Intergalactic Medium

About half a million years after the big bang, the ever-fading cosmic blackbody radiation cooled below 3000 K and shifted first into the infrared and then into the radio, and the smooth baryonic plasma that filled the universe became neutral. The universe then entered a ‘dark age’ which persisted until the first cosmic structures collapsed into gravitationally bound systems and evolved into stars, galaxies and black holes that lit up the universe again. Some time between redshifts of 7 and 15, stars within protogalaxies created the first heavy elements; these systems, together perhaps with an early population of quasars, generated the ultraviolet radiation that reheated and reionized the cosmos. The history of the universe during and soon after these crucial formative stages is recorded in the all-pervading intergalactic medium (IGM), which is believed to contain most of the ordinary baryonic material left over from the big bang. Throughout the epoch of structure formation, the IGM became clumpy and acquired peculiar motions under the influence of gravity and acted as a source for the gas that becomes accreted, cools and forms stars within galaxies and as a sink for the metal-enriched material, energy and radiation which they eject. Observations of absorption lines in quasar spectra at redshifts up to 5 provide invaluable insight into the chemical composition of the IGM and the primordial density fluctuation spectrum of some of the earliest formed cosmological structures, as well as of the ultraviolet background radiation that ionizes them.

Cosmological reionization

At epochs corresponding to z=1000, the IGM is expected to recombine to remain neutral until sources of radiation develop that are capable of reionizing it. The detection of transmitted flux shortward of the Lyα wavelength in the spectra of sources at z=5 implies that the hydrogen component of this IGM was ionized at even higher redshifts. There is some evidence that the double reionization of helium may have occurred later, but this is still controversial. It appears then that substantial sources of ultraviolet photons were already present when the universe was less than 7% 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 (such as carbon, oxygen and silicon) in the IGM, while the integrated radiation emitted from quasars is probably responsible for the reionization of intergalactic helium. Establishing the epoch of reionization and reheating is crucial for determining its impact on several key cosmological issues, from the role reionization plays in allowing protogalactic objects to cool and make stars to determining the small-scale structure in the temperature fluctuations of the cosmic background radiation. Conversely, probing the reionization epoch may provide a means for constraining competing models for the formation of cosmic structures and for detecting the onset of the first generation of stars, galaxies and black holes in the universe.

Intergalactic hydrogen density

The proper mean density of hydrogen nuclei at redshift z may be expressed in standard cosmological terms as

\[
\bar{n}_H = \left( \frac{\rho_{\mathrm{crit}}}{m_\text{H}} \right) (1 - Y) \Omega_b (1 + z)^3
= (1.1 \times 10^{-5} \, \text{cm}^{-3}) (1 - Y) \Omega_b h^2 (1 + z)^3
\]

where \(Y\) is the primordial He abundance by mass, \(\rho_{\mathrm{crit}} = 3H_0^2/8\pi G\) is the critical density, \(\Omega_b = \rho_b/\rho_{\mathrm{crit}}\) is the current baryonic density parameter and \(H_0 = 100h\) km s\(^{-1}\) Mpc\(^{-1}\) is the present-day Hubble constant. Standard nucleosynthesis models together with recent observations of deuterium yield \(Y = 0.247 \pm 0.02\) and \(\Omega_b h^2 = 0.0193 \pm 0.0014\). Thus,

\[
\bar{n}_H = (1.6 \times 10^{-5} \, \text{cm}^{-3}) \frac{\Omega_b h^2}{0.019} (1 + z)^3.
\]

As some of the baryons had already collapsed into galaxies at \(z=2-5\), the value of \(\Omega_b h^2=0.019\) should strictly be considered as an upper limit to the intergalactic density parameter.

