A POSSIBLE BIAS MODEL FOR QUASARS

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ABSTRACT

We propose that the majority of quasars at redshift \( z \approx 1-5 \) formed in the environment of newborn collapsed halos with one-dimensional velocity dispersion \( \sigma_{v}^{1D} \approx 400 \) km \( s^{-1} \). The harboring coefficient \( f \) of quasars per halo and the lifetime of quasars depend only on local processes; they are not modulated by the density inhomogeneities on scales larger than the size of the halos. Thus, the bias of quasars on scales larger than the size of these halos is mainly determined by the parameter \( q_{e} \), which is used for quasar environment identification. With this model, the popular structure formation models, like the standard cold dark matter (SCDM) and the low-velocity CDM, can be fairly well reconciled with the data of quasars, including (1) observed features of the environment for quasars, (2) the redshift evolution of quasar abundance, and (3) the two-point correlation functions of quasars. This bias model predicts that the correlation function of quasars does not significantly evolve or only slightly increases with redshift.

Subject headings: cosmology: theory — large-scale structure of universe — quasars: general

1. INTRODUCTION

Mass distribution at high redshifts is currently a hot topic in the study of the large-scale structure of the universe. Data of various objects at moderate and high redshifts—in particular, clusters of galaxies—are becoming available for probing the formation and evolution of structures and for discriminating among popular dark matter models (e.g., Jing & Fang 1994; Eke et al. 1996; Bahcall, Fan, & Cen 1997; Kitayama & Suto 1997). Considering that quasars are the most distant of the various luminous objects, they have also been applied in this approach (e.g., Bi & Fang 1997).

However, as a mass tracer of the cosmic matter field, quasars are still playing a role different from that of clusters of galaxies. The problem stems from so-called bias. Clusters are a biased tracer of the mass distribution. The correlation amplitude of clusters is believed to be much higher than that of the underlying matter, and it increases strongly with the cluster richness (Bahcall & Soneira 1983). This bias is plausibly explained by the mechanism that the observed clusters are identified as massive collapsed halos of the density field (Kaiser 1984). That is, the bias of clusters is completely determined by the gravitational parameters, like mass \( M \) and virial radius \( r_{vir} \), used to identify the halos. With this approach, a detailed comparison can be made between the theories and the observations of clusters.

Quasars may also be biased tracers of the mass distribution. Recent observations indicate that the correlation amplitude of quasars may also be different from the underlying dark matter (Mo & Fang 1993; Koomberg, Kravtsov, & Lukash 1994; Croom & Shanks 1996; La Franca, Andreani, & Cristiani 1997). However, so far no detailed model is available for the bias of quasars, although their high clustering strength and environment imply that quasars are hosted by massive halos (see below). Because of the lack of such a model, one cannot compare the data of quasars with theoretical models in the same manner as for clusters. For instance, the abundance of quasars can only be used as an upper or lower limit to certain massive halos; no detailed comparison between the number densities of quasars and of halos is allowed. Obviously, it is very important to understand what kind of mass halos are associated with the majority of quasars. Such knowledge will not only enable the observational data of quasars to be powerful tests for theoretical models of galaxy formation but will also tell us what type of local environment is responsible for initiating the nuclear activities of quasars.

