SIGNATURES OF THE BARYON ACOUSTIC OSCILLATIONS ON 21 cm EMISSION BACKGROUND

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ABSTRACT

The baryon acoustic oscillations (BAOs) prior to recombination should be imprinted onto the 21 cm emission background from the epoch of reionization through the underlying density perturbations. Using an analytical approach for both matter power spectrum (CDM+baryons) and reionization process, we demonstrate the BAO-induced signatures on the power spectrum of 21 cm emission fluctuations. Future low-frequency radio telescopes such as LOFAR and MWA should be able to detect these weak BAO wiggles with an integration time of \(\approx 1\) yr. A combination of the BAO measurements at different redshifts \(z \approx 1000\) (CMB), \(z \approx 10\) (epoch of reionization), and \(z \approx 0\) (clustering of galaxies) may allow one to set more robust constraints on the determinations of cosmological parameters including dark energy and its equation of state.

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

Online material: color figures

1. INTRODUCTION

Prior to recombination, free electrons coupled the baryons and photons tightly through Compton scattering, and these three species moved together as a single fluid. In this relativistic plasma, the primordial small-scale perturbations propagated as sound waves, resulting in pressure-induced oscillations. The neutral gas can still retain some memory of such acoustic oscillations even after recombination, manifesting themselves in the last scattering surface as the harmonic series of maxima and minima on the cosmic microwave background (CMB) at redshift \(z \approx 1000\). The longest BAO wavelength of \(\lambda \approx 100\) Mpc imprinted on large-scale structures is still visible in the local universe through surveys of 3D galaxy distributions (Eisenstein et al. 2005; Cole et al. 2005).

Because BAOs can be served as an ideal cosmic ruler for many cosmological applications especially for probing dark energy (Hu & White 1996; Barkana & Loeb 2005; Wyithe et al. 2007), it is of great interest to explore how BAOs evolve with cosmic time, and in particular how and when the BAO peaks at smaller scales are washed out by the emergence of larger structures. Indeed, in addition to the detection of BAO signatures in the CMB at \(z \approx 1000\) and galaxy spatial distributions at lower redshifts, one may be able to extract valuable information on BAOs at redshifts around \(z \approx 10\) from the study of 21 cm absorption/emission generated in the dark ages and epoch of reionization. This will complement our knowledge of structure formation at this important phase when galactic dark halos started to develop. The existing modes and positions of BAOs at the epoch of reionization would make a sensitive diagnosis of nonlinear structures evolved by that time. Most importantly, the statistical uncertainties in the determination of cosmological parameters including dark energy and its equation of state can be significantly reduced when more independent measurements of BAOs through the epoch of reionization are incorporated with the BAO features already detected in the CMB and large-scale structures of the local universe. Note that the 21 cm absorption/emission observations provide a tomographic imaging of the universe at the epoch of reionization and dark ages, yielding many independent constraints on the theory of cosmology.

The goal of this Letter is to demonstrate the signatures of BAOs on the redshifted 21 cm fluctuations and discuss the feasibility of detections with existing and planned low-frequency radio telescopes such as 21CMA, LOFAR, and MWA. We focus on the 21 cm emission of neutral hydrogen during the process of reionization instead of the 21 cm absorption at \(z > 20\) (Barkana & Loeb 2005). For the latter, the detection of BAO signatures turns to be much more difficult because of their longer wavelength and the limitation of angular resolutions with exiting and even future radio telescopes. A sophisticated treatment of the problem requires a detailed knowledge of the history of reionization and radiative transfer of ionizing photons through the gas density field, which may be achievable by numerical simulations (e.g., Furlanetto et al. 2004). Here we would rather employ an analytic approach to simplify the problem and highlight the essentials of the physical process at the epoch of reionization. Throughout the Letter we adopt a concordance cosmology of \(\Omega_m = 0.265\), \(\Omega_b = 0.735\), \(\Omega_\gamma = 0.044\), \(h = 0.71\), \(n_s = 1\), and \(\sigma_8 = 0.772\), as revealed by the WMAP 3 yr observations (Spergel et al. 2007).

