radiation is always much smaller than the horizon (this is also true after ‘overlapping’ because of the residual H I still present in the Ly\( \alpha \) forest clouds and the Lyman-limit systems), the filling factor of cosmological H II regions is equal at any given time \( t \) to the total number of ionizing photons emitted per hydrogen atom by all radiation sources present at earlier epochs, \( \int_0^t \dot{n}_{\text{ion}} dt'/\bar{n}_H \), minus the total number of radiative recombinations per atom, \( \int_0^t Q dt'/\bar{\tau}_{\text{rec}} \). This statement reflects the simple fact that every ultraviolet photon that is emitted is either absorbed by a newly ionized hydrogen
atom or by a recombining one. Differentiating one gets

\[
\frac{dQ}{dt} = \frac{\dot{n}_{\text{ion}}}{\bar{n}_H} - \frac{Q}{t_{\text{rec}}}.
\] (3)

It is this differential equation – and its equivalent for expanding helium zones – that statistically describes the transition from a neutral Universe to a fully ionized one (Madau et al. 1999). Initially, when the filling factor is \(\ll 1\), recombinations can be neglected and the ionized volume increases at a rate fixed solely by the ratio \(\dot{n}_{\text{ion}}/\bar{n}_H\). As time goes on and more and more Lyc photons are emitted, radiative recombinations become important and slow down the growth of the ionized volume, until \(Q\) reaches unity, the recombination term saturates, and reionization is finally completed (except for the high density regions far from any source which are only gradually eaten away, Miralda-Escudé, Haehnelt, & Rees 2000). In the limit of a fast recombining IGM (\(t_{\text{rec}} \ll t\)), one can neglect the derivative on the left-hand side of equation (3) and derive

\[
Q \lesssim \frac{\dot{n}_{\text{ion}}t_{\text{rec}}}{\bar{n}_H},
\] (4)

i.e. the volume filling factor of ionized bubbles must be less (or equal) to the number of Lyc photons emitted per hydrogen atom in one recombination time. In other words, because of radiative recombinations, only a fraction \(t_{\text{rec}}/t \ll 1\) of the photons emitted above 1 ryd is actually used to ionize new IGM material. The Universe is completely reionized when

\[
\dot{n}_{\text{ion}}t_{\text{rec}} \gg \bar{n}_H,
\] (5)

i.e. when the emission rate of ultraviolet photons exceeds the mean rate of recombinations.
4. A clumpy Universe

The simplest way to treat reionization in an inhomogeneous medium is in terms of a clumping factor that increases the effective gas recombination rate. In this case the volume-averaged recombination time is

$$\tau_{\text{rec}} = [(1 + 2\chi)n_p\alpha_B C]^{-1} = 0.06 \text{ Gyr} \left(\frac{\Omega_B h^2}{0.019}\right)^{-1} \left(\frac{1 + z}{10}\right)^{-3} \frac{n_H}{n_p} C_{10}^{-1},$$

where $\alpha_B$ is the recombination coefficient to the excited states of hydrogen (at an assumed gas temperature of $10^4$ K), $\chi$ the helium to hydrogen abundance ratio, and the factor $C \equiv \langle n_p^2 \rangle/n_p^2 > 1$ takes into account the degree of clumpiness of photoionized regions (hereafter $C_{10} \equiv C/10$). If ionized gas with density $n_p$ filled uniformly a fraction $1/C$ of the available volume, the rest being empty space, the mean square density would be $\langle n_p^2 \rangle = n_p^2/C = \langle n_p^2 \rangle C$. More in general, if $f_m$ is the fraction of baryonic mass in photoionized gas at an overdensity $\delta$ relative to the mean, and the remaining (underdense) medium is distributed uniformly, then the fractional volume occupied by the denser component is

$$f_v = f_m/\delta,$$

the density of the diffuse component is

$$\frac{n_p}{1 - f_m},$$

and the recombination rate is larger than that of a homogeneous Universe by the factor