Like clusters and groups of galaxies, it is generally believed that quasars should be associated with a certain type of collapsed dark matter halos. Yet, in contrast to the identification of clusters, the environment suitable for forming quasars is not merely determined by gravitational parameters, since the hydrodynamic processes are also involved. Therefore, the identification of quasar-harboring halos should be given by both gravitational and hydrodynamic parameters. In other words, not all halos with certain \( M \) and/or velocity dispersion \( q_{e} \) harbor quasars because certain hydrodynamic conditions must be satisfied. However, considering that the hydrodynamic processes are local, it is reasonable to assume that the hydrodynamic conditions may not be modulated by the density inhomogeneities on scales much larger than the size of the halo \( l \). In this case, the probability of a halo having a quasar should be the same for all halos of the same kind, without depending on structures larger than \( l \). Thus, the relative fractions of quasars with respect to the certain collapsed halos should be the same for all volumes larger than \( l^3 \). Consequently, when averaged on a scale larger than \( l \), the distribution of quasars \( n_{qso}(r, z) \) at redshift \( z \) should be proportional to that of the considered halos, \( n_{halo}(r, z) \). Thus, all effects of the hydrodynamic processes can be absorbed into a “normalization factor” \( A \), i.e., \( n_{qso}(r, z) = An_{halo}(r, z) \), and \( A \) is less dependent on \( z \) than \( n_{halo}(r, z) \). The bias of quasar distribution with respect to the mass distribution is then dominated by the bias of the selected halos with respect

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to the mass. Based on this analysis, quasar bias, at least on large scales, may also be only gravitational, depending on the gravitational parameters used for selecting the quasar-suitable halos.

Accordingly, a possible model for quasar bias should at least satisfy these three conditions. (1) The gravitational environment given by the identified halos is consistent with the observed environment around quasars. (2) The abundance of quasars, \( n_{qso}(z) \), at redshift \( z \) is proportional to the number density of the identified halos, \( n_{halo}(z) \), in a redshift-independent way, i.e., \( n_{qso}(z) = An_{halo}(z) \), where \( A \) is a \( z \)-independent constant. (3) The amplitude and \( z \)-evolution of the halo-halo correlation function are consistent with the observed correlation function of quasars.

In this Letter, we will show within the framework of the cold dark matter (CDM) cosmogenic theories that such a bias model can indeed be settled following the above-mentioned conditions. The details of conditions 1, 2, and 3 will be discussed in §§ 2, 3, and 4, respectively.

2. BASIC ASSUMPTION: THE GRAVITATIONAL CONDITION FOR A QUASAR HALO

A bias model of quasars is just a phenomenological relationship between the cosmic density field and quasars. With this relationship, quasars can be identified from the mass density field. In this sense, bias, in fact, is a model for the environment that is suitable for the quasar formation.

In what environment are quasars most likely to be formed? Many observations indicate that quasars are preferentially located in groups of galaxies. The evidence includes the quasar-galaxy covariance function (Yee & Green 1987), the galaxy environments around quasars (Ellingson, Yee, & Green 1991), the clustering of quasars (Bahcall & Chokshi 1991; Mo & Fang 1993; Komberg, Kravtsov, & Lukash 1994; Croom & Shanks 1996; La Franca et al. 1997), and the \( C IV \)-associated absorption in high-redshift radio-loud quasars (Foltz et al. 1988). Recently, an observation of a companion to quasar BR 1202−0725 with high redshift (\( z = 4.7 \)) directly showed that the width of their \( Lyalpha \) emission lines is \( \sim 400 \) km s\(^{-1} \) (Petitjean et al. 1996). These observations seemingly point to quasars being identified with the newly collapsed halos with one-dimensional velocity dispersion like groups, i.e., \( \sigma_{v} \approx 400 \) km s\(^{-1} \). It should be pointed out that this environmental condition may not be necessary for low-redshift quasars (Smith, Boyle, & Maddox 1995) because the galaxies and clusters underwent a significant evolution at \( z \approx 0.5 \). However, it is reasonable to assume that the environment with \( \sigma_{v} \approx 400 \) km s\(^{-1} \) is favored by the formation of quasars at higher redshifts: it has (1) enough collapsed objects to form the engine of a quasar; (2) dispersed gas to feed the engine through accretion; and (3) not too many protogalaxies to possibly disrupt the process of quasar formation. In the next two sections, we shall compare, within the framework of CDM cosmogenic models, the theoretical predictions for such halos with the observed quasar abundance and correlation functions.

