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Scale-Dependent Bias of Galaxies from Baryonic Acoustic Oscillations

Rennan Barkana[1] and Abraham Loeb[2⋆]
[1] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel*
[2] *Astronomy Department, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA*

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ABSTRACT

Baryonic acoustic oscillations (BAOs) modulate the density ratio of baryons to dark matter across large regions of the Universe. We show that the associated variation in the mass-to-light ratio of galaxies should generate an oscillatory, scale-dependent bias of galaxies relative to the underlying distribution of dark matter. A measurement of this effect would calibrate the dependence of the characteristic mass-to-light ratio of galaxies on the baryon mass fraction in their large scale environment. This bias, though, is unlikely to significantly affect measurements of BAO peak positions.

Key words: cosmology:theory – galaxies:formation

1 INTRODUCTION

The rapid acoustic waves in the radiation-baryon fluid prior to cosmological recombination were not followed by the dark matter at that time. Following recombination, the baryons were freed from the strong radiation pressure and fell into the gravitational potential fluctuations of the dark matter. As a result, the fractional difference between the density fluctuations of baryons and dark matter decreased steadily with cosmic time. But since the baryons amount to a sizeable fraction of the total mass density of matter ($\Omega_b/\Omega_m \approx 17\%$), the gravitational effect of the baryons on the dark matter imprinted baryonic acoustic oscillations (BAOs) on the matter power spectrum. The characteristic comoving scale of BAOs ~ 100 Mpc (corresponding to the sound horizon at recombination), provides a yardstick that can be used to measure the dependence of both the angular diameter distance and Hubble parameter on redshift (see review by Eisenstein 2005).

When analyzing galaxy surveys, it is often assumed that galaxies are biased tracers of the underlying matter distribution (Kaiser 1984), with a bias factor that approaches a constant value on sufficiently large scales where density fluctuations are still linear (e.g., Mo & White 1996; Tegmark & Peebles 1998; Sheth et al. 2001). However, the imprint of primordial acoustic waves on the baryon fluid at recombination introduced a scale-dependent modulation of the ratio between the density fluctuations of baryons and dark matter that has not been completely erased by the present time. A large-scale region with a higher baryon mass fraction than average (in the perturbations that lead to galactic halos) is expected to produce more stars per unit total mass and hence result in galaxies with a lower mass-to-light ratio.

In this paper we characterize the associated scale-dependent bias in flux-limited surveys of galaxies. The ratio between the power spectra for fluctuations in the luminosity density and number density of galaxies is expected to show BAO oscillations that reflect the large-scale variations in the baryon-to-matter ratio.

In §2, we formulate the oscillatory BAO signature on galaxy bias in terms of a simple analytical model. The quantitative results from this model are presented in §3. Finally, we summarize our main conclusions in §4.

2 THE MODEL

2.1 Basic Setup

Since galaxies sample the high peaks of the underlying matter density, they are biased tracers of the matter density. When the clustering of galaxies is usually analyzed, the bias is considered simply with respect to the matter density, without separating out the effects of the baryons. As long as the baryon fluctuations follow the same spatial pattern as those of the dark matter, biasing with respect to each of them cannot be separated since this separation is degenerate with an overall change of the bias factor, which is not known apriori. However, since the BAOs induce a scale-dependent difference between the baryons and dark matter, it becomes important to consider their influence on galaxies separately.

Consider the power spectrum of fluctuations in the galaxy number density $n_{\rm gal}$ and in the luminosity density

⋆ E-mail: barkana@wise.tau.ac.il (RB); aloeb@cfa.harvard.edu (AL)