Because of the overwhelming abundance of hydrogen, the ionization of this element is of great importance for determining the physical state of the IGM. Popular cosmological models predict that most of the intergalactic hydrogen was reionized by the first generation of stars or quasars at \(z=7-15\). The case that has received the most theoretical studies is one where hydrogen is ionized by the absorption of photons, \(H+\gamma\rightarrow p+e\) (as opposite to collisional ionization \(H+e\rightarrow p+e+e\)) shortward of 912 Å; that is, with energies exceeding 13.6 eV, the energy of the Lyman edge. The process of reionization began as individual sources started 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 switched on, the ionized volume grew in size. The reionization ended when the cosmological H II regions overlapped and filled the intergalactic space.

Photoionization equilibrium

At every point in an optically thin, pure hydrogen medium of neutral density \(n_{\mathrm{HI}}\), the photoionization rate per unit volume is

\[
\dot{n}_{\mathrm{HI}} \int_{\nu_\text{L}}^\infty 4\pi f_\nu \sigma_{\mathrm{e}}(\nu) \frac{\nu}{h\nu^2} \, d\nu
\]

where \(f_\nu\) is the mean intensity of the ionizing radiation (in energy units per unit area, time, solid angle and...
frequency interval) and $h_p$ is the Planck constant. The photoionization cross-section for hydrogen in the ground state by photons with energy $h_p \nu$ (above the threshold $h_p \nu_{\text{th}} = 13.6$ eV) can be usefully approximated by

$$\sigma_\text{H}(\nu) = \sigma_\text{H}(\nu/\nu_{\text{th}})^{-1} \quad \sigma_\text{H} = 6.3 \times 10^{-11} \text{ cm}^2.$$

At equilibrium, this is balanced by the rate of radiative recombinations $p+e \to H+\gamma$ per unit volume,

$$n_e n_p \sigma_\text{H}(T),$$
where $n_e$ and $n_p$ are the number densities of electrons and protons and $\sigma_\text{H} = \sum \sigma_\text{H}(\nu, \nu')$ is the radiative recombination coefficient, i.e. the product of the electron capture cross-section $\sigma_\text{H}$ and the electron velocity $v_e$, averaged over a thermal distribution and summed over all atomic levels $n$. At the commonly encountered gas temperature of $10^4$ K, $\alpha_\text{H} = 4.2 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$.

Consider, as an illustrative example, a point in an intergalactic H II region at (say) $z=6$, with density $n_\text{HII} = 1.6 \times 10^{-7} \text{ cm}^{-3}(1+2)^3 = 5.5 \times 10^{-5} \text{ cm}^{-3}$. The H II region surrounds a putative quasar with specific luminosity $L_\nu = 10^{30} (\nu_\lambda/\nu)^2 \text{ erg s}^{-1} \text{ Hz}^{-1}$, and the point in question is at a distance of $r=3 \text{ Mpc}$ from the quasar. To a first approximation, the mean intensity is simply the radiation emitted by the quasar reduced by geometrical dilution,

$$4\pi I_\nu = \frac{L_\nu}{4\pi r^2}.$$

We then have for the photoionization timescale

$$t_{\text{ion}} = \frac{1}{n_e \sigma_\text{H}} = 5 \times 10^{12} \text{ s}$$
and for the recombination timescale

$$t_{\text{rec}} = \frac{1}{n_p \sigma_\text{H}} = 5 \times 10^8 \text{ s} \times \frac{r}{n_e}.$$

As in photoionization equilibrium $n_{\text{HII}} / n_\text{ion} = n_p / n_e$, these values imply $n_{\text{HII}} / n_p \approx 10^{4}$, that is hydrogen is very nearly completely ionized.

A source radiating ultraviolet photons at a finite rate cannot ionize an infinite region of space, and therefore there must be an outer edge to the ionized volume (this is true unless, of course, there is a population of UV emitters and all individual H II regions have already overlapped). One fundamental characteristic of the problem is the very small value of the mean free path for an ionizing photon if the hydrogen is neutral ($\sigma_\text{H} n_\text{HII}^{-1} = 0.9 \text{ kpc}$ at threshold, much smaller than the radius of the ionized region. If the source spectrum is steep enough that little optical depth is so large that detectable absorption will be produced by relatively small column (or surface) densities of intergalactic neutral hydrogen.