2. MATTER POWER SPECTRA

We begin with the linear matter power spectrum \(P_{\text{lin}}(z, k) \propto D^2(z)k^{n_s-1}T^2(k)\), which describes how the initial matter power spectrum \(k^n\) is modulated by the transfer function \(T(k)\) and growth factor \(D(z)\). The baryon content, and thereby BAOs, is incorporated into \(T(k)\), which can be approximately separated into the cold dark matter (CDM) and baryon components: \(T(k) = (\Omega_b/\Omega_m)T_b(k) + (\Omega_c/\Omega_m)T_c(k)\), where \(\Omega_c\) is the CDM density parameter relative to the critical density at present, \(\Omega_c = \Omega_m - \Omega_b\). We adopt the asymptotic solutions to both \(T_b(k)\) and \(T_c(k)\) near the sound horizon given by Eisenstein & Hu (1998) in which the suppression effect of baryons on scales below the sound horizon is included. Nonetheless, the linear matter power spectrum becomes inaccurate at smaller scales and later cosmic time. We employ a halo model to evaluate the nonlinear power spectrum (see Cooray & Sheth 2002), which accounts for contributions from the single-halo term \(P_{\text{bh}}\) plus the clustering term \(P_{\text{clust}}\). We take the Press-Schechter
BAO wiggles occur at $k \sim 0.1$ Mpc$^{-1}$ and nonlinear structures dominate at $k > 1$ Mpc$^{-1}$. The matter power spectrum at $z = 6$ is also plotted for comparison (dotted line). [See the electronic edition of the Journal for a color version of this figure.]

unaffected by the formation of nonlinear structures. This arises because the gravitationally bound systems such as dark halos and their associated large-scale structures at $z = 6$ have sizes much smaller than the typical scales ($\sim 100$ Mpc) of BAOs. In other words, many of the interesting modes of BAO should leave their imprints on the matter power spectrum before $z = 6$.

3. 21 cm POWER SPECTRA

BAO signatures enter into the redshifted 21 cm emission background from the epoch of reionization through the underlying matter density fluctuations ($\delta$). If we restrict ourselves to the 21 cm emission generated from the neutral hydrogen in the surroundings of the ionized bubbles of first-generation luminous objects, the surface brightness of the emission can be evaluated through (see Zaldarriaga et al. 2004)

$$\delta T_e \approx T_0(1 + \delta)(1 - x),$$

$$T_0 = 16 \text{ mK} h^{-1} \left(\frac{\Omega_b h^2}{0.02} \right) \left(\frac{1 + z}{10} \frac{0.3}{\Omega_m}\right)^{1/2},$$

where $x = x_i(1 + \delta_i)$ is the ionization fraction, $x_i$ is the average ionization fraction, and $\delta_i$ is the perturbation in the ionization fraction across the sky, for which we will take the reionization model of Santos et al. (2005). The corresponding power spectrum of the 21 cm emission can be written as

$$P_{21}^{3D}(z, k) = T_0^2[(1 - x_i)^2P_{\delta}(z, k) + x_i^2P_{\delta}(z, k)]$$

$$- [2x_i(1 - x_i)P_{\delta}(z, k)].$$

The three terms on the right-hand side represent the contributions of the matter power spectrum, the power from the perturbations in the ionization fraction, and the cross-correlation power, respectively. For the latter two, we use the model of Santos et al. (2003) to proceed with our numerical computation. The angular power spectrum $C_l(\nu)$ of the redshifted 21 cm brightness sky is derived under the flat-sky approximation.