$\rho_{\rm L}$. For a given galaxy population,

$$\rho_{\rm L} = n_{\rm gal} \times \langle L \rangle \ , \tag{1}$$

where $\langle L \rangle$ is the mean luminosity of the galaxies. Since galaxy formation is driven by halo collapse, which depends on the evolution of the overall matter perturbations, the number density fluctuations $\delta_{\rm n}$ are driven by the fluctuation $\delta_{\rm tot}$ in the total matter density, with a bias $b_{\rm n}$ that should be approximately constant on large scales (at least for a sample at a given luminosity):

$$\delta_{\rm n} = b_{\rm n} \delta_{\rm tot} \ . \tag{2}$$

The mean luminosity of galaxies may depend on their environment through their merger rate history, which is correlated with the local matter density. This can lead to fluctuations $\delta_{\rm L}$ in $\rho_{\rm L}$ with a different bias factor that should also approach a constant on large scales:

$$\delta_{\rm L} = (b_{\rm n} + b_{\rm L;t}) \delta_{\rm tot} \ , \tag{3}$$

where the overall bias factor of the luminosity density with respect to the total matter includes the number density bias $b_{\rm n}$ as well as a possible additiona bias $b_{\rm L;t}$ from the dependence of $\langle L \rangle$ on the matter density.

However, the luminosity is also affected separately by the baryon fluctuations, since the luminosity depends on the gas fraction in halos $f_{\rm b}$. Regions that have halos with a higher baryon fraction will proportionally have more baryons in the galaxies within them. If, e.g., we assume that the star formation rate per baryon is on average constant, then $\langle L \rangle \propto f_{\rm b}$. In fact, the dependence of the luminosity on the gas fraction is likely to be non-linear. For instance, in simple models for disk formation within halos (Mo et al. 1998), the disk radius is approximately independent of the gas fraction. Thus, if we assume that the disk mass is a fixed fraction of the halo gas mass, then the typical gas surface density within the disk varies in proportion to the overall halo gas fraction. According to the Schmidt-Kennicutt law (e.g., Kennicutt 1998), the star formation rate in the disk should vary with the gas surface density to the power 1.4. Thus, in general we assume that

$$\langle L \rangle \propto (f_{\rm b})^{b_{\rm L;f}} \ , \tag{4}$$

where these simple considerations suggest that $b_{\rm L;f} \approx 1.4$. The notation for this power index is chosen since equation (4) (together with equation 3) implies fluctuations

$$\delta_{\rm L} = (b_{\rm n} + b_{\rm L;t}) \delta_{\rm tot} + b_{\rm L;f} \delta_{\rm f} \ , \tag{5}$$

where $\delta_{\rm f}$ is the perturbation in the halo gas fraction $f_{\rm b}$. Thus, $b_{\rm L;f}$ is the bias factor of the luminosity density with respect to the halo baryon fraction. Note that in our notation all the perturbations are the actual ones at the considered redshift (i.e., we do not use the common practice of linear extrapolation to redshift zero).

2.2 Halo Baryon Fraction

We would expect the baryon fraction within halos to reflect that of their surroundings, but the precise relation is complex due to the non-linear process of halo collapse. Here we employ reasonable simplifications to derive an approximate result, which is partly verified and quantified by simulation results shown in § 3.

We find it useful to analyze the baryon fraction in several steps, where the first step is to avoid halo collapse and simply consider

$$\gamma_{\rm b} \equiv \frac{\rho_{\rm b}}{\rho_{\rm tot}} \ , \tag{6}$$

where we use $\gamma_{\rm b}$ for the general baryon fraction and reserve $f_{\rm b}$ for the baryon fraction inside halos. The mean of this quantity is the cosmic mean baryon fraction:

$$\bar{\gamma}_{\rm b} = \frac{\Omega_b}{\Omega_m} \ , \tag{7}$$

and its fluctuation is simply

$$\delta_\gamma = \delta_{\rm b} - \delta_{\rm tot} = r \delta_{\rm tot} \ . \tag{8}$$

Here we have measured the fractional difference between the baryonic and total matter fluctuations with $r \equiv (\delta_{\rm b}/\delta_{\rm tot}) - 1$, in general a function of both wavenumber k and redshift.