**Gunn–Peterp efekt**

Consider radiation emitted at some frequency $\nu_e$ that lies blueward of Ly$\alpha$ by a source at redshift $z_e$ and observed at Earth at frequency $\nu_0 = \nu_e (1+z_e)^{-1}$. At a redshift $z$ such that $1+z(z_0+1) \nu_0/\nu_e$, the emitted photons pass through the local $\text{Ly}\alpha$ resonance as they propagate towards us through a smoothly distributed sea of neutral hydrogen atoms and are scattered off the line of sight with a cross-section (neglecting stimulated emission) of

$$\sigma(\nu_e (1+z_e)) \approx \frac{1}{n_e} \frac{\pi e^2}{m_e} f(\nu_e (1+z_e)),$$

where $f=0.4162$ is the upward oscillator strength for the transition, $q$ is the line profile function (with normalization $\int q(\nu) d\nu = 1$), $c$ is the speed of light and $e$ and $m_e$ are the electron charge and mass, respectively. The total optical depth for resonant scattering at the observed frequency is given by the line integral of this cross-section multiplied by the neutral hydrogen proper density $n_{\text{HII}}(z)$,

$$n_{\text{HII}} = \int_0^r \sigma(\nu_e (1+z)) I_{\nu}(z) d\xi$$

Copyright © Nature Publishing Group 2002
Brunel Road, Houndmills, Basingstoke, Hampshire, RG21 6XS, UK Registered No. 785998
and Institute of Physics Publishing 2002
Dirac House, Temple Back, Bristol, BS2 6BE, UK
Intergalactic Medium

where \( d \omega / dz = c H_0^{-1} (1+z)^{-1} [\Omega_M (1+z)^3 + \Omega_K (1+z)^2 + \Omega_L]^{1/2} \) is the proper line element in a Friedmann–Robertson–Walker metric and \( \Omega_M, \Omega_L \) and \( \Omega_K = 1 - \Omega_M - \Omega_L \) are the matter, vacuum and curvature contributions to the present density parameter. As the scattering cross-section is sharply peaked around \( \nu_n \), we can write

\[
\tau_{\text{GP}} = \int_0^\infty \sigma \left( \nu (1+z) \right) n_{\text{H}}(z) \frac{d\nu}{dz} dz
\]

In an Einstein–de Sitter (\( \Omega_M = 1, \Omega_L = 0 \)) universe, this becomes

\[
\tau_{\text{GP}}(z) = \frac{\pi e^2 f n_{\text{H}}}{m_e H_0 \nu_n (1+z)^{3/2}} = 6.6 \times 10^5 \frac{\Omega_M^{1/2} n_{\text{H}}}{0.019} \frac{1}{1+z}^{3/2}.
\]

The same expression for the opacity is also valid in the case of optically thin (to Ly\( \alpha \) scattering) discrete clouds as long as \( n_{\text{H}} \) is replaced with the average neutral density of individual clouds multiplied by their volume filling factor.

In an expanding universe homogeneously filled with neutral hydrogen, the above equations apply to all parts of the source spectrum to the blue of Ly\( \alpha \). An absorption trough should then be detected in the level of the rest-frame UV continuum of the quasar; this is the so-called ‘Gunn–Peterson effect’. Between the discrete absorption lines of the Ly\( \alpha \) forest clouds, quasar spectra do not show a pronounced Gunn–Peterson absorption trough. The current upper limit at \( z \approx 5 \) is \( \tau_{\text{GP}} < 0.1 \) in the region of minimum opacity, implying from equation (14) a neutral fraction of \( n_{\text{H}} / n_{\text{H}}^\text{eq} < 10^{-6} h^4 \). Even if 99% of all the cosmic baryons fragment at these epochs into structures that can be identified with quasar absorption systems, with only 1% remaining in a smoothly distributed component, the implication is a diffuse IGM which is ionized to better than 1 part in 10\(^4\).