The theoretically predicted 3D and 2D power spectra of the redshifted 21 cm emission fluctuations are shown in Figures 3
and 4, respectively. While the amplitudes of the 21 cm power spectra themselves are relatively low, with a maximum value of \( \approx 10 \) mK, the BAO-induced wiggles are clearly presented. It appears that an angular resolution of \( \approx 10' \) is needed in order to identify the BAO features on the 2D power spectra, apart from the requirement of high sensitivity. Moreover, the positions of BAO tend toward large \( l \) with the increase of redshift, indicating that radio arrays with baselines of \( \approx 1 \) km will be needed to reveal these structures. We have also calculated the 1D power spectrum of the 21 cm emission along the line of sight but found that the BAO features are completely washed out due to projection effect, in agreement with the result of Wang & Hu (2006). Finally, we point out that our analytical model does not take the size distribution of ionized bubbles into account. The typical sizes of the ionized bubbles near \( z \approx 6 \) can reach \( \sim 20 \) Mpc, which is already comparable to the BAO wiggles at large \( k \) or \( l \). Whether or not the ionized bubbles produce oscillations on the same scales as BAOs should be investigated in future studies.

4. DETECTABILITY

The detection of BAO signatures on the redshifted 21 cm fluctuations indeed poses a technique challenge for existing and planned low-frequency radio telescopes. We demonstrate the observability using the 21 CentiMeter Array (21CMA), Low Frequency Radio Array (LOFAR), and Mileura Wide-field Array (MWA), and only work with the angular power spectrum \( C_l \) at a fixed frequency. Supposing that strong foreground contamination can be entirely removed from the low-frequency sky through either the two-point correlation technique in frequency domain (e.g., Zaldarriaga et al. 2004) or the pixel-by-pixel algorithm (Wang et al. 2006), we can estimate the variance in \( C_l \) through \( \Delta C_l \propto \left[ 2z/(2l+1)f_{\text{sky}}^2 \right]^2 (C_l + N_l) \), in which \( f_{\text{sky}}^2 = \left( w_{\text{sky}}^2 \right)^{-1} \) is the sky coverage, and \( N_l \) is the noise power spectrum if we adopt a Gaussian function with width \( \theta_{e} \) for the experimental beam and use \( w_{\text{sky}}^{-1} = 4\pi \sigma_{\text{pix}}^2/N_{\text{pix}} \) to denote the contribution of the white noise with \( \sigma_{\text{pix}} \) and \( N_{\text{pix}} \) being the pixel noise and total number of pixels, respectively. In radio interferometric measurement, the pixel noise can be represented in terms of brightness temperature as \( \sigma_{\text{pix}} = T_{\text{sys}}/\eta(2N\Delta\nu t)^{1/2} \), where \( T_{\text{sys}} \) is the system temperature, \( \eta \) is the efficiency factor of the telescope, \( N \) is the total number of independent baselines, \( \Delta\nu \) is the bandwidth, and \( t \) is the observing time.

To proceed further, for 21CMA we take a system temperature of \( T_{\text{sys}} = 250 \) K and an efficiency of \( \eta = 0.64 \). The total dishes of 21CMA are \( N_{\text{dish}} = 81 \) and the longest baseline is 6 km, which gives rise to an angular resolution of \( \theta_{e} \approx 1' \). We use a conservative value of \( \theta_{e} = 2' \) in the present estimate. The sky coverage is, nevertheless, very small: \( f_{\text{sky}} = 10^{-3} \). For LOFAR (compact core), the corresponding parameters are chosen as \( T_{\text{sys}} = 100 \) K, \( \eta = 0.64 \), \( N_{\text{dish}} = 32 \), \( \theta_{e} = 3' \), and \( f_{\text{sky}} = 0.1 \). We utilize the following parameters for MWA: \( T_{\text{sys}} = 200 \) K, \( \eta = 0.64 \), \( N_{\text{dish}} = 500 \), \( \theta_{e} = 5' \), and \( f_{\text{sky}} \approx 0.4 \). The errors \( \Delta C_l \) in the measurement of the 21 cm power spectra with 21CMA, LOFAR (core), and MWA are displayed in Figure 5 for \( z = 10 \) and \( z = 20 \). While it is promising for all three experiments to detect the reionization signals in the angular power spectra of 21 cm fluctuations over a wide range of redshifts beyond \( z = 6 \) and angular scales from \( l \sim 10^3 \) to \( 10^6 \), after an integration time of \( \sim 1 \) yr, a significant detection of the BAO wiggles on the 21 cm angular power spectrum turns to be still difficult especially at higher redshifts (or lower frequencies) due to both the weak signals of BAOs themselves and the limitation of the angular resolutions of current radio telescopes. The strategy is that the maximum variations of BAOs (e.g., the power difference between acoustic peaks and adjacent troughs) should exceed the errors at the corresponding modes. To optimize the detection, one should choose to work at higher frequencies near 200 MHz, although the total 21 cm signals may become weaker because the reionization process is almost completed by \( z = 6 \). To be specific, the relatively smaller sky coverage and higher system temperature of 21CMA prevent a significant detection of the BAO wiggles on the angular power spectra of 21 cm fluctuations unless a longer integration time of \( \sim 10 \) yr is allowed. In contrast, both LOFAR and MWA may be able to capture the BAO signals within \( \sim 1 \) yr. In particular, MWA can even trace all the BAO wiggles out to \( z \approx 30 \) and on very small angular scales of a few arcminutes because of its numerous independent baselines. We anticipate that

