THE LUMINOSITY DEPENDENCE OF QUASAR CLUSTERING

Adam Lidz1, Philip F. Hopkins1, Thomas J. Cox1, Lars Hernquist1, Brant Robertson1
1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT

We investigate the luminosity dependence of quasar clustering, inspired by numerical simulations of galaxy mergers that incorporate black hole growth. These simulations have motivated a new interpretation of the quasar luminosity function. In this picture, the bright end of the quasar luminosity function consists of quasars radiating nearly at their peak luminosities, while the faint end consists mainly of very similar sources, but at quasar lifetimes in this scenario than in most previous models. Although Hopkins et al. (2005e) demonstrate that this theory reproduces well a wide range of quasar observations not explained by previous models of the quasar light curve, the luminosity dependence of quasar clustering provides a direct probe of the most fundamental distinction between these models, and can be tested even at high redshift where observations of e.g. the Eddington ratio distribution of quasars are not currently practical.

In fact, Adelberger & Steidel (2005) have recently measured the galaxy-quasar cross correlation function, finding no evidence for luminosity-dependent clustering. Their interpretation of this observation is that faint quasars are longer-lived than bright quasars which populate high mass halos. In the model of Hopkins et al. (2005e) most bright and faint quasars are similar sources, seen at a different stage in their evolution. Therefore, one expects quasar clustering to depend less strongly on luminosity in this scenario than in most previous models. Although Hopkins et al. (2005e) demonstrate that this theory reproduces well a wide range of quasar observations not explained by previous models of the quasar light curve, the luminosity dependence of quasar clustering provides a direct probe of the most fundamental distinction between these models, and can be tested even at high redshift where observations of e.g. the Eddington ratio distribution of quasars are not currently practical.

In fact, Adelberger & Steidel (2005) have recently measured the galaxy-quasar cross correlation function, finding no evidence for luminosity-dependent clustering. Their interpretation of this observation is that faint quasars are longer-lived than bright quasars. While this interpretation is qualitatively similar to the one we advocate, we will further demonstrate that it is, in fact, a natural consequence of our numerical models.

The aim of the present paper is to provide quantitative predictions for the luminosity dependence of quasar clustering, based on our numerical simulations. Our analysis proceeds in two steps. The first, described in §2, characterizes the relationship between quasar luminosity and the
mass of quasar host dark matter halos. We use the numerical
simulations of Springel et al. (2005a) to formulate our
description of the connection between quasar luminosity
and halo mass. The next step of our analysis is to connect
quasar properties with the statistics of the dark matter ha-
os that host quasars, as has been done previously (e.g., Ef-
statthiou & Rees 1998; Kauffmann & Haehnelt 2000; Mar-
tini & Weinberg 2001; Haiman & Hui 2001; Porciani et al.
2004; Wyithe & Loeb 2005). This part of our calculation
is described in §3, where we determine which dark matter
halos host active quasars, and provide predictions for the
luminosity dependence of quasar bias. In §4 we explore the
redshift evolution of quasar clustering. In §5 we conclude
and summarize the present status of, and future prospects
for, measurements of the luminosity dependence of quasar
clustering.

2. THE RELATION BETWEEN QUASAR LUMINOSITY AND
HALO MASS

We begin by connecting quasar luminosity with the mass
of quasar host halos. The key point here is that the
halo mass is correlated with the peak luminosity of quasar
sources, and is connected only indirectly with the instan-
taneous luminosity through the quasar light curve. We
therefore separate the connection between instantaneous
quasar luminosity and halo mass into two distinct pieces.
The first part is the correlation between peak luminosity
and halo mass. The second part involves the quasar light
curve which connects the instantaneous and peak lumi-
nosities of quasar activity. We illustrate this by evaluat-
ing the correlation between halo mass and peak luminosity,
considering numerical simulations of merging galaxies at
z = 2, i.e., close to the epoch of peak quasar activity.