In modern interpretations of the IGM, it is difficult to use the Gunn–Peterson effect to quantify the amount of ionizing radiation that is necessary to keep the neutral hydrogen absorption below the detection limits. This is because, in hierarchical clustering scenarios for the formation of cosmic structures (the cold dark matter model being the most studied example), the accumulation of matter in overdense regions under the influence of gravity reduces the optical depth for Ly\( \alpha \) scattering considerably below the average in most of the volume of the universe, and regions of minimum opacity occur in the most underdense areas (expanding ‘cosmic minivoids’).

A clumpy IGM

Owing to the non-linear collapse of cosmic structures, the IGM is well known to be highly inhomogeneous. The discrete gaseous systems detected in absorption in the spectra of high-redshift quasars blueward of the Ly\( \alpha \) emission line are assigned different names based on the appearance of their absorption features (see figure 1).

The term ‘Ly\( \alpha \) forest’ (Lyman alpha forest) is used to denote the plethora of narrow absorption lines whose measured equivalent widths imply H I column densities ranging from \( 10^{10} \) cm\(^{-2} \) down to \( 10^{12} \) cm\(^{-2} \). These systems, observed to evolve rapidly with redshift between \( 2 < z < 4 \), have traditionally been interpreted as intergalactic gas clouds associated with the era of baryonic infall and galaxy formation, photoionized (to less than a neutral atom in 10\(^4\)) and photoheated (to temperatures close to 20 000 K) by an ultraviolet background close to the one inferred from the integrated contribution from quasars. Recent spectra at high resolution and high signal-to-noise ratio obtained with the Keck telescope have shown that most Ly\( \alpha \) forest clouds at \( z = 3 \) down to the detection limit of the data have undergone some chemical enrichment, as evidenced by weak, but measurable, C IV lines. The typical inferred metallicities range from 0.3% to 1% of solar values, subject to uncertainties of photoionization models. Clearly, these metals were produced in stars that formed in a denser environment; the metal-enriched gas was then expelled from the regions of star formation into the IGM.

An intervening absorber at redshift \( z \) having a neutral hydrogen column density exceeding \( 2 \times 10^{17} \) cm\(^{-2} \) is optically thick to photons having energy greater than 13.6 eV and produces a discontinuity at the hydrogen Lyman limit, i.e. at an observed wavelength of 912(1+z) Å. These scarcer LLSs are associated with the extended gaseous haloes of bright galaxies near the line of sight and have metallicities which appear to be similar to that of Ly\( \alpha \) forest clouds.

In ‘damped Ly\( \alpha \) systems’ the H I column is so large (\( N_{\text{HI}} \geq 10^{20} \) cm\(^{-2} \), comparable with the interstellar surface...
density of spiral galaxies today) that the radiation damping wings of the \( \text{Ly} \alpha \) line profile become detectable (see LYMAN ALPHA ABSORPTION: THE DAMPED SYSTEMS). While relatively rare, damped systems account for most of the neutral hydrogen seen at high redshifts. The typical metallicities are about 10% of solar and do not evolve significantly over a redshift interval 0.5<z<4 during which most of today’s stars were actually formed.

Except at the highest column densities, discrete absorbers are inferred to be strongly photoionized. From quasar absorption studies we also know that neutral hydrogen accounts for only a small fraction, ~10%, of the nucleosynthetic baryons at early epochs.