In reality, halos form out of perturbations that eventually grow to an overdensity of hundreds, making the contribution of the mean density negligible, and thus we expect the baryon fraction to reflect the relative mass of the baryon perturbation that formed the halo:

$$f_{\rm b} = \frac{\Omega_b \delta_{\rm b}}{\Omega_{\rm tot} \delta_{\rm tot}} = \bar{\gamma}_{\rm b} \frac{\delta_{\rm b}}{\delta_{\rm tot}} \ . \tag{9}$$

Before discussing non-linear collapse, we wish to apply this equation to the linear perturbations that will form a halo, but even in the linear case we cannot easily apply this equation in Fourier space, since halos form out of a sum of perturbations on all scales, and taking a ratio as in equation (9) is a non-linear operation.

To make further progress, we make a separation of scales (also called a peak-background split; Cole & Kaiser 1989), where we assume that the fluctuations that we wish to observe (in the galaxy luminosity, etc.) are on much larger scales than the (initial comoving) scales that formed the halos. Typically, we are interested in measuring fluctuations on BAO scales, which are ~ 2 orders of magnitude above the halo formation scale of galaxies. Thus, we separate out the linear halo perturbations (i.e., the initial perturbations that will form a halo, linearly extrapolated to the redshift of halo formation):

$$\delta_{\rm tot} = \delta^l_{\rm tot} + \delta^s_{\rm tot} \ , \tag{10}$$

$$\delta_{\rm b} = \delta^l_{\rm b} + \delta^s_{\rm b} = (1 + r_{\rm l}) \delta^l_{\rm tot} + (1 + r_{\rm s}) \delta^s_{\rm tot} \ , \tag{11}$$

where the relative difference between the baryonic and total matter perturbations is $r_{\rm l}$ and $r_{\rm s}$ on large and small scales, respectively.

We now use the standard result of spherical collapse, that a forming halo has a linear $\delta_{\rm tot} = \delta_{\rm c}$, where the critical density of collapse $\delta_{\rm c}$ is independent of mass (and equals 1.69 in the Einstein de-Sitter limit, valid over a wide range of redshifts). We also assume that we are considering sufficiently large scales so that $\delta^l_{\rm tot}$ can be treated as a perturbation of $\delta_{\rm tot}$ (or $\delta^s_{\rm tot}$), and that $r_{\rm l}$ and $r_{\rm s}$ are also small quantities. Then the mean baryon fraction in halos is

$$\bar{f}_{\rm b} = \bar{\gamma}_{\rm b} (1 + r_{\rm s}) \ , \tag{12}$$

and the lowest order perturbation comes out

$$\delta_{\rm f} = \frac{r_{\rm l} - r_{\rm s}}{\delta_{\rm c}} \delta^l_{\rm tot} \ . \tag{13}$$

We now use the actual value of $r(k)$ (see § 3), specifically the fact that it approaches a constant on scales below the BAOs, with a value (depending on redshift but not k) that we denote $r_{\rm LSS}$ following Naoz & Barkana (2007). Thus, in the just-derived equations we can treat $r_{\rm s} = r_{\rm LSS}$ as a constant (at a given redshift), since most of the density $\delta_{\rm c}$ needed to form a halo comes from scales well below the BAO scale. Thus, the mean baryon fraction in halos is

$$\bar{f}_{\rm b} = \bar{\gamma}_{\rm b}(1 + r_{\rm LSS}) \ , \tag{14}$$

while on large scales (i.e., small k) the fluctuation is

$$\delta_{\rm f} = \frac{r(k) - r_{\rm LSS}}{\delta_{\rm c}} \delta_{\rm tot} \ . \tag{15}$$