3. REDSHIFT EVOLUTION OF ABUNDANCE OF QUASARS

For a Gaussian initial perturbation, the comoving number density of halos with one-dimensional velocity dispersion \( \sigma_{v} \) can be calculated with the Press & Schechter (1974) formalism as

\[
N(\sigma_{v}, z) d\sigma_{v} = -\frac{\sqrt{3}}{2\pi R^{3/2}} \frac{d\ln \Delta(R, z)}{d\ln R} d\ln R \times \frac{\delta_{c}}{\Delta(z)} \exp \left[-\frac{\delta_{c}^{2}}{\Delta^{2}(R, z)} \right] dR,
\]

where \( R \) is the Lagrangian radius of the dark halo being considered, and \( \delta_{c} \approx 1.69 \) is almost independent of cosmologies. \( \Delta(R, z) \) is the rms of the linear density fluctuations at redshift \( z \) within a top-hat window of radius \( R \) and is determined by the initial density spectrum \( P(k) \) and normalization factor \( \sigma_{v} = \Delta(8 h^{-1} \text{Mpc}, 0) \). The relationship between \( \sigma_{v} \) and \( R \) is given by (Narayan & White 1988)

\[
\sigma_{v} = c_{s} \Omega_{a}^{1/2} H_{0} R_{0} (1 + z)^{1/2},
\]

for a universe with the density parameter \( \Omega_{a} \). The \( N \)-body simulation results (Jing & Fang 1994) showed \( c_{s} \approx 1.2 \), which is used for all calculations in this work. Two representative CDM models, i.e., the standard CDM (SCDM) and flat low-density CDM (LCDM) models are employed. The Hubble constant \( h = H_{0}/100 \) km s\(^{-1} \) Mpc\(^{-1} \), mass density \( \rho_{m} \), and cosmological constants \( \lambda_{c} \) and \( \sigma_{50} \) are taken to be \((0.5, 1, 0.58) \) and \((0.75, 0.3, 0.7, 1) \) for the SCDM and LCDM, respectively. Models with these parameters seem to provide a good approximation to many observational properties of the universe, especially the abundance of clusters (which is closely related to the topic of this work).

The total number density of the collapsed halos with the velocity dispersion greater than a certain value, say \( \sigma_{v} \), is

\[
N(> \sigma_{v}) = \int_{0}^{\sigma_{v}} n(\sigma_{v}, z) d\sigma_{v}.
\]

The birthrate of halos with \( \sigma_{v} \geq \sigma_{v} \) is \( dN(> \sigma_{v})/d\tau \). This birthrate is shown in Figure 1 for \( \sigma_{v} = 200, 400, \) and 800 km s\(^{-1} \). For each \( \sigma_{v} \), the birthrate in the two models possesses a similar shape. As has been discussed in §§ 1 and 2, each newly collapsed halo with \( \sigma_{v} > \sigma_{v} \) may host f quasars on average, and the harboring coefficient f is \( z \)-independent.
the comoving number density of quasars at the epoch of redshift \( z \) is given by

\[
n(z) = f \int_{r(z) - \rho_{qso}}^{\rho_{qso}} \frac{\partial N(> \sigma_{\text{lim},z}, z')}{ \partial z'} \, dz' \, dt.
\]

An accurate quasar lifetime \( t_{\text{qso}} \) is not important only if it is \( z \)-independent and is much less than the age of the universe for redshifts \( z \leq 5 \). Considering that the birthrate of the halos slowly varies with redshift when \( z > 1 \), we have approximately

\[
n(z) \approx f t_{\text{qso}} [\sigma(> \sigma_{\text{lim},z})/\partial z] (dz/dt).
\]

Since the shape of the birthrate is a strong function of the velocity dispersion (especially as a function of \( z \)), the abundance of quasars provides a strong test of the bias model proposed here.

