Part 2

Extra Galactic Neutral Hydrogen and Cosmology

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Signatures of HI in the Early Universe: The End of the Dark Ages

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Abstract. Future radio surveys using facilities like the Giant Metrewave Radio Telescope or a Square Kilometre Array may detect 21-cm radiation from the Intergalactic Medium (IGM) in either emission or absorption against the Cosmic Microwave Background (CMB) at high redshift. Prior to the reionization of the IGM, the first radiation sources would reveal their presence through their effect on the IGM. The signatures include a sharp absorption feature in the radio sky against the CMB resulting from a rapid rise of a Lyman-alpha continuum background shortly after the birth of the first UV sources in the universe, and 21-cm emission and absorption shells created on the several Mpc scale by the first bright QSOs. The detection of these signatures would map the end of the 'dark ages', the period of transition from the post-recombination universe to one populated by radiation sources.

1. Introduction

One of the outstanding riddles of modern cosmology is the process of galaxy formation. In the framework of the standard Big Bang model, the baryons gathered from a uniformly distributed state after the recombination epoch to the clumped state we see as galaxies today. The most promising mechanism by which this occurred is by the gravitational growth of primordial density fluctuations in the distribution of some form of dark matter, the Cold Dark Matter variety being the current favourite. A detailed description of how this occurred, or even when, however, is still lacking.

There have been several recent dramatic successes in establishing the epoch of the origin of galaxies. Surveys based on the Lyman–dropout method in the optical have demonstrated that galaxies already existed at rather early times, corresponding to redshifts of up to $z \sim 4.5$ (Steidel *et al.* 1999). Recently galaxies have been discovered to redshifts $z > 5$ (Dey et al. 1998) and possibly even $z > 6$ (Chen, Lanzetta, & Pascarelle 1999). Observations in the sub–millimetre suggest evidence for a very dusty population of galaxies in the range $3 < z < 4$ undergoing large bursts of star formation (Hughes et al. 1998; Barger, Cowie, & Sanders 1999).

At the same time the upper redshift limit of QSOs is also climbing, with the current record holder, found by the Sloan Digital Sky Survey (SDSS), at $z = 5.00$ (Fan *et al.* 1999). The absence of a Lyα trough in its spectrum shows that the IGM was reionized by this time. Beyond that the epoch of reionization is almost completely unknown, but may be as recent as $z = 6$ if QSOs were the dominant sources that reionized the IGM (Meiksin & Madau 1993; Madau, Haardt, & Rees 1998).

To date, the radio sky has remained silent on the nature of the earliest radiating objects. However, it is in the radio that the discovery of the epoch of first light may be first made by detecting the influence of the first sources on the surrounding IGM (Madau, Meiksin, & Rees 1997). The physical mechanisms by which this may occur are reviewed below. The possible impact of sources on the IGM is then illustrated within the context of cosmological models for structure formation. Finally a possible radio telescope design strategy is presented for discovering the "End of the Dark Ages."

2. 21–cm Emission and Absorption Mechanisms

2.1. The Spin Temperature

The emission or absorption of 21–cm radiation from a neutral IGM is governed by the spin temperature T_S of the hydrogen, defined by

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{T_*}{T_S}\right), \tag{1}$$

where n_0 and n_1 are the singlet and triplet $n = 1$ hyperfine levels, $T_* \equiv h\nu_{10}/k_\mathrm{B} = 0.07\,\mathrm{K}$, where ν_{10} is the frequency of the 21–cm transition, h is Planck's constant, and k_B is Boltzmann's constant. In the presence of only the Cosmic Microwave Background (CMB) radiation, the spin temperature will be the same as the temperature of the CMB, and no emission or absorption relative to the CMB will be detectable. A mechanism is required that decouples the two temperatures. This may be achieved by coupling the spin temperature to the kinetic temperature of the gas itself. Two mechanisms are available, collisions between hydrogen atoms (Purcell & Field 1956) and scattering by Lyα photons (Wouthuysen 1952; Field 1958). The collision-induced coupling between the spin and kinetic temperatures is dominated by the spin-exchange process between the colliding hydrogen atoms. The rate, however, is too small for realistic IGM densities at the redshifts of interest, although collisions may be important in dense regions (Madau et al. 1997).