The remaining issue is the effect of non-linear collapse, and the relation between the baryon fraction in the linearly-extrapolated halo perturbation and the baryon fraction in the actual virialized halo. We show simulation results in § 3 that only test the mean baryon fraction in halos (equation 12) but do so over a range of redshifts, and suggest that halo collapse enhances the effect and results in an effective value of $r_{\rm LSS}$ that is amplified by a factor of several. One way to understand this enhancement is to consider the variation of $r_{\rm LSS}$ with time. It declines (in absolute value) approximately as $r \propto 1/a$ (where $a = 1/(1+z)$ is the scale factor), since $(\delta_{\rm tot} - \delta_{\rm b}) \approx$const while $\delta_{\rm tot} \propto a$ (until the cosmological constant becomes significant at low redshift). The decline of $r_{\rm LSS}$ with time is of critical importance, since we are computing it according to linear theory, and it may not be appropriate to extrapolate $r_{\rm LSS}$ all the way to the halo formation time when we evaluate it in equation (12). The baryon fluctuations, which were erased on small scales before cosmic recombination, later continuously catch up with the dark matter (and thus with the total matter as well) in linear perturbation theory. However, once a perturbation begins to form a halo and enters the non-linear stage of collapse, we expect that the rapid collapse will bring with it only the baryons already present within the perturbation, and the continued decline of the linear-theory $r_{\rm LSS}$ will become irrelevant for the halo gas content. The upshot is that the simulations suggest that if we use the linear-theory $r_{\rm LSS}$ (and similarly for $r(k)$) then we must multiply them by an effective amplification factor A_r:

$$\bar{f}_{\rm b} = \bar{\gamma}_{\rm b}(1 + A_r\, r_{\rm LSS}) \ , \tag{16}$$

$$\delta_{\rm f} = \frac{A_r}{\delta_{\rm c}} [r(k) - r_{\rm LSS}] \delta_{\rm tot} \ . \tag{17}$$

The resulting fluctuations in the luminosity density (equation 5) are

$$\delta_{\rm L} = (b_{\rm n} + b_{\rm L;t})\delta_{\rm tot} + b_{\rm L;\Delta}[r(k) - r_{\rm LSS}]\delta_{\rm tot} \ , \tag{18}$$

where

$$b_{\rm L;\Delta} \equiv b_{\rm L;f} \frac{A_r}{\delta_{\rm c}} \tag{19}$$

is an effective bias factor that measures the overall dependence of galaxy luminosity on the underlying difference Δ between the baryon and total density fluctuations.

2.3 Flux Limits

We have assumed thus far that we observe a fixed galaxy population, regardless of the varying luminosity of its members. In reality, observed samples are limited by flux, or equivalently by luminosity if for simplicity we consider galaxies at a single redshift. Suppose the fraction of galaxies above luminosity L is

$$F(L) = \int_{L'=L}^{\infty} \phi(L') dL' \ , \tag{20}$$

where ϕ is the luminosity function. Then the observed number density of galaxies is

$$n_{\rm obs} = n_{\rm gal} F(L) \ , \tag{21}$$

and the luminosity density of these galaxies is

$$\rho_L = n_{\rm gal} \langle L \rangle F(L) \ , \tag{22}$$

where

$$\langle L \rangle = \frac{1}{F(L)} \int_{L'=L}^{\infty} L' \phi(L') dL' \ . \tag{23}$$

We assume for simplicity that the same luminosity distribution holds in different regions, except that the luminosity of all galaxies is enhanced or diminished uniformly in response to changes in the total density and the halo baryon fraction, as discussed in § 2.1. If a sample only includes galaxies above a detection threshold $L_{\rm min}$, then we can analyze the variations of $F(L)$ by keeping ϕ fixed and varying the effective threshold $L_{\rm min}$, while in $\rho_{\rm L}$ we also include the perturbation in the luminosity of each galaxy. From equation (20) we obtain a relative fluctuation

$$\delta_F = C_{\rm min}[b_{\rm L;t}\delta_{\rm tot} + b_{\rm L;f}\delta_{\rm f}] \ , \tag{24}$$

where the dimensionless coefficient

$$C_{\rm min} = \frac{L_{\rm min}\, \phi(L_{\rm min})}{F(L_{\rm min})} \ . \tag{25}$$

