ON THE DIRECT DETECTABILITY OF THE COSMIC DARK AGES: 21 CENTIMETER EMISSION FROM MINIHALOS

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ABSTRACT

In the standard cold dark matter (CDM) theory of structure formation, virialized minihalos (with $T_{\text{vir}} \lesssim 10^4$ K) form in abundance at high redshift ($z > 6$), during the cosmic “dark ages.” The hydrogen in these minihalos, the first nonlinear baryonic structures to form in the universe, is mostly neutral and sufficiently hot and dense to emit strongly at the 21 cm line. We calculate the emission from individual minihalos and the radiation background contributed by their combined effect. Minihalos create a “21 cm forest” of emission lines. We predict that the angular fluctuations in this 21 cm background should be detectable with the planned Low Frequency Array (LOFAR) and Square Kilometer Array (SKA), thus providing a direct probe of structure formation during the dark ages. Such a detection will serve to constrain the basic CDM paradigm while constraining the shape of the power spectrum of primordial density fluctuations down to much smaller scales than have previously been constrained, the onset and duration of the reionization epoch, and the conditions that led to the first stars and quasars. We present results here for the currently favored, flat CDM model, for different tilts of the primordial power spectrum.

Subject headings: cosmology: theory — diffuse radiation — galaxies: formation — intergalactic medium — large-scale structure of universe — radio lines: galaxies

1. INTRODUCTION

No direct observation of the universe during the period between the recombination epoch at redshift $z \approx 10^3$ and the reionization epoch at $z \approx 6$ has yet been reported. It is a number of suggestions for the future detection of the reionization epoch, itself, have been made, this period prior to the formation of the first stars and quasars—the cosmic “dark ages” (e.g., Rees 2000)—has been more elusive. Standard big bang cosmology in the cold dark matter (CDM) model predicts that nonlinear baryonic structure first emerges during this period, with virialized halos of dark and baryonic matter that span a range of masses from less than $10^4$ $M_\odot$ to about $10^9$ $M_\odot$ that are filled with neutral hydrogen atoms. The atomic density $n_i$, kinetic temperature $T_i$ of this gas are high enough that collisions populate the hyperfine levels of the ground state of these atoms in a ratio close to that of their statistical weights ($3 : 1$), with a spin temperature $T_S$ that greatly exceeds the excitation temperature $T_{\text{exc}} = 0.0681$ K. Since, as we shall show, $T_S > T_{\text{CMB}}$, the temperature of the cosmic microwave background (CMB), as well, for the majority of the halos, these “minihalos” can be a detectable source of redshifted 21 cm line emission. The direct detection of minihalos at such high redshift would be an unprecedented measure of the density fluctuations in the baryons and of the total matter power spectrum at small scales, which will not be probed by other methods yet discussed (e.g., CMB anisotropy).

The possibility of 21 cm line emission or absorption by neutral H at high redshift has been considered before (Hogan & Rees 1979; Scott & Rees 1990; Subramanian & Padmanabh 1993; Kumar, Padmanabhan, & Subramanian 1995; Bagla, Nath, & Padmanabhan 1997; Madau, Meiksen, & Rees 1997; Shaver et al. 1999; Tozzi et al. 2000). Prior to the release of radiation by nonlinear baryonic structures that condense out of the background universe, the spin temperature of H i in the diffuse, uncollapsed gas in the intergalactic medium (IGM) is coupled to the CMB, so that $T_S = T_{\text{CMB}}$ and neither emission nor absorption in the 21 cm line is possible. Recently, attention has focused on the possibility that radiation from early stars and quasars might decouple $T_S$ from $T_{\text{CMB}}$ by “Lyα pumping”—resonant scattering in the H Lyα transition followed by decay of the upper state $n = 2$ to the ground state $n = 1$ into one or the other of the hyperfine levels (Madau et al. 1997; Tozzi et al. 2000). This mechanism, it has been suggested, will operate on H i in the diffuse, uncollapsed IGM during reionization, first to make $T_S < T_{\text{CMB}}$, so that the 21 cm transition can be seen in absorption against the CMB, until the same Lyα scattering heats the gas shortly thereafter and makes $T_S > T_{\text{CMB}}$, thereby causing 21 cm emission in excess of the CMB, before reionization finally destroys the H i. In what follows, however, we show that a substantial fraction of the baryons in the universe may already have condensed out of the diffuse IGM into virialized minihalos, prior to and during reionization. Under these conditions, collisional excitation alone is sufficient to decouple $T_S$ from $T_{\text{CMB}}$ and cause 21 cm emission in excess of the CMB, thereby providing a signature of the cosmic dark ages and of their retreat during reionization.