\[ T_{\text{sys}} = \frac{1}{\eta} (2N\Delta\nu t)^{1/2} \]

\[ f_{\text{sky}} = 10^{-3} \]

\[ T_{\text{sys}} = 200 \text{ K}, \quad \eta = 0.64, \quad N_{\text{dish}} = 500, \quad \theta_{e} = 5', \quad \text{and} \quad f_{\text{sky}} \approx 0.4. \]

\[ \Delta C_l \text{ in the measurement of the 21 cm power spectra with 21CMA, LOFAR (core), and MWA are displayed in Figure 5 for } z = 10 \text{ and } z = 20. \]

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\[ \eta \approx 0.4. \]
a similar result can be reached when all the 77 stations in the planned LOFAR start to operate.

5. CONCLUSIONS

BAOs should be imprinted onto the 21 cm emission background from the epoch of reionization through the underlying density perturbations. Detection of the signals will provide valuable information about the formation and evolution of cosmic structures at higher redshifts beyond $z \approx 6$. It also furnishes a standard ruler to the probe of topology and geometry of the universe including dark energy and its equation of state. In particular, many of the BAO modes were not erased by the formation of large-scale structures by $z = 6$, and we may be able to see the BAO wiggles at smaller scales. This will complement our knowledge of the BAO at intermediate redshifts in addition to the detections of BAO signatures in the CMB at $z \approx 1000$ and in large-scale distribution of galaxies at $z \approx 0$. A combination of these BAO measurements at different redshifts will allow us to set more robust constraints on the determinations of cosmological parameters.

We have used an analytic approach based on halo models of the distribution and evolution of dark matter, in which baryons trace essentially dark matter but the standard CDM power spectrum is modified by the presence of baryons. We have then calculated the 21 cm emission power spectrum from neutral hydrogen surrounding the ionized bubble of each halo, following a simple model of ionization history. Our results show that BAOs are indeed presented at the power spectra of the redshifted 21 cm emission from the epoch of reionization, and are almost unaffected by the presence of nonlinear structures beyond $z > 6$. This indicates that one should be able to see many of the BAO modes at the 21 cm power spectrum.

We have worked with the angular power spectra of the 21 cm emission from the epoch of reionization for a fixed frequency. The BAO signatures are clearly seen at $l \approx 500–3000$ throughout the entire history of reionization. However, detections of these wiggles with existing and planned radio interferometric arrays such as 21CMA, LOFAR, and MWA do pose a technical challenge. The primary difficulty, apart from the extremely faint signals of 21 cm emission themselves from the epoch of reionization and the strong foreground at low frequency, arises from the high system noise and the limitation of angular resolutions. Yet, within an integration time of about 1 yr, it seems that both LOFAR and MWA are capable of capturing the BAO signatures at $l \sim 1000$, provided that the foreground contamination can be successfully removed.

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