The dependence of luminosity on the halo baryon fraction introduces a dependence of the galaxy number density on the baryon fluctuations (i.e., on $r(k)$). Putting our results together, for a flux-limited survey we find

$$\delta_{\rm n} = (b_{\rm n} + C_{\rm min} b_{\rm L;t})\delta_{\rm tot} + C_{\rm min} b_{\rm L;\Delta}[r(k) - r_{\rm LSS}]\delta_{\rm tot} \ , \tag{26}$$

and

$$\delta_{\rm L} = [b_{\rm n} + (1+D_{\rm min}) b_{\rm L;t}]\delta_{\rm tot} + (1+D_{\rm min}) b_{\rm L;\Delta}[r(k) - r_{\rm LSS}]\delta_{\rm tot} \ , \tag{27}$$

where

$$D_{\rm min} = \frac{L_{\rm min}}{\langle L \rangle} C_{\rm min} \ , \tag{28}$$

with $\langle L \rangle$ evaluated for $L = L_{\rm min}$.

In the limit where $L_{\rm min}$ is well below the peak of the luminosity function, $C_{\rm min}$ and $D_{\rm min}$ both approach zero, and these expressions simplify to the previous ones (equation 2 and 18). In the opposite limit, e.g., in the exponential tail of a Schechter function, we can approximately set $\phi(L) \propto e^{-L/L_*}$, and then $C_{\rm min} = L_{\rm min}/L_*$ and $D_{\rm min} = C_{\rm min} L_{\rm min}/(L_{\rm min} + L_*)$ are both $\gg 1$ when $L_{\rm min} \gg L_*$.

2.4 Observational Goals

As we have shown, both the galaxy luminosity density and (for a flux-limited sample) number density depend on the halo gas fraction. The scale-dependence of the relation between the baryon and dark matter fluctuations implies that the BAOs can be observed in ratios that previously would have been expected to be scale-independent.

One proposal is to compare the power spectrum of fluctuations in the galaxy number density ($P_{\rm n}$) with that of the luminosity density ($P_{\rm L}$), with both measured for the same galaxy sample. Taking the ratio may help to clear away some systematic effects that affect both power spectra. Their ratio (square-rooted) should have the form (assuming $r(k) \ll 1$):

$$\left(\frac{P_{\rm L}}{P_{\rm n}}\right)^{1/2} = B_1 \left\{1 + B_2[r(k) - r_{\rm LSS}]\right\} \ , \qquad (29)$$

where the various bias factors enter into the coefficients B_1 and B_2. If we denote the bias ratio $b_{\rm r} \equiv b_{\rm L;t}/b_{\rm n}$, then

$$B_1 = \frac{1 + (1 + D_{\rm min}) b_{\rm r}}{1 + C_{\rm min} b_{\rm r}} \ , \qquad (30)$$

and

$$B_2 = \frac{b_{\rm L;\Delta}}{b_{\rm n}} \frac{1 + D_{\rm min} - C_{\rm min}}{(1 + C_{\rm min} b_{\rm r}) \cdot [1 + (1 + D_{\rm min}) b_{\rm r}]} \ . \qquad (31)$$

Note that in the limit where most of the galaxy population is observed (i.e., the flux limits are unimportant), these expressions simplify to $B_1 = 1 + b_{\rm r}$ and $B_2 = b_{\rm L;\Delta}/(b_{\rm n} B_1)$.

In practice, using these expressions is not as daunting as it may appear. For a given galaxy sample, $C_{\rm min}$ and $D_{\rm min}$ can be calculated from the measured luminosity function. This leaves two unknowns, $b_{\rm r}$ and the ratio $b_{\rm L;\Delta}/b_{\rm n}$. Within the ratio, we have a well-motivated expectation for $b_{\rm L;\Delta} = b_{\rm L;f} A_r/\delta_{\rm c}$, given that $\delta_{\rm c} \approx 1.7$, $b_{\rm L;f} \approx 1.4$ (§ 2.1), and $A_r \approx 3$ from simulations (see § 3). Now, if r were independent of scale, then we could only measure a degenerate combination of the unknown quantities. However, a precise measurement of the power spectrum ratio can separate out the constant and BAO terms, thus yielding B_1 and B_2 separately, which in turns yields $b_{\rm r}$ and the ratio $b_{\rm L;\Delta}/b_{\rm n}$.