2. THE 21 CENTIMETER EMISSION FROM INDIVIDUAL MINIHALOS

The 21 cm emission from a single halo depends on its internal atomic density, temperature, and velocity structure. We model each CDM minihalo here as a nonsingular, truncated isothermal sphere (TIS) of dark matter and baryons in virial and hydrostatic equilibrium, in good agreement with the results of gas and N-body simulations from realistic initial conditions (Shapiro, Iliev, & Raga 1999; Iliev & Shapiro 2001, 2002). This model uniquely specifies the internal structure of each halo (e.g., total and core sizes $r_1$ and $r_2$, central total mass density $\rho_v$, dark matter velocity dispersion $\sigma_v = (4\pi r_v^2 \rho_v)^{1/3}$, and gas temperature $T_g = \mu m_n \sigma_v^2/k_B$, where $\mu$ is the mean molecular weight) for a given background cosmology as functions of two parameters, the total mass $M$ and collapse redshift $z_{\text{coll}}$.

The minihalos that contribute significantly to the 21 cm emission span a mass range from $M_{\text{min}}$ to $M_{\text{max}}$ that varies with redshift. The value of $M_{\text{min}}$ is close to the Jeans mass of
the uncollapsed IGM prior to reionization, \( M_\star = 5.7 \times 10^3 (\Omega_\Lambda h^2/0.15)^{-1/2} (\Omega_\Lambda h^2/0.02)^{-3/5} [(1 + z)/10]^{1/2} M_\odot \), while \( M_{\text{max}} = 3.95 \times 10^2 (\Omega_\Lambda h^2/0.15)^{-1/2} (1 + z)/10^{3/2} \) is the mass for which \( T_{\text{vir}} = 10^4 \) K according to the TIS model (Iliev & Shapiro 2001) (since halos with \( T_{\text{vir}} \approx 10^4 \) K are largely collisionally ionized). Halos with \( T_{\text{vir}} \approx 10^4 \) K may have radiatively cooled gas inside them, which would add to the signal we compute, but such gas is expected to lead to the formation of internal sources of ionizing radiation, which will largely offset the effect. Since these additional effects are highly uncertain and are related to the onset of radiative feedback and reionization, which we are neglecting in these calculations, we will not consider the role of higher temperature halos further.

The flux per unit frequency, \( \dot{\Omega}_v \equiv (dF/dv)_{\text{rec}} \), received at redshift \( z = 0 \) at frequency \( v_{\text{rec}} \) from a minihalo at redshift \( z \) that emits at frequency \( v_v = v_{\text{rec}}(1 + z) \), is expressed in terms of the brightness temperature \( T_{b,\text{em}} = T_{b,\text{rec}}(1 + z) \) according to

\[
\dot{\Omega}_v = \frac{2}{c^3} \frac{v_v^2}{k_e} T_{b,\text{rec}} (\Delta \Omega)_{\text{halo}},
\]

where \( (\Delta \Omega)_{\text{halo}} = \pi r_0^2 D_{\text{L}}^2 = \pi (\Delta \theta_{\text{halo}}/2)^2 \) is the solid angle subtended by the minihalo and \( D_{\text{L}} \) is the angular diameter distance. The brightness temperature \( T_{b,\text{em}} \) is determined by solving the equation of radiative transfer to derive the brightness profile of the minihalo and integrating this profile over the projected surface area, as follows.

The brightness temperature along a line of sight through a minihalo at projected distance \( r \) from the center obeys the equation

\[
T_b(r) = T_{\text{CMB}} e^{-\tau(r)} + \int_0^{r(r)} T_s e^{-\tau} \, dr',
\]

where quantities are defined in the comoving frame of the minihalo, frequency \( \nu \) refers here and henceforth to \( \nu_{\text{rec}} \) \( \tau(r) \) is the total optical depth through the halo, and the effective absorption coefficient \( \kappa_e \) is given when \( T_s \ll T_b \) by

\[
\kappa_e = \frac{3 c^2 A_{\text{H}_1}}{32 \pi \nu^2} f(\nu) \frac{T_s}{T_b},
\]

(Field 1958), where \( A_{\text{H}_1} = 2.85 \times 10^{-15} \) s \(^{-1} \) is the Einstein A-coefficient for the 21 cm transition and \( f(\nu) \) is the normalized line profile. The spin temperature \( T_s \) is determined by the balance between collisional and radiative excitation and deexcitation by atoms and electrons and by CMB and Ly\( \alpha \) photons, respectively, according to

\[
T_s = \frac{T_{\text{CMB}} + \gamma_e T_e + \gamma_\gamma T_\gamma}{1 + \gamma_e + \gamma_\gamma},
\]