Specifically, we consider 24 simulations of merging galax-
ies at z = 2. The simulations, described in more detail
in Springel et al. (2005a) and Robertson et al. (2005),
model merging galaxies of varying halo mass, initial disk
gas fraction, and effective equation of state for the inter-
stellar gas. In each simulation, we determine the amount
of time the merger spends in each of several logarithmic
bins in bolometric luminosity. We then determine the peak
bolometric luminosity of a particular merger by identifying
the highest luminosity bin reached. The peak bolometric
luminosity is converted into a peak optical, B-band lumin-
osity using the relation of Marconi et al. (2004), given
by log10 (LB) = 0.80 − 0.067L + 0.017L2 − 0.0023L3, with
L = log10 (Lbol/L⊙) − 12. Here, LB denotes the quasar
B-band luminosity, while Lbol indicates the quasar boltom-
metric luminosity. The resulting peak B-band luminosity
from our simulations, and its dependence on halo mass is
shown in Fig. 1. The red open circles in the plot indicate
the result of each merger simulation, while the cyan
closed circles show the results (logarithmically) averaged
over simulations with identical halo mass.

The plot indicates a clear correlation between the peak
luminosities of quasars and the masses of their host dark
matter halos. This correlation is a natural consequence of
the self-regulated nature of quasar activity. Specifically,
analytic models of self-regulated black hole growth pre-
dict that the peak luminosity scales with the halo circular

\[ v_c \text{, either as } L_p \propto v_c^5, \text{ or } L_p \propto v_c^4. \]

The first scaling is the result of assuming that the peak luminosity
is set by equating the feedback energy from accretion cou-
ped to the halo gas in a dynamical time with the binding
energy of the gas (Silk & Rees 1998; Ciotti & Ostriker
2001; Wyithe & Loeb 2002). The second scaling results
from assuming that momentum, as opposed to energy, is
conserved in the evolution of the quasar “outflow” that
eventually unbinds the surrounding gas (e.g., King 2003,
Di Matteo et al. 2005). This scaling is appropriate if the
outflowing gas can cool efficiently.

Indeed, these authors suggest that this self-regulation
likely explains the tight correlation observed between black
hole mass and stellar velocity dispersion in local black hole
populations (e.g., Gebhardt et al. 2000; Ferrarese & Mer-
riss 2000; Tremaine et al. 2002), with the peak luminos-
ity corresponding to the Eddington luminosity of the final
black hole mass. Ferrarese (2002) further argues that there
is direct observational support for a correlation between
black hole mass and halo circular velocity, as expected
in the analytic models. Since the halo circular velocity
is proportional to the one-third power of the halo mass,
the first scaling implies that peak luminosity scales with
halo mass as \( L_p \propto M^{5/3} \), while the second scaling implies
\( L_p \propto M^{4/3} \).

A comparison between these scalings and the simu-
lation results is shown in Fig. 1. The green dotted
line indicates the first scaling, with the normalization
adopted by Wyithe & Loeb (2003) which, at \( z = 2 \), is
\( L_p = 6.78 \times 10^{10} L_\odot (M/10^{12} M_\odot)^{5/3} \). The second scaling,
\( L_p \propto M^{4/3} \), with the same normalization, is indicated by

![Fig. 1.](image-url)
the black solid line in the figure. Neither scaling is a perfect
description of the mean trend seen in the simulations,
though the somewhat shallower relation, \( L_p \propto M^{4/3} \),
is clearly a better overall match. This corresponds to a
M_{BH} - \sigma \propto \sigma^4 \) (see Di Matteo et al.
2005, Robertson et al. 2005 for direct measurements of the
\( M_{BH} - \sigma \) relation in our simulations), which agrees
better with observations (e.g. Tremaine et al. 2002) than
the alternate scaling. In practice, we find that halos with
only a narrow range in mass host active quasars (see §3).
Hence, we find that our results are quite similar if we use
a direct spline fit to the mean simulated trend, (shown by
the cyan circles in Fig. 1), or instead adopt the approxi-
mate \( L_p \propto M^{4/3} \) scaling. Likewise, we have also analyzed
in detail the difference between assuming an
scaling. This corresponds to a
in good agreement with that observed by e.g. Marconi &
Hunt 2003).

This represents the main difference between our modeling
and previous work: in our picture, quasars spend an ex-
tended amount of time radiating at less than their peak
luminosity, in contrast to models in which sources follow
simplified ‘on/off’ (‘light bulb’) or pure exponential light
curves. The observed quasar luminosity function should
then be thought of as a convolution of the quasar light
curve with an intrinsic distribution of sources of a given
peak luminosity. We will follow Hopkins et al. (2005c,e)
and extract the peak luminosity distribution from the ob-
served luminosity function, using the quasar light curves
obtained from our numerical simulations. Given the peak
luminosity distribution, and the correlation between peak
luminosity and halo mass described above, we can then
predict the clustering properties of quasars.