Although it is implicit in the equations, $r(k)$ and $r_{\rm LSS}$ are also (declining) functions of time. However, even at low redshift $r(k)$ contains a signature of the BAOs, since the BAOs are still imprinted more strongly in the baryon fluctuations than in those of the dark matter or the total matter. This clear signature offers a chance to detect this effect, even if the various bias factors that we have assumed to be constant actually vary slowly with k. A detection of the effect can be combined with an estimate of $b_{\rm n}$ from comparing $P_{\rm n}$ with the underlying matter power spectrum (e.g., as measured with weak lensing on large scales). Extraction of the value of $b_{\rm L;\Delta}$ would yield a new quantity in galaxy formation, a combination of the way in which the luminosity of a galaxy depends on the baryonic content of its host halo, and of how this baryonic content depends on the underlying difference between the baryon and total density fluctuations.

Another possibility is to compare the power spectra of number density (or luminosity density) between two different samples. Their ratio should again have a form similar to equation (29), from which the constant and BAO term can be separately measured. It is well known that galaxy bias depends on galaxy luminosity (**?**), but here the bias would be scale dependent in a way that depends on $L_{\rm min}$.

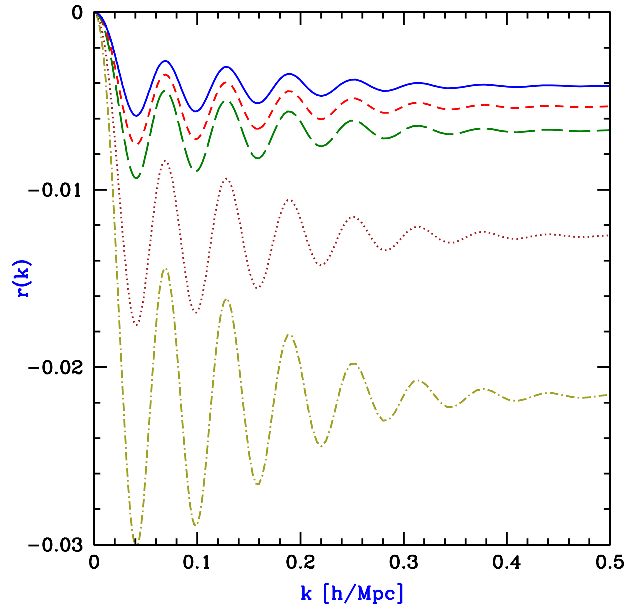

Figure 1. The fractional baryon deviation $r(k) = \Delta/\delta_{\rm tot} = (\delta_{\rm b}/\delta_{\rm tot}) - 1$ as a function of k, at various redshifts ($z = 0$, 0.5, 1, 3, and 6, from top to bottom).

3 QUANTITATIVE PREDICTIONS

For our quantitative results, we use the CAMB linear perturbation code (Lewis et al. 2000), with the WMAP 5-year cosmological parameters (Komatsu 2009), matching the simulation that we compare with below.

We show the dependence of r on both wavenumber and redshift in Figure 1. At a given redshift, $r(k)$ approaches a constant at $k \gtrsim 0.5$ h/Mpc, which we denote $r_{\rm LSS}$ following Naoz & Barkana (2007). Using $r_{\rm LSS}$ (itself a function only of redshift) we can separate out the two variables k and z in their effect on r, as shown in Figure 2. The function $[r(k)/r_{\rm LSS}] - 1$ is independent of redshift (i.e., the curves for five different redshifts overlap exactly), so the k dependence of r is determined by a single, fixed function of k. Thus, the redshift dependence of r is the same at all k, and it suffices to show the dependence of $r_{\rm LSS}$. Figure 2 shows that, as noted in the previous section, $r_{\rm LSS}$ indeed varies approximately in proportion to $1/a$, but in detail the variation with redshift is slightly slower than that.