Instead the dominant mechanism is likely to be Lyα scattering through the Wouthuysen-Field effect. This process mixes the hyperfine levels of neutral hydrogen in its ground state via an intermediate transition to the $2p$ state. An atom initially in the $n = 1$ singlet state may absorb a Lyα photon that puts it in an $n = 2$ state, allowing it to return to the triplet $n = 1$ state by a spontaneous decay.

When the IGM is highly opaque to the scattering of Lyα photons, as it is when still neutral, the large number of scatterings of Lyα photons in an ambient radiation field will ensure a Boltzmann distribution for the photon energies near the Lyα frequency, with a temperature given by the kinetic temperature T_K of the IGM (Field 1959). In this case, the spin temperature of the neutral hydrogen becomes

$$T_S = \frac{T_{\rm CMB} + y_\alpha T_K}{1 + y_\alpha}, \tag{2}$$

where $T_{\rm CMB} = 2.73(1+z)$ K is the temperature of the CMB (Mather et al. 1994), and

$$y_\alpha \equiv \frac{P_{10}}{A_{10}} \frac{T_*}{T_K} \tag{3}$$

is the Lyα pumping efficiency. Here, $A_{10} = 2.9 \times 10^{-15}\,{\rm s}^{-1}$ is the spontaneous decay rate of the hyperfine transition of atomic hydrogen, P_{10} is the indirect de-excitation rate of the triplet via absorption of a Lyα photon to the $n = 2$ level, and $T_S \gg T_*$ was assumed. In the absence of Lyα pumping the spin temperature goes to equilibrium with the 21–cm background radiation field on a timescale $T_*/(T_{\rm CMB}A_{10}) \approx 5 \times 10^4$ yr, and neutral intergalactic hydrogen will produce neither an absorption nor emission signature. If y_α is large, $T_S \to T_K$, signifying equilibrium with the matter. A consideration of the net transition rates between the various hyperfine $n = 1$ and $n = 2$ levels above shows that the $1 \to 0$ transition rate via Lyα scattering is related to the total rate P_α by $P_{10} = 4P_\alpha/27$ (Field 1958). In the limit $T_K \gg T_{\rm CMB}$, the fractional deviation in a steady state of the spin temperature from the temperature of the CMB is

$$\frac{T_S - T_{\rm CMB}}{T_S} \approx \left(1 + \frac{T_{\rm CMB}}{y_\alpha T_K}\right)^{-1}. \tag{4}$$

There exists then a critical value of P_α which, if greatly exceeded, would drive $T_S \to T_K$. This thermalization rate is (Madau et al. 1997)

$$P_{\rm th} \equiv \frac{27 A_{10} T_{\rm CMB}}{4T_*} \approx (5.3 \times 10^{-12}\ {\rm s}^{-1}) \left(\frac{1+z}{7}\right). \tag{5}$$

2.2. 21–cm Emission Efficiency

The basic principle of the proposed observations may be illustrated by considering a region of neutral material with spin temperature $T_S \neq T_{\rm CMB}$, having angular size on the sky which is large compared to a beamwidth, and radial velocity extent due to the Hubble expansion which is larger than the bandwidth. Its intergalactic optical depth at $21(1+z)$ cm along the line of sight,

$$\tau(z) = \frac{3c^3 h^3 n_{\rm HI}(0) A_{10}}{32\pi H_0 k_{\rm B}^3 T_*^2 T_S}(1+z)^{1.5} \approx 10^{-2.9} h_{50}^{-1} \left(\frac{T_{\rm CMB}}{T_S}\right) \left(\frac{\Omega_{\rm IGM} h_{50}^2}{0.05}\right) (1+z)^{1/2}, \tag{6}$$

will typically be much less than unity. The experiment envisaged consists of two measurements, separated in either angle or frequency, such that one measurement, the fiducial, detects no line feature, either because there is no H I or because $T_S \approx T_{\rm CMB}$, and the second at $T_S \neq T_{\rm CMB}$. Since the brightness temperature through the IGM is $T_b = T_{\rm CMB}e^{-\tau} + T_S(1 - e^{-\tau})$, the differential antenna temperature observed at the Earth between this region and the CMB will be