where \( T_e \) is the color temperature of the Ly\( \alpha \) photons, and \( \gamma_e \) and \( \gamma_\gamma \) are radiative and collisional excitation efficiencies, respectively (Purcell & Field 1956; Field 1958, 1959). The efficiency \( \gamma_\gamma \) includes contributions from H\(^+\)-H\(^+\) collisions, \( \gamma_{\text{H}^+} \), and from \( e^-\text{-H}^+ \) collisions, \( \gamma_e \). Prior to the reionization epoch, Ly\( \alpha \) pumping is unimportant and collisional excitation alone must compete with excitation by the CMB. This is possible only for gas that is highly nonlinear and sufficiently hot. Such conditions are achieved only inside virialized halos. As shown in Figure 1, the optical depth of an individual halo is not negligible, particularly for smaller mass halos (owing to their lower \( T_s \)). Since \( T_s \) varies with radial position inside the halo, as a result of its significant central concentration, we must integrate equation (2) numerically.

The face-averaged \( T_s \), of this single halo is given by \( \langle T_s \rangle_{\text{halo}} = \langle \int T_s(r) dA/A \rangle_{\text{halo}} \), where \( A(M, z) \) is the geometric cross section of a halo of mass \( M \) and collapse redshift \( z \). The observed flux from an individual halo is then expressed with respect to the CMB by the differential antenna temperature \( \delta T_b \) of the 21 cm line as observed at \( z = 0 \) at received frequency \( \nu_{\text{rec}} = \nu_{\text{d}}(1 + z)^{-1} \).

The line-integrated flux \( F(M, z) \) received from this minihalo is equal to the flux calculated for \( \nu = \nu_{\text{d}} \) multiplied by a redshifted effective line width \( \Delta \nu_{\text{eff}}(z) \), defined by \( \Delta \nu_{\text{eff}}(z) = (\nu^2 dF/d\nu)_{\nu_{\text{d}}} \). For an optically thin minihalo, \( \Delta \nu_{\text{eff}} \) reduces to \( \Delta \nu_{\text{eff}}(z) = [f(\nu_{\text{d}})(1 + z)^{-1}] \). In that case, for a thermal Doppler-broadened line profile, \( \Delta \nu_{\text{eff}}(z) = [(2 \pi \nu_{\text{d}})^2 \sigma_t/(1 + z)^{-1}] \). We have checked that this approximation is adequate even for the optically thicker halos at the small-mass end of the mass function. The differential line-integrated flux \( \delta F(M, z) \) is given
by replacing $T_{b,\text{rec}}$ in equation (1) by $\delta T_b$ and integrating over frequency as described above.

Our results for individual minihalos are summarized in Figure 1. Line profiles of different minihalos along the same line of sight should not typically overlap. The proper mean free path $\lambda_{\text{mfp}} = (\langle n_{\text{halo}} \delta_{\text{halo}} \rangle)^{-1}$ for photons to encounter minihalos in $\Lambda$CDM is 160 kpc at $z = 9$ (Shapiro 2001), corresponding to a frequency separation, $\Delta f_{\text{mfp}} \approx \nu_c H(z) \lambda_{\text{mfp}}/[c(1+z)] \sim 0.1 \text{ MHz} \gg \Delta f_{\text{eff}} \lesssim 10 \text{ kHz}$.

These results predict a “21 cm forest” of minihalo emission lines. At $z = 9$, for example, there are about 160 minihalo lines per unit redshift along a typical line of sight in an untilted CDM universe (Shapiro 2001). Detecting the stronger lines would require subarcsecond spatial resolution, $\sim 1$ kHz frequency resolution, and approximately nanojansky sensitivity.

The Square Kilometer Array (SKA) is expected to have sufficient sensitivity for such observation but probably not sufficient sensitivity.

3. The 21 Centimeter Radiation Background from Minihalos

The average differential flux per unit frequency relative to that of the CMB from all the minihalos observed within a given beam of angular size $\Delta \theta_{\text{beam}}$ and frequency bin $\Delta \nu_{\text{bin}}$ is

$$\frac{\delta \overline{T}_n}{\delta \nu_b} (z) = \frac{\Delta z (\Delta \Omega_{\text{beam}})}{\Delta \nu_{\text{bin}}} \frac{d^2 V(z)}{dz \, d\Omega} \int_{M_{\text{min}}}^{M_{\text{max}}} \nu_c H(z) \overline{\delta T_{b,\text{rec}}} \, dn \, dM,$$  \hspace{1cm} \hspace{1cm} (5)

where $d^2 V(z)/dz \, d\Omega$ is the comoving volume per unit redshift per unit solid angle, the solid angle $(\Delta \Omega_{\text{beam}}) = \pi (\Delta \theta_{\text{beam}}/2)^2$, and $\Delta \nu_{\text{bin}}/\Delta z = \nu_c/(1+z)^2$. We calculate the comoving density of halos at different redshifts using the Press-Schechter approximation for the halo mass function $dn/dM$. If we define the beam-averaged “effective” differential antenna temperature $\overline{\delta T}_b$ using $\overline{\delta T}_n = 2\nu_c^2 \overline{\delta T}_b (\Delta \Omega_{\text{beam}})/c^2$, then

$$\overline{\delta T}_b = \nu_c H(z) \int_{M_{\text{min}}}^{M_{\text{max}}} \Delta \nu_{\text{bin}} \overline{\delta T}_{b,\text{rec}} \, A \, dn \, dM.$$  \hspace{1cm} \hspace{1cm} (6)