**Distribution of column densities and evolution**

The bivariate distribution \( f(N_{\text{HI}},z) \) of \( \text{HI} \) column densities and redshifts is defined by the probability \( dP \) that a line of sight intersects a cloud with column density \( N_{\text{HI}} \) in the range \( dN_{\text{HI}} \) at redshift \( z \) in the range \( dz \).

\[
\frac{dN}{dz} = f(N_{\text{HI}}, z) \cdot dN_{\text{HI}}
\]

As a function of column density, a single power law with slope ~1.5 appears to provide at high redshift a surprisingly good description over 9 decades in \( N_{\text{HI}} \), i.e. from \( 10^{12} \) to \( 10^{21} \) cm\(^{-2}\). It is a reasonable approximation to use for the distribution of absorbers along the line of sight:

\[
f(N_{\text{HI}}, z) = A N_{\text{HI}}^{-\gamma} (1+z)^\nu.
\]

Ly\( \alpha \) forest clouds and LLSs appear to evolve at slightly different rates, with \( \gamma=1.5\pm0.4 \) for the LLSs and \( \gamma=2.8\pm0.7 \) for the forest lines. Let us assume, for simplicity, a single redshift exponent, \( \gamma=2 \), for the entire range in column densities. In the power-law model (16) the number \( N \) of absorbers with column densities greater than \( N_{\text{HI}} \) per unit increment of redshift is

\[
\frac{dN}{dz} = \int_0^\infty f(N_{\text{HI}}, z) \cdot dN_{\text{HI}} = 2A N_{\text{HI}}^{-\gamma} (1+z)^\nu.
\]

A normalization value of \( A=4.0\times10^7 \) produces then ~3 LLSs per unit redshift at \( z=3 \) and, at the same epoch, ~150 forest lines above \( N_{\text{HI}}=10^{13.8} \) cm\(^{-2}\), in reasonable agreement with the observations.

If absorbers at a given surface density are conserved, with fixed comoving space number density \( \tau_0=\int_0^{1+z} \Sigma d\nu \) and geometric cross-section \( \Sigma \), then the intersection probability per unit redshift interval is

\[
\frac{dP}{dz} = \Sigma \frac{d\nu}{dz} = \Sigma \nu_0 (1+z)^\nu \frac{d\nu}{dz}.
\]

If the universe is cosmologically flat, the expansion rate and the redshift distribution for conserved clouds is predicted to be

\[
\frac{dP}{dz} \propto (1+z)^{\frac{3}{2}} \frac{d\nu}{dz} \propto (1+z)^{1/2}.
\]

The rate of increase of \( f(N_{\text{HI}},z) \) with \( z \) in both the Ly\( \alpha \) forest and LLSs is considerably faster than this, indicating rapid evolution. The mean proper distance between absorbers along the line of sight with column densities greater than \( N_{\text{HI}} \) is

\[
L = \frac{\frac{d}{dz} \cdot dN}{dz} \approx \frac{cN_{\text{HI}}^{1/2}}{H_0 \sigma_{\text{HI}}^2 24 \pi (1+z)^4}.
\]

For clouds with \( N_{\text{HI}}>10^{14} \) cm\(^{-2}\), this amounts to \( L\approx7.7\times10^{-3} \) Mpc at \( z=3 \). At the same epoch, the mean proper distance between LLSs is \( L\approx30 \) Mpc.

**Intergalactic continuum opacity**

Even if the bulk of the baryons in the universe are fairly well ionized at all redshifts \( z<5 \), the residual neutral hydrogen still present in the Ly\( \alpha \) forest clouds and Lyman limit systems significantly attenuates the ionizing flux from cosmological distant sources. To quantify the degree of attenuation we have to introduce the concept of an effective continuum optical depth \( \tau_{\text{eff}} \) along the line of sight to redshift \( z \),

\[
\frac{\langle e^{-\tau} \rangle \equiv e^{-\tau}}{\langle e^{-\tau} \rangle \equiv e^{-\tau}}
\]

where the average is taken over all lines of sight. Neglecting absorption due to helium, if we characterize the Ly\( \alpha \) forest clouds and LLSs as a random distribution of absorbers in column density and redshift space, then the effective continuum optical depth of a clumpy IGM at the observed frequency \( \nu_0 \) for an observer at redshift \( z_0 \) is