$$\delta T = (1+z)^{-1}(T_S - T_{\rm CMB})(1 - e^{-\tau}) \approx (0.011\ {\rm K}) h_{50}^{-1} \left(\frac{\Omega_{\rm IGM} h_{50}^2}{0.05}\right) \left(\frac{1+z}{9}\right)^{1/2} \eta, \tag{7}$$

where the 21–cm radiation efficiency is defined as

$$\eta \equiv x_{\rm HI}\left(\frac{T_S - T_{\rm CMB}}{T_S}\right). \tag{8}$$

Here $x_{\rm HI}$ refers to the neutral fraction of the hydrogen in the region for which $T_S \neq T_{\rm CMB}$. As long as T_S is much larger than $T_{\rm CMB}$ (hence if there has been significant preheating of the intergalactic gas), $\eta \to x_{\rm HI}$, and the IGM can be observed in emission at a level which is independent of the exact value of T_S. By contrast, when $T_{\rm CMB} \gg T_S$ (negligible preheating), the differential antenna temperature appears, in absorption, a factor $\sim T_{\rm CMB}/T_S$ larger than in emission, and it becomes relatively easier to detect intergalactic neutral hydrogen (Scott & Rees 1990).

2.3. Preheating the IGM

The role of the spin temperature is apparent from eq. (8): when $T_S < T_{\rm CMB}$ the IGM absorbs 21–cm radiation from the CMB, while for $T_S > T_{\rm CMB}$ the IGM emits 21–cm radiation in excess of the CMB. In the absence of decoupling mechanisms, $T_S = T_{\rm CMB}$. The presence of Lyα photons with sufficient intensity will thus permit the IGM to be revealed. The adiabatic expansion of the Universe will generally bring the kinetic temperature of the IGM well below the temperature of the CMB. Coupling T_S to T_K will permit the IGM to be detectable in absorption. If there are sources of radiation that heat the IGM, however, it may be possible instead to detect the IGM in emission.

Possible heating sources are soft X–rays from an early generation of QSOs or thermal bremsstrahlung emission produced by the ionized gas in the collapsed halos of young galaxies. In Cold Dark Matter (CDM) dominated cosmologies, the latter may be in sufficient number to heat the IGM above the CMB temperature by $z \approx 7$ (Madau et al. 1997).

An additional heating source is the Lyα photon scattering itself. The average relative change in a Lyα photon's energy E after having been scattered by a hydrogen atom at rest is

$$\left\langle\frac{\Delta E}{E}\right\rangle = -\frac{h\nu_\alpha}{m_{\rm H}c^2} \approx -10^{-8}, \tag{9}$$

where $m_{\rm H}$ is the mass of the hydrogen atom. (It should be noted that this is an approximation valid only for $h\nu_\alpha \gg kT_K$. In the opposite limit, energy will flow from the atoms to the photons.) Through recoil, energy is transferred from photons to atoms at a rate

$$\dot{E}_\alpha = -\left\langle\frac{\Delta E}{E}\right\rangle h\nu_\alpha P_\alpha. \tag{10}$$

where P_α is the Lyα scattering rate per H atom. In the case of excitation at the thermalization rate $P_{\rm th}$, equation (10) becomes (Madau et al. 1997)

$$\dot{E}_{\rm th} = \frac{27}{4}\frac{(h\nu_\alpha)^2}{m_{\rm H}c^2}\frac{A_{10}T_{\rm CBR}}{T_*} \approx (220\ {\rm K\,Gyr^{-1}})\left(\frac{1+z}{7}\right). \tag{11}$$

The characteristic timescale for heating the medium above the CMB temperature via Lyα resonant scattering at this rate is

$$\Delta t_{\rm heat} = \frac{2}{9}\frac{m_{\rm H}c^2\nu_{10}}{h\nu_\alpha^2}A_{10}^{-1} \approx 10^8\,{\rm yr}, \tag{12}$$

about 20% of the Hubble time at $z \approx 8$. The result is a finite interval of time during which Lyα photons couple the spin temperature to the kinetic temperature of the IGM before heating the IGM above the CMB temperature. If Lyα sources turned on at redshifts $z_\alpha \lesssim 10$, this interval would present a window in redshift space near $z \approx 8$ that would enable a large fraction of intergalactic gas to be observable at $\sim$ 150 MHz in *absorption* against the CMB, and so isolate the epoch of First Light.