Figure 2 plots \( n(z) \) for the SCDM and LCDM models. The “normalization constant” \( t_{\text{qso}} \) is adjusted in order that the theoretical maximum number densities of quasar abundance can fit with the observed one. The data points are the number density of quasars complete to absolute magnitude \( M_p = -26 \) (Pei 1995; Hewett, Foltz, & Chaffee 1993; Schmidt, Schneider, & Gunn 1991). In these observations, the density \( n(z) \) is measured in the Einstein–de Sitter cosmology (\( \Omega = 1 \), \( \lambda_0 = 0 \), and \( h = 0.5 \)). These data have been corrected to the case of nonzero \( \lambda_0 \) in the right-hand (LCDM) panel of the figure. The figure shows the redshift evolution of quasar abundances is fairly well described by the newly collapsed halos with \( \sigma_{\text{lim}} = 400 \) km s\(^{-1} \). The SCDM and LCDM models are both in reasonably good agreement with the observed abundance \( n_{\text{obs}}(z) \) if the constant \( (z \)-independent) parameter \( t_{\text{qso}} \) is taken to be 0.02 \( \times 10^7 \) yr for the SCDM model and 0.33 \( \times 10^7 \) yr for the LCDM model, although the best-fitting value of \( \sigma_{\text{lim}} \) is slightly lower (\( \sim 340 \) km s\(^{-1} \)) for the SCDM model. However, for \( \sigma_{\text{lim}} = 200 \) and 800 km s\(^{-1} \), the predictions cannot fit with the observed redshift evolution regardless of how the normalization constant \( t_{\text{qso}} \) is adjusted. Therefore, the consistency between the theoretical and the observed redshift evolution of quasar abundance can be achieved only for \( \sigma_{\text{lim}} \approx 400 \) km s\(^{-1} \), which is not trivial. This result strongly supports the notion that the majority of quasars are associated with newborn halos with one-dimensional \( \sigma_{\text{lim}} \approx 400 \) km s\(^{-1} \).

Particularly, for an environment with a given mass or velocity dispersion, the luminosities and lifetimes of quasars are still dispersed. However, if the distributions of the luminosities and of the lifetimes for this type of halo are not modulated by large-scale perturbations, all conclusions here should hold.

4. Amplitude and Redshift Evolution of the Quasar Correlation Function

According to the analysis of § 1, the bias model for \( \sigma_{\text{lim}} \sim 400 \) km s\(^{-1} \) halos is available on scales larger than their typical size, which is \( \sim 3(1 + z)^{-1/2} \Omega_\text{e}^{1/2} h^{-1} \) Mpc. Therefore, on scales larger than 5 \( h^{-1} \) Mpc, the bias of quasar distribution is due mainly to the bias of \( \sigma_{\text{lim}} \) halos. On such large scales and at high redshifts, the mass distribution is still linear. Therefore, the two-point correlation function of the halos at redshift \( z \) is given by

\[
\xi(r, z) = b^2(R, z) \xi_{\text{lin}}(r, z),
\]

where \( r \) is the physical radius, \( \xi_{\text{lin}}(r, z) \) is the linear mass correlation function, and the bias factor \( b \) is given by (Mo & White 1996)

\[
b(R, z) = 1 + \frac{1}{\delta_c^2} \left[ \frac{\delta_c^2}{\Delta^2(R, z)} - 1 \right].
\]

