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The 21 centimeter background from the cosmic dark ages: Minihalos and the intergalactic medium before reionization

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Abstract

The H atoms inside minihalos (i.e., halos with virial temperatures $T_{\rm vir} \leqslant 10^4$ K, in the mass range roughly from $10^4 M_\odot$ to $10^8 M_\odot$) during the cosmic dark ages in a ΛCDM universe produce a redshifted background of collisionally-pumped 21-cm line radiation which can be seen in emission relative to the cosmic microwave background (CMB). Previously, we used semi-analytical calculations of the 21-cm signal from individual halos of different mass and redshift and the evolving mass function of minihalos to predict the mean brightness temperature of this 21-cm background and its angular fluctuations. Here we use high-resolution cosmological N-body and hydrodynamic simulations of structure formation at high redshift ($z \gtrsim 8$) to compute the mean brightness temperature of this background from both minihalos and the intergalactic medium (IGM) prior to the onset of Lyα radiative pumping. We find that the 21-cm signal from gas in collapsed, virialized minihalos dominates over that from the diffuse shocked gas in the IGM.

Keywords: Cosmology; Theory; Diffuse radiation; Intergalactic medium; Large-scale structure of universe; Radio lines

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Contents

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1. Introduction

Neutral hydrogen atoms in the early universe can be detected in absorption or emission against the cosmic microwave background (CMB) at redshifted radio wavelength 21 cm, depending upon whether their spin temperature T_S is less than or greater than that of the CMB, respectively. Minihalos which form during the "dark ages" have density and temperature high enough to appear in emission (Iliev et al., 2002, 2003). The intergalactic medium (IGM), on the other hand, appears in either emission or absorption. New radio telescopes are being designed to detect this 21 cm signal.

Iliev et al. (2002, ISFM hereafter) showed that atomic collisions inside minihalos are sufficient to decouple the spin temperature of the neutral hydrogen from the CMB temperature. They predicted the mean and angular fluctuations of the corresponding 21 cm signal by a semi-analytical calculation based upon integrating the individual minihalo contributions for different halo masses and redshifts, over the evolving statistical distribution of minihalo masses in the ΛCDM universe. The fluctuations, they found, are substantial enough to be detectable with future radio telescopes. Furlanetto and Loeb (2004), on the other hand, have recently suggested that the gas in the diffuse IGM (prior to the onset of Lyα radiative pumping) is also capable of producing the 21 cm emission signal and that the IGM contribution to the mean signal will dominate over that from gas inside minihalos.

In order to quantify these effects, we have computed the 21 cm signal both from minihalos and the IGM at $z \gtrsim 8$, using high-resolution cosmological N-body and hydrodynamic simulations of structure formation. We use a flat, ΛCDM cosmology with matter density parameter $\Omega_m = 0.27$, cosmological constant $\Omega_\Lambda = 0.73$, baryon density $\Omega_b = 0.043$, Hubble constant $H = 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, $\sigma_{8h^{-1}} = 0.9$ and the Harrison–Zel'dovich primordial power spectrum.

2. The calculation

2.1. Basics of 21-cm radiation background from the dark ages

Foreground emission or absorption by neutral hydrogen atoms at redshift z is seen against the CMB at redshifted wavelength, $21(1+z)$ cm. The spin temperature (T_S) of a hydrogen atom determines whether the signal is in emission or absorption. Emission occurs when $T_S > T_{\mathrm{CMB}}$, while absorption occurs when $T_S < T_{\mathrm{CMB}}$. T_S can deviate from T_{CMB} in various ways. A hydrogen atom can: (1) absorb a 21 cm photon from CMB (CMB pumping), (2) collide with another atom (collisional pumping), and (3) absorb a Lyα photon to make a Lyα transition, then decay to one of hyperfine 21 cm levels (Lyα pumping).

During the dark ages, when there is no Lyα pumping, the mean 21 cm signal against the CMB will be zero at $z \gtrsim 150$, then in absorption at $20 \lesssim z \lesssim 150$ mostly due to unperturbed IGM, and finally in emission at $z \lesssim 20$ due primarily to minihalos. We restrict ourselves to regions such that the Lyα pumping is negligible even after sources turn on at $z \lesssim 20$. In other words, we only consider collisional pumping in minihalos and the IGM at $8 \lesssim z \lesssim 100$.

2.2. Semi-analytic calculations

Here we briefly summarize the semi-analytical calculation of the 21 cm signal from minihalos by ISFM and from the unperturbed IGM. For minihalos, the differential brightness temperature,

$$\delta T_b = \frac{T_S - T_{\mathrm{CMB}}(z)}{1+z}(1 - e^{-\tau}), \tag{1}$$

is averaged over individual minihalos to give the mean differential antenna temperature $\overline{\delta T_b}$ (for detail, see ISFM). On the other hand, the unperturbed IGM of the universe has a kinetic temperature smaller than the CMB temperature at $z \lesssim 100$, resulting in an absorption signal until collisional pumping becomes negligible at $z \simeq 20$ (Fig. 1) .

2.3. Numerical simulations

We have run a high resolution cosmological N-body and gasdynamic simulation to derive the effects of gravitational collapse and hydrodynamics on the predicted 21 cm signal from the high redshift universe. Our computational box has a comoving size of 0.7 Mpc, with 1024^3 cells and 512^3 dark matter particles, which is optimal for adequately resolving both the minihalos and small-scale structure-for-

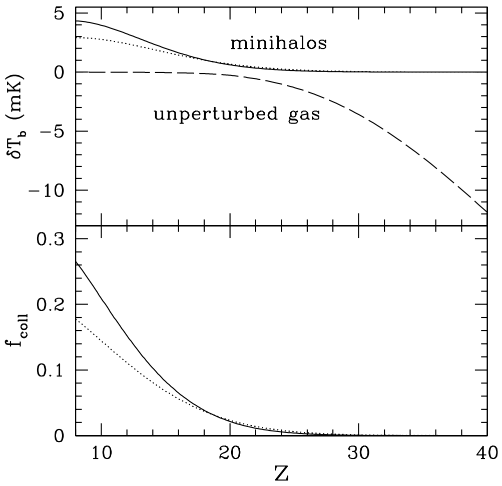

Fig. 1. Analytical prediction for the mean 21 cm differential brightness temperature due to collisionally-decoupled minihalos and an unperturbed IGM. Shown are the results based on the Press–Schechter (solid) and the Sheth–Tormen (dotted) mass functions for halos and the contribution from the IGM gas with cosmic mean density and temperature (dashed). In the bottom panel we show the minihalo collapsed fraction, again based on the Press–Schechter (solid) and the Sheth–Tormen (dotted) mass functions.