\[
\tau_{\text{eff}}(z_0, z, \nu_0) = \int_0^\infty \int_0^\infty dN_{\text{HI}} \cdot f(N_{\text{HI}}, z)(1-e^{-\tau}),
\]

where \( \tau=\int_0^\infty \tau_{\text{eff}}(z_0, z, \nu_0) dz \). This formula can be easily understood if we consider a situation in which all absorbers have the same optical depth to independent of redshift and the mean number of systems along the path is \( \Delta N = f dz / dz_{\text{eff}} \). In this case the Poissonian probability of encountering a total optical depth \( \tau_{\text{eff}} \) along the line of sight (with \( k \) integer) is \( p(k\tau_{\text{eff}}) = e^{-\Delta N} / (k! \cdot \Delta N / k!) \), and

\[
<e^{-\tau_{\text{eff}}}>=e^{-\tau_{\text{eff}}}=e^{-\frac{\tau_{\text{eff}}}{k!}} / \frac{\tau_{\text{eff}}}{k!} = e^{-\Delta N / k}.
\]

If we extrapolate the \( N_{\text{HI}}^{-1.5} \) power law in equation (16) to very small and large column densities, the effective optical depth becomes an analytical function of redshift and wavelength,

\[
\tau_{\text{eff}}(z_0, z, \nu_0) = \frac{4}{3} \pi \nu_0^{5/2} A \left( \frac{\nu_0}{0.01} \right)^{-15} (1+z_0)^{1.5} \cdot (1+z)^{1.5}.
\]

Because of the rapid increase with lookback time of the number of absorbers, the mean free path of photons at 912 Å becomes so small beyond a redshift of 2 that the radiation field is largely ‘local’. Expanding equation (23) around \( z \) one obtains \( \tau_{\text{eff}}(\nu_0)\approx0.36(1+z)^2 \Delta z \).
means that at $z=3$, for example, the mean free path for a photon near threshold is only $\Delta z=0.18$, and sources of ionizing radiation at higher redshifts are severely attenuated.

Recent observational results

NASA’s Far Ultraviolet Spectroscopic Explorer (FUSE) satellite has given astronomers a glimpse of the ghostly cobweb of helium gas left over from the Big Bang, which underlies the universe’s structure. The helium is not found in galaxies or stars but spread thinly through space. The observations help confirm theoretical models of how matter in the expanding universe condensed into a web-like structure pervading all the space between galaxies. The helium traces the architecture of the universe back to very early times. This structure arose from small gravitational instabilities seeded in the chaos just after the Big Bang.

Bibliography

For a recent deuterium abundance measurement and its implications for the baryon density parameter see Burles S and Tytler D 1999 Astrophys. J. 499 699

A short and hardly comprehensive list of references on issues related to the reionization of the IGM includes

Arons J and Wingert D W 1972 Astrophys. J. 177 1

The use of Ly$\alpha$ resonant absorption as a sensitive probe of intergalactic neutral hydrogen was predicted independently by

Shklovsky I S 1965 Sov. Astron. 8 638
Scheuer P A G 1965 Nature 207 963

The quoted upper limit to the Gunn–Peterson optical depth at $z=5$ is from


The high-resolution quasar spectrum shown in figure 1 was taken from

Songaila A 1998 Astron. J. 115 2184

who also discusses the evolution of metal abundances in the Ly$\alpha$ forest. An extensive discussion of the physics of the intergalactic medium can be found in


The physics of an ionized hydrogen gas is covered in Osterbrock D E 1989 Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley, CA: University Science Books) ch 2 and 3

Our present understanding of the Ly$\alpha$ forest is summarized in


The use of hydrodynamic cosmological simulations to make quantitative prediction of the physical state of the IGM was pioneered by


Piero Madau