As noted in the previous section, we expect the nonlinear evolution that takes place during halo formation to magnify the gas depletion effect compared to the linear theory calculation. We can test this effect using the hydrodynamical simulation of Naoz, Yoshida, & Barkana (2010). Although superficially it appears that they studied a quite different regime (low-mass halos forming at high redshift), their results should be applicable here. In the linear theory, the gas depletion factor $r_{\rm LSS}$ is constant all the way from the BAO scale ($k \sim 0.1$ h/Mpc) down to just above the Jeans scale ($k \gtrsim 100$ h/Mpc). Naoz, Yoshida, & Barkana (2010) investigate the gas depletion in virialized halos from below the Filtering mass (which is a time-averaged Jeans mass) up to a 10^3 times higher mass scale. Thus, the most massive halos in their simulation were well into the large-scale

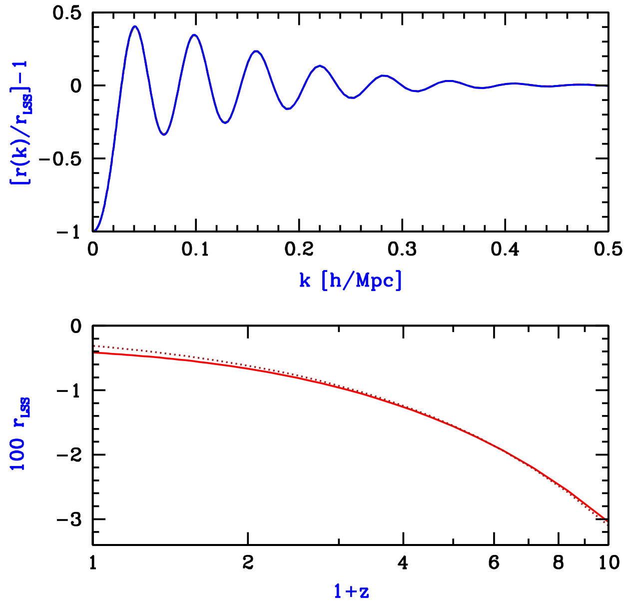

Figure 2. Top panel: $[r(k)/r_{\rm LSS}] - 1$ as a function of k, at the same redshifts as in Figure 1 (the curves all lie on top of each other). Bottom panel: The quantity $100 r_{\rm LSS}$ versus $1+z$ (solid curve). Equivalently, this shows the value of $r_{\rm LSS}$ in units of per-cent. Also shown is the function $-0.31/a$ (dotted curve). For both panels, in practice we set $r_{\rm LSS} \equiv r(k = 1{\rm h/Mpc})$.

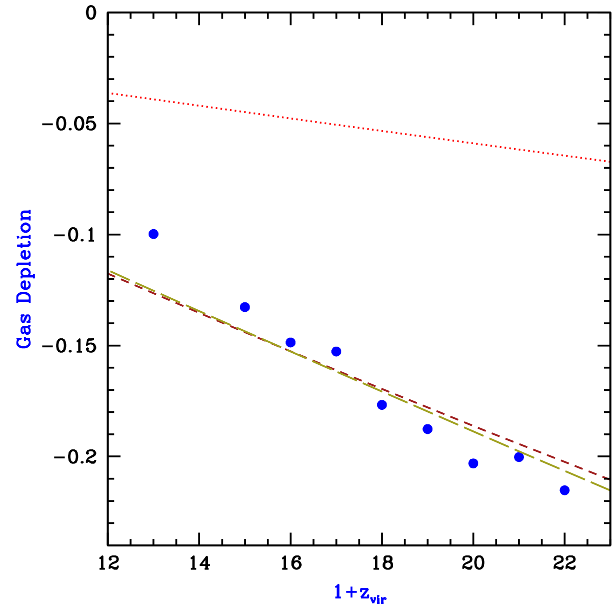

Figure 3. The fractional gas depletion in halos versus redshift. We show the results from the simulation of Naoz, Yoshida, & Barkana (2010) (data points), where the corresponding redshift (at which the virialized halos are identified in the simulation) can be denoted $z_{\rm vir}$. We compare the depletion as measured in the simulations to $r_{\rm LSS}$ at $z_{\rm vir}$ (dotted curve), $3.2 r_{\rm LSS}$ at $z_{\rm vir}$ (long-dashed curve), and $r_{\rm LSS}$ at a value of $(1+z)$ equal to $3.5(1+z_{\rm vir})$ (short-dashed curve).

structure regime, where pressure is negligible, and the effect we are interested in (i.e., non-linear gas depletion on large scales) should operate.