We proceed by describing the relation between the
quasar light curve, the peak luminosity distribution, and
the quasar luminosity function. Specifically, the quasar
luminosity function can be written as (Hopkins 2005c):

\[
\frac{d\Phi}{dL}(t_0) = \frac{dL}{dP} \left[ \int_{t_0-t_p(L_p)} dt \int \frac{dL_p'}{L_p} \frac{dP(t')}{dL_p} \right],
\]

(2)

where \( d\Phi(t_0)/dL \) denotes the luminosity function at (cos-
ic) time \( t_0 \), \( t_p(L_p) \) represents the amount of time quasars
with a given peak luminosity, \( L_p \), spend at lower
luminosities, \( L_s \), and \( dn/L_p \) is the rate at which quasars
of a given \( L_p \) are created or ‘activated’. If we further
assume that \( dn/L_p \) is approximately constant over the
lifetime of the quasar activity (as shown in Hopkins et al.
2005c), it follows that

\[
\frac{d\Phi}{dL}(t_0) \sim \frac{dL_p}{dP} \left[ \int \frac{dL_p'}{L_p} \frac{dn_p(t_0)}{dL_p} \right] \frac{dP(L_p)}{dL}.
\]

(3)

The second equality in the above equation further as-
serts that the product of the rate of producing quasars
and the amount of time they spend at a given luminos-
ity, is equal to the abundance of sources multiplied by
the probability of finding an object at a given luminosity.
This is justified by assuming that each quasar has a sim-
ilar activation timescale, \( t_{ac} \), so that \( n_p \sim n_p/t_{ac} \). The
product of the lifetime, and the rate of producing quasars,
\( dn_q(L_p)/dL \times\#p/dL \), is then equal to \( dP(L_p)/dL \times\#p/dL \),
where the probability, \( dP(L_p)/dL \), is the ratio of the
lifetime to the activation timescale. Essentially, this is
just a refinement of the commonly adopted proportion-
ality between the probability of observing an object and its
lifetime. We measure the quasar lifetime, \( t_{q}(L_p)/dL \),
directly in our simulations, and so we know the above
probability distribution up to a proportionality constant
set by the activation timescale. In this paper we will not
try to predict this proportionality constant theoretically,
and hence our constraints come solely from the shape
of the luminosity function, and not its absolute normal-
ization. We then adopt the power law fitting formula for the
quasar lifetime from Hopkins et al. (2005b):

\[
L_{bol} \frac{dP(L_{bol} | L_{bol}, \alpha)}{dL_{bol}} \propto |\alpha| \frac{L_{bol}}{10^{35} L_{bol}} \alpha.
\]

(4)

This applies for luminosities less than the peak luminos-
ity, \( L_{bol} < L_{bol} \), but is zero otherwise. In this equa-
tion, \( \alpha \) is a function of the peak bolometric luminosity,
\( L_{bol} \). Specifically, Hopkins et al. (2005b) give \( \alpha = \min[-0.2, -0.95 + 0.32 \log_{10}(L_{bol}/10^{35} L_{bol})] \). The above
expressions are then converted from bolometric luminos-
ity to optical B-band luminosity using the Marconi et al.
(2004) formula, including a Jacobian factor to convert
between the two differential probability distributions.2

We then invert Eq. 3 to find the distribution of quasar
peak luminosities, \( L_pdn_p/dL \) (Hopkins et al. 2005c,e).

2We neglect here the obscuration effects modeled by Hopkins et al.
(2005b,d,e) which relate the quasar light curves at different fre-
frequencies. We estimate that these effects are less important than
uncertainties in the distribution of peak luminosities resulting from
the poorly constrained faint end of the quasar luminosity function.
In performing this inversion, we use the double power law fit from Boyle et al. (2000), to represent the observed luminosity function. We refer the reader to Hopkins et al. (2005c) for a plot of the resulting distribution, and present here only a qualitative description as follows. At high peak luminosity, the shape of the peak luminosity distribution tracks the shape of the observed luminosity function, it then reaches a peak near the break in the observed luminosity function, and turns over at low peak luminosity. The behavior of the distribution of peak luminosities simply reflects the fact that quasars with large peak luminosity spend long periods of time at low luminosity, and account, mostly by themselves, for the faint end of the quasar luminosity function: there is no need for quasars with small peak luminosity. The sharpness of the turnover in the peak luminosity distribution depends, however, on the poorly measured faint end of the quasar luminosity function. This behavior is insensitive to which of the many measured quasar luminosity functions we adopt, as demonstrated in Hopkins et al. (2005c).