Figure 3a shows the correlation functions for \( \sigma_{\text{lim}} = 200 \), 400, and 800 km s\(^{-1} \) halos at \( z = 2 \). It shows that for \( \sigma_{\text{lim}} = 400 \) km s\(^{-1} \), the correlation length \( r_0 \) defined by \( \xi(r) = (r/r_0)^{-1.8} \)
is \( \sim 6\ h^{-1}\) Mpc for the SCDM model and \( \sim 14\ h^{-1}\) Mpc for the LCDM model. Observationally, the two-point correlation function of quasars is found to obey the same power law. With \( d_0 \) taken to be 0.5, the correlation length \( r_\theta \) at \( z = 1.5 \) is found to be \( \sim 6.6 \pm 0.5 \) (Mo & Fang 1993), \( 10 \pm 2 \) (Komberg, Kravtsov, & Lukash 1994), and 6.2–8.0 \( h^{-1}\) Mpc (La Franca et al. 1997). Actually, these results do not sensitively depend on \( d_0 \) because on the length scales of \( \sim 10\ h^{-1}\) Mpc, the influence of the parameter \( q_0 \) is small. We should be careful in comparing the observed data with Figure 3a. Generally, the samples of quasars employed for the correlation statistics possess different limit magnitudes for different redshifts. The samples employed for the correlation statistics contain quasars with \( M_B > -26 \). Namely, they are not complete in the same sense as the data used in Figure 2. The larger \( M_B \) may lead to a lower amplitude of the correlations. Considering this uncertainty, both SCDM and LCDM models with \( \sigma_{100} = 400\ km\ s^{-1} \) halos are acceptable, although a smaller or larger value of \( \sigma_{100} \) may also be tolerated by the clustering observation alone.

The redshift evolution of the halo-halo correlations for the SCDM and LCDM models is plotted in Figure 3b. It is interesting to see that the amplitudes of the correlation functions do not significantly evolve with redshift, having only a slight increase with redshift. This is because the clustering in the mass distribution of dark matter, \( \xi(r, z) \), always increases with time or decreases with redshift, but the bias factor \( b(R,z) \) increases with redshift. The two effects seem to be balanced by each other, which results in a very slowly varying of \( \xi(r, z) \) with \( z \).

The \( z \)-evolution of quasar clustering has been studied for more than one decade (e.g., Chu & Fang 1987; Shaver 1988), and the results are quite scattered. Some studies showed a weak decrease of the correlation amplitudes around redshift 1.5 on scales greater than \( 10\ h^{-1}\) Mpc (Mo & Fang 1993; Komberg et al. 1994; Croom & Shanks 1996). Some concluded that there is no significant \( z \)-dependence from \( z \sim 1.5-2.9 \) (Zitelli et al. 1992), and some even showed a very weak increase with redshift. Recently, a weak \( z \)-increasing correlation from \( z < 1.4 \) to \( z > 1.4 \) was reported (La Franca et al. 1997). Obviously, these diverse data cannot provide a concrete test of the prediction of Figure 3b. Although there is a bit of uncertainty in the observed redshift evolution, the current result—no significant evolution of either \( z \)-increase and \( z \)-decrease—is consistent with the developed bias models.

5. CONCLUSIONS

We showed that velocity dispersion–selected halos are a possible mechanism for the bias of quasars. The majority of quasars at redshift \( z \sim 1-5 \) formed in the environment of newborn collapsed halos with one-dimensional velocity dispersion \( \sigma_{100} \sim 400\ km\ s^{-1} \). Both the harboring coefficient \( f \) per halo and the lifetime of quasars are \( z \)-independent. With this bias model, the popular structure formation models, like the SCDM and LCDM models, can be fairly well reconciled with data of the abundance and correlations of quasars at \( z \geq 0.5 \).

It is interesting to point out that the velocity dispersion–identified halos generally do not have the same mass. Equation (2) shows that for a given \( \sigma_{100} \), the higher the redshift, the smaller the mass of the halos. This result has already been recognized in an earlier study, which shows that in order to fit with quasar abundance at high redshift, the mass of the halos has to be smaller than that at the lower redshift (Bi & Fang 1997).

With this model, one can predict that (1) the environment for quasars at redshifts from \( z \sim 1 \) to \( 5 \) should be characterized by a velocity dispersion, \( \sigma_{100} \sim 400\ km\ s^{-1} \); (2) the amplitudes of quasar two-point correlation function at high redshifts do not significantly evolve with redshifts. In this letter, only models of the SCDM and the LCDM are considered. We can expect that as better data on quasars becomes available, the bias model of quasars will play a more important role for discriminating among models of structure formations.

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