$$C = f_m\delta + \frac{(1 - f_m)^2}{1 - f_v}.$$

It is difficult to estimate the clumping factor accurately. According to hydrodynamics simulations of structure formation in the IGM (within the framework of CDM-dominated cosmologies), Lyα forest clouds with moderate overdensities, $5 \lesssim \delta \lesssim 10$, occupy a fraction of the available volume which is too small for them to dominate the clumping at high redshifts (e.g. Theuns et al. 1998). In hierarchical clustering models, it is the virialized gas with $\delta \approx 200$ in the earliest non-linear objects with $T_J \leq T_v \leq 10^4$ K (here $T_J$ is the virial temperature corresponding to the cosmological Jeans mass) which will boost the recombination rate by large factors as soon as the collapsed mass fraction exceeds $\sim 0.5\%$ (Haiman, this volume). The importance of photoevaporating minihalos as sinks of ionizing photons during cosmological reionization has been recently discussed by Haiman et al. (2000). Note that such minihalos are not yet resolved in large-scale three-dimensional cosmological simulations. Halos or halo cores which are dense and thick enough to be self-shielded from UV radiation will stay neutral and will not contribute to the recombination rate. This is also true of gas in more massive halos, which will be virialized to higher temperatures and ionized by collisions with thermal electrons.
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Figure 2. The red damping wing of the Gunn-Peterson trough for a source at $z_{\text{em}} = 7$. The transmission is plotted as a function of the fractional wavelength interval from the Ly$\alpha$ resonance at $\lambda_{\alpha}(1 + z_{\text{em}})$. The neutral IGM is assumed to be completely reionized by $z_{\text{rei}} = 6$. **Solid curve:** absorption profile neglecting the effect of the local H$\text{II}$ region around the source. Note how a fraction $> \exp(-0.5) = 0.6$ of the radiated flux will only be transmitted $> 1200$ km s$^{-1}$ (corresponding to $> 40$ A) to the red of the resonance. **Dashed curves:** absorption profiles including the local H$\text{II}$ zone generated by a QSO shining for 10$^7$ yr. From top to bottom, the curves are plotted for four decreasing ionizing photon luminosities, $\dot{N}_i = 10^{58}$, $10^{57}$, $10^{56}$, and $10^{55}$ s$^{-1}$ (Einstein-de Sitter Universe with $h = 0.5$ and $\Omega_B h^2 = 0.019$).

5. The Earliest Luminous Sources and the Damping Wing of the Gunn-Peterson Trough

Prior to complete reionization, sources of ultraviolet radiation will be seen behind a large column of intervening gas that is still neutral. In this case, because of scattering off the line-of-sight due to the diffuse neutral IGM, the spectrum of a source at $z_{\text{em}} > z_{\text{rei}}$ should show the red damping wing of the Gunn-Peterson absorption trough at wavelengths longer than the local Ly$\alpha$ resonance, $\lambda_{\text{obs}} > \lambda_{\alpha}(1 + z_{\text{em}})$, where $\lambda_{\alpha} = c/\nu_{\alpha} = 1216$ A. At $z > 6$, this characteristic feature extends for more than 1500 km s$^{-1}$ to the red of the resonance, and may significantly suppress the Ly$\alpha$ emission line in the spectra of the first generation of objects in the Universe. Measuring the shape of the absorption profile of the damping wing could provide a determination of the density of the neutral IGM near the source (Miralda-Escudé 1998).

Cen & Haiman (2000) and Madau & Rees (2000) have recently focused on the width of the red damping wing – related to the expected strength of the Ly$\alpha$ emission line – in the spectra of very distant QSOs as a flag of the observation of the IGM before reionization. They have assessed, in particular, the impact of the photoionized, Mpc-size regions which will surround individual luminous sources of Lyc radiation on the transmission of photons redward of the
Lyα resonance, and shown that the damping wing of the Gunn-Peterson trough may nearly completely disappear because of the lack of neutral hydrogen in the vicinity of a bright QSO. If the quasar lifetime is shorter than the expansion and gas recombination timescales, the volume ionized will be proportional to the total number of photons produced above 13.6 eV: the effect of this local photoionization is to greatly reduce the scattering opacity between the redshift of the quasar and the boundary of its H II region. The transmission on the red side of the Lyα resonance is always greater than 50% for sources radiating a total of $\gtrsim 10^{69.5}$ ionizing photons into the IGM (Figure 2). The detection of a strong Lyα emission line in the spectra of bright QSOs shining for $\gtrsim 10^7$ yr cannot then be used, by itself, as a constraint on the reionization epoch. The first signs of an object radiating prior to the transition from a neutral to an ionized Universe may be best searched for in the spectra of luminous sources with a small escape fraction of Lyman-continuum photons into the IGM, or sources with a short duty cycle.

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