3. WHICH DARK MATTER HALOS HOST ACTIVE QUASARS?

We now proceed to connect quasar properties with the properties of their host dark matter halos. Our motivation here is that the abundance and clustering of dark matter halos is well understood, and these quantities are easily extracted from numerical simulations of structure formation. Moreover, the results of detailed simulations (e.g. Springel et al. 2005c) agree well with analytic models based on an excursion set formalism in the context of an ellipsoidal collapse model (Sheth & Tormen 2002). We can use these analytic models to specify the abundance and clustering of dark matter halos, and relate these to quasar properties. In this section we perform calculations at $z = 2$ as an illustrative example; we generalize to other redshifts in §4.

In order to carry out this procedure, we adopt a simple phenomenological model: we assume that a fraction, $f_{\text{on}}(M)$, of halos of mass $M$ host active quasars. In the future, we will attempt to predict this quantity theoretically, but for now we will determine $f_{\text{on}}(M)$ from the distribution of peak luminosities above, the correlation between peak luminosity and halo mass from our simulations, and theoretical models for the abundance of dark matter halos. In what follows, we will use the mass function — i.e., the abundance of dark matter halos with mass between $M$ and $M + dM$ — derived by Sheth & Tormen (2002), $dN_{\text{halo}}/dM$.\(^1\) The peak luminosity distribution is related to the halo mass function in our simple model by the relation

$$L_p \frac{dn_p}{dL_p} = \int dM \frac{dN_{\text{halo}}}{dM} f_{\text{on}}(M) L_p \frac{dP(L_p|M)}{dL_p}. \quad (5)$$

In principle, this equation can be inverted to find $f_{\text{on}}(M)$. In practice, we instead adopt a lognormal form for $f_{\text{on}}(M)$, $f_{\text{on}}(M) = \left(\frac{2\pi\Delta_m}{\sqrt{e}}\right)^{-1} \exp \left[-\ln(M/M_\text{m})^2/(2\Delta_m^2)\right]$, and

\(^3\)Specifically, we use the pure luminosity evolution fit in which the break magnitude is a quadratic function of redshift (Boyle et al. 2000).

\(^4\)We perform all calculations with the Eisenstein & Hu (1999) fitting formula for the transfer function, and adopt a cosmological model with the parameters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b h^2 = 0.02$, and $\sigma_8(z = 0) = 0.9$.

determine the parameters of the lognormal, $\Delta_m$, $M_\text{m}$, that best match the distribution of peak luminosities, which is in turn constrained to match the observed luminosity function (see Eq. 3). The lognormal form is a convenient parameterization, since, as we will illustrate, our model predicts that quasar host halos have a well-defined characteristic mass. The peak of the lognormal distribution conveniently represents this characteristic mass, while the width of the distribution indicates how broad a range of halo masses host active quasars. As described in §2, we infer the peak luminosity distribution only up to an overall normalization constant, and so we are fitting only the shape of the $f_{\text{on}}(M)$ distribution, and not the absolute normalization.

The results of this exercise are shown in Fig. 2. The bottom panel of the figure shows two models for the fraction of halos of mass $M$ that host active quasars, while the top panel shows the corresponding predictions for the quasar luminosity function. The red solid line indicates the best fit, while the black dotted line describes a model that is an acceptable, but less good fit to the data. In our best fit model at $z = 2$, active quasars are hosted by dark matter halos with a characteristic mass, $M \sim 1.3 \times 10^{13} M_\odot$. Moreover, only a narrow range of halo masses appear to house active quasars: the fractional width of the distribution $f_{\text{on}}(M)$ is only $\Delta_m \sim 0.75$. The narrowness of $f_{\text{on}}(M)$ is a reflection of the narrowness of the peak luminosity distribution seen in Hopkins et al. (2005c).