Figure 3 shows that the fractional gas depletion measured in virialized halos in the simulation of Naoz, Yoshida, & Barkana (2010) was much larger than the depletion $r_{\rm LSS}$ predicted for linear perturbations at the same redshift $z_{\rm vir}$. The simulated results can be reasonably fit either by multiplying $r_{\rm LSS}$ by a factor of 3.2, or by adopting $r_{\rm LSS}$ from a higher redshift z [where $(1+z) = 3.5(1+z_{\rm vir})$]. Additional simulations are required to test whether these results can indeed be extrapolated to our regime of much more massive halos at low redshift, but these results suggest that the gas depletion in halos is amplified by a factor $\gtrsim 3$ compared to the linear regime.

As an example of typical numbers, we consider an example with $C_{\rm min} = D_{\rm min} = 0$, $b_{\rm n} = 2$, and $b_{\rm L;t} = 1$. As noted in section 2.4, we expect in this case $b_{\rm L;\Delta} \sim 2.6$, and also $b_{\rm r} = 0.5$, so in the observational ratio of equation (29), $B_1 = 1.5$ and $B_2 = 0.9$. Thus, the oscillations in the square-root ratio of the luminosity and number density power spectra are at the level of 0.4% at $z = 1$ (measured from the first peak, i.e. at the lowest k, to the following trough; the variation from $k = 0$ to the first peak is roughly twice as large). This is a weaker effect by about a factor of five compared to the normal BAOs in the total matter power spectrum. Thus, if high precision is achieved in the regular BAO measurement, then the scale-dependent bias that we have highlighted should also be measurable.

This scale-dependent bias is unlikely to significantly affect the standard BAO measurements. Such measurements are usually carried out on the power spectrum of the galaxy number density. Scale-dependent bias enters this quantity only in proportion to $C_{\rm min}$ (see equation 26), so it would be present only in a sample for which the flux limit plays a significant role. Even then, the effect on the BAO peak positions would be quite weak, since the BAOs in $\delta_{\rm tot}$ are physically a result of the influence of the baryons on the dark matter. Thus, the peak positions in $\delta_{\rm tot}$ and in δ_b are nearly identical. For instance, even in the case that in equation 26 the coefficients $(b_{\rm n} + C_{\rm min} b_{\rm L;t})$ and $C_{\rm min} b_{\rm L;\Delta}$ are equal, the BAO peak positions are shifted only by $\sim 0.3\%$.

4 CONCLUSIONS

We have shown that the variation in the baryon to matter ratio imprinted by acoustic waves prior to cosmological recombination should result today in an oscillatory, scale-dependent bias of galaxies relative to the underlying matter distribution (see Figs. 1 & 2). The percent-level amplitude of this signature depends on how the typical luminosity of galaxies scales with the baryon mass fraction in the large-scale region in which they reside. Simulations suggest that this signature is significantly amplified by non-linear effects during halo collapse (Fig. 3). The resulting amplitude can be measured from the ratio between the power spectra of fluctuations in the luminosity density and number density of galaxies (Eq. 29), or from the dependence of the BAO bias on galaxy luminosity. An observational calibration of this amplitude would offer a new cosmological probe of the physics of galaxy formation.

This effect may be marginally observable with current data, but it should certainly be feasible using future galaxy surveys (such as BOSS[1] or BigBOSS[2]). However, since the baryonic and the matter fluctuations have nearly identical BAO peak positions, the scale-dependent bias is unlikely to significantly affect the standard BAO measurements, even at percent-level precision.

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