We consider the currently favored, flat CDM model with cosmological constant (“$\Lambda$CDM”, $\Omega_\Lambda = 0.3$, $\Omega_m = 0.7$, COBE-normalized, $\Omega_\Lambda h^2 = 0.02$, $h = 0.7$) for three values of the primordial power spectrum index $n_s = 0.9$, 1, and 1.1, using the power spectrum of Eisenstein & Hu (1999).

Results for $\overline{\delta T}_n$ and $\overline{\delta T}_b$ are plotted in Figure 2. In principle, the variation of $\overline{\delta T}_b$ with observed frequency implied by the redshift variations in Figure 2 should permit a discrimination between the 21 cm emission from minihalos and the CMB and other backgrounds, owing to their very different frequency dependences. However, the average differential brightness temperature of this minihalo background is very low and its evolution is fairly smooth, so such measurement may be difficult in practice with currently planned instruments like the Low Frequency Array (LOFAR) and SKA. The angular fluctuations in this emission, on the other hand, should be much easier to detect, as discussed in § 4.

4. Angular Fluctuations in the 21 Centimeter Emission Background

The amplitude of $q$-sigma angular fluctuations (i.e., $q$ times the rms value) in the differential antenna temperature is given in the linear regime by

$$\frac{(\delta T_b)^{1/2}}{\delta T_b} = q b(z) \sigma_p,$$  \hspace{1cm} \hspace{1cm} (7)

where $\sigma_p$ is the rms mass fluctuation at redshift $z$ in a randomly placed cylinder that corresponds to the observational volume defined by the detector angular beam size, $\Delta \theta_{\text{beam}}$, and frequency bandwidth, $\Delta \nu_{\text{bin}}$, and $b(z)$ is the bias factor that accounts for the clustering of random density peaks relative to the mass. We assume $b(z)$ is the flux-weighted average over the mass function of $b(M, z) = 1 + (\nu_s^2 - 1)/\delta_b$, the linear bias factor, where $\nu_s = \delta_b/\sigma(M)$, $\delta_b$ is the value of the linearly extrapolated overdensity $\partial \rho/\rho$ corresponding to the epoch when a top-hat collapse reaches infinite density, and $\sigma(M)$ is the standard deviation of the density contrast filtered on mass scale $M$ (e.g., Mo & White 1996). For a cylinder of comoving radius $R = \Delta \theta_{\text{beam}}/(1+z) D_L(z)/2$, and length $L \approx (1+z)cH(z)^{-1}(\Delta \nu/\nu_b)$, we have

$$\sigma_p^2 = \frac{8 D^2(z)}{\pi^2 R^2 L^2} \int_0^L \frac{dx}{\sin^2(kLx/2J_z^2[kR(1-x^2)/x^2])] x^2(1-x^2)} \times (1 + f x^2)^2 P(k) \frac{dn}{k^2}.$$  \hspace{1cm} \hspace{1cm} (8)

(Tozzi et al. 2000; with several typos in the corresponding expression in this paper corrected here), where $D(z) \equiv \delta_b(0)/\delta_b(z)$ is the linear growth factor, $P(k)$ is the linear power spectrum at $z = 0$, and the factor $(1 + f x^2)^2$, with $f \approx (\Omega(z))^{0.6}$, is the correction to the cylinder length for the departure
from Hubble expansion due to peculiar velocities (Kaiser 1987).

Illustrative results are plotted for 3σ fluctuations as a function of Δθ_{beam} for z = 7 and 8.5, in Figure 3, along with the expected sensitivity limits for the planned LOFAR (300 m filled aperture) and SKA (1 km filled aperture) arrays. We plot in Figure 4 the predicted spectral variation of these fluctuations versus redshift for illustrative beam sizes of 9′ and 25′. These 3σ fluctuations should be observable with both LOFAR and SKA with integration times of between 100 and 1000 hr. For a 25′ beam, for example, 3σ fluctuations can be detected for untilted ΛCDM by both with a 100 hr integration for z ~ 6–7.5 and a 1000 hr integration for z ≤ 11.5, while for a 9′ beam, SKA can detect them after 100 hr for z ≤ 9 and after 1000 hr for z ≤ 13. Results for different values of z and Δθ_{beam} are available upon request.

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