On the other hand, current measurements of the quasar
luminosity function do in principle accommodate a substantially broader $f_{\text{on}}(M)$ distribution. This is illustrated by the black dotted line in each panel of the figure. Here, the model luminosity function is normalized to match the observed luminosity function at a luminosity close to the break in the luminosity function. In this case, the characteristic mass of quasar host halos is the same as in our best fit model, while the fractional width of the distribution is $\Delta_m \sim 1.8$, nearly two and a half times as large as in our best fit model. This model is clearly a worse match to the Boyle et al. (2000) luminosity function, but it is still within the range allowed by the measurement errors. Finally, we note that if the mean peak luminosity, $L_m$, of Eq. 1 instead follows the Wyithe & Loeb (2003) relation, $L_m \propto M^{5/3}$, the characteristic halo mass would be $\sim 7.5 \times 10^{12} M_\odot$, and the width of the distribution would be $\Delta_m \sim 0.5$.

To reiterate, quasars with large peak luminosity sit in massive halos, and spend a significant amount of time at lower luminosities. These sources already account for the faint end of the luminosity function, and hence one over-produces the abundance of faint quasars if low mass halos host active quasars. Moreover, if very massive halos house active quasars, one might over-produce the bright end of the quasar luminosity function. Consequently, a wide range of quasar luminosities corresponds to only a narrow range in host halo mass. The extent to which this is true depends on the details of the faint end of the quasar luminosity function, which is thus far poorly measured.

We can now turn our constraint on the fraction of halos of mass $M$ that host active quasars into a constraint on the luminosity dependence of quasar clustering. It will first be useful to write down an expression for the conditional probability that a halo of mass $M$ houses a quasar with instantaneous B-band luminosity $L$. This is analogous to the conditional luminosity function in the halo-occupation distribution formalism, considered in the context of the abundance and clustering of galaxies (e.g., Yang, Mo, & van den Bosch 2003). This probability distribution can be written as

$$L \frac{dP(L|M)}{dL} = f_{\text{on}}(M) \int P_{\text{dark}} L \frac{dP(L_p|L)}{dL} L_p \frac{dP(L_p|M)}{dL_p} .$$

(6)

We can then express the luminosity function as an integral over halo mass. (This is in contrast to Eq. 3 where we expressed the quasar luminosity function as an integral over peak luminosity.) This relation is

$$L \frac{d\Phi}{dL} = \int dM \frac{dN_M}{dM} L \frac{dP(L|M)}{dL} .$$

(7)

An expression for the bias of a quasar of instantaneous B-band luminosity, $L$, then follows in terms of the bias of a halo of mass $M$, $b(M)$.

$$b(L) = \left[ L \frac{d\Phi}{dL} \right]^{-1} \int dM \frac{dN_M}{dM} b(M) L \frac{dP(L|M)}{dL} .$$

(8)

To complete the calculation, we require an expression for the bias of a halo of mass $M$, $b(M)$. We use the formula from Sheth, Mo, & Tormen (2001), which agrees well with measurements from N-body simulations.

We investigate the luminosity dependence of quasar clustering in three different models. The first two are each based on our simulated quasar light curves. These two correspond to the curves shown in Fig. 2 and are meant to bracket the possible range allowed by present luminosity function measurements. We contrast these models with one in which the instantaneous luminosity is related to the halo mass in the same way that the peak luminosity is related to the halo mass in our model, i.e., $L \propto M^{4/3}$. Furthermore, in this scenario we neglect any scatter in the relation between luminosity and halo mass. This is equivalent to the ‘light bulb’ model assumption in which quasars radiate at exactly their peak luminosity for their entire lifetime.

The results of this calculation are shown in Fig. 3, which illustrates the main point of this paper. The plot reveals significant differences between the three models. Our first model corresponds to the $f_{\text{on}}(M)$ distribution which best matches the observed luminosity function, as shown in Fig. 2. The bias in this model, denoted by the red solid line, is quite flat as a function of luminosity, before ramping up at very high luminosity. Our second model corresponds to the broader $f_{\text{on}}(M)$ distribution of Fig. 2, which provides a marginal match to the observed luminosity function. The

Fig. 3.— Bias-squared of quasars as a function of their luminosity at $z = 2$. The red solid line shows the luminosity dependence of quasar clustering in our best-fit model (see the red solid line in Fig. 2). The black dotted line shows the same in our model which is a marginal fit to the quasar luminosity function (see the corresponding line in Fig. 2). Finally, the green dashed line shows the luminosity dependence of quasar clustering in a ‘light bulb’ model in which quasars radiate at their peak luminosity for their entire lifetime.
bias in this model, denoted by the black dotted line, is qualitatively similar to that in our best fit model, although it is a less flat function of luminosity. Finally, in the ‘light bulb’ model, the results are quite different