3. Signatures of the First Radiation Sources

3.1. The First Stars

The first stars (Pop III) to form will produce a background of UV continuum photons near the Lyα frequency which will immediately escape into the IGM. Lyα photons will propagate into uncollapsed, largely neutral regions of the IGM where the kinetic temperature in the absence of preheating will be (Couchman 1985)

$$T_K(z) \approx 26\,{\rm mK}\ (1+z)^2, \tag{13}$$

well below $T_{\rm CMB}$ because of adiabatic cooling during cosmic expansion. If Pop III sources are in sufficient abundance throughout the universe, the Lyα flux will couple the spin temperature to the kinetic temperature, and T_S will be pulled below $T_{\rm CMB}$ everywhere. After about 10^8 yr (see eq. 12), the same Lyα photons responsible for the coupling will warm the IGM to a temperature well above that of the CMB.

Soon after the first stars turn on the IGM will be detectable in absorption. When P_α is smaller than $P_{\rm th}$ ($z > z_{\rm th}$), the Lyα photons will heat the IGM, and the kinetic temperature will increase according to

$$\frac{dT_K}{dz} = \frac{2\mu}{3}\frac{\dot{E}_{\rm th}}{k_B}\frac{dt}{dz} + 2\frac{T_K}{(1+z)}, \tag{14}$$

until $T_K > T_{\rm CMB}$, when the IGM is emitting against the CMB. Here, $\mu = 16/13$ is the mean molecular weight for a neutral gas with a fractional abundance by mass of hydrogen equal to 0.75. The IGM will leave a characteristic imprint on the CMB which marks the epoch of reheating by the first generation of stars. At 150 MHz ($z_{\rm th} = 8.5$), the brightness temperature (Figure 1) shows an absorption feature of 40 mK, with a width of about 10 MHz. Such a depression in the CMB is much easier to observe compared with brightness fluctuations, as the isotropic signal may be recorded with a larger beam area.

3.2. The First Bright Quasars

Very little is actually known observationally about the nature of the first bound objects and the thermal state of the universe at early epochs. If ionizing sources are uniformly distributed, like an abundant population of pregalactic stars, the ionization and thermal state of the IGM will be the same everywhere at any given epoch, with the neutral fraction decreasing rapidly with cosmic time. This may be the case in CDM dominated cosmologies, since bound objects sufficiently massive ($\sim 10^6 M_\odot$) to make stars form at high redshift. On the other hand, reionization may also occur in a highly inhomogeneous fashion, as widely separated but very luminous sources of photoionizing radiation such as QSOs, present at the time the IGM is largely neutral, generate expanding H II regions on Mpc scales: the universe will be divided into an ionized phase whose filling factor increases with time, and an ever shrinking neutral phase. If the ionizing sources are randomly distributed, the H II regions will be spatially isolated at early epochs.

In such a scenario, 21–cm emission on Mpc scales will be produced in the quasar neighborhood as the medium surrounding it is heated by soft X–rays from the QSO itself (Madau et al. 1997; Tozzi et al. 2000). Outside the H II bubble, an inner thin shell of neutral gas forms within which the IGM is heated to $T_S = T_K > T_{\rm CMB}$ as the hyperfine levels are mixed by Lyα continuum photons from the QSO, and a much larger external shell where $T_S = T_K < T_{\rm CMB}$ because of adiabatic cooling. At larger distances from the quasar the Lyα coupling strength is weakening as r^{-2}, and $T_S \rightarrow T_{\rm CMB}$. As the warming front produced by the quasar expands, a growing amount of the surrounding IGM is unveiled both in emission and in absorption. The size and intensity of the detectable 21–cm region depend on the QSO luminosity and age. Typical differential signals (relative to the CMB) are a few μJy per beam.

4. A Telescope Design Strategy

One approach to detecting the 21-cm signatures would be to build a special purpose and dedicated telescope. If the absorbing regions occupy a size of 30 arcmin, the fluctuations will be in excess of 1 mK (Tozzi et al.). A 30 arcmin region would be resolved at 150 MHz by a telescope with a diameter of 250 m. The *rms* brightness temperature is given by the radiometer equation (Burke & Graham-Smith 1997) as

$$\Delta T_B \approx 0.33 \text{ mK} \left(\frac{T_{\rm sys}}{200 \text{ K}}\right) \left(\frac{1 \text{ MHz}}{\Delta\nu}\right)^{1/2} \left(\frac{100 \text{ h}}{\Delta t}\right)^{1/2}, \tag{15}$$

for a bandwidth $\Delta\nu$ and integration time Δt. The system temperature $T_{\rm sys}$ is sky-limited to 200 K in the coldest directions (Burke & Graham-Smith). A 5σ detection of the IGM would be possible with a 300 hour integration. The greatest challenge of a single dish experiment is controlling the effect of sidelobes on both the frequency and angular variations of the signal, although the expected spectral signature of the features should assist. Since such a device is less expensive to build than the SKA, a possible strategy would be to detect interesting regions on the sky and in frequency space with a special purpose telescope, and to use the SKA to study its detailed structure.

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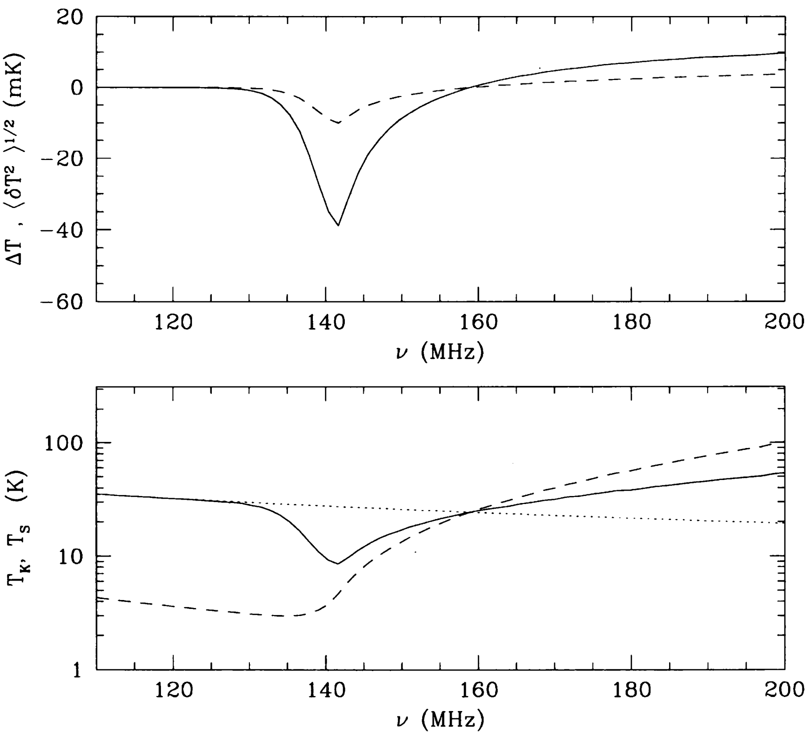

Figure 1. *Top:* Mean $\Delta T = T_b - T_{\rm CMB}$ versus frequency for an angular resolution of 1 arcmin and frequency resolution of 1 MHz (*solid line*), together with the *rms* fluctuation value (*dashed line*). The IGM is reheated at $z_{\rm th} = 9$. The strong absorption feature in the mean antenna temperature is associated with the fast rise of a Lyα continuum background on a time scale ≈ 10 Myr (see text), coupling T_S to T_K. *Bottom:* Corresponding evolution of the kinetic (*dashed line*), spin (*solid line*), and CMB temperatures (*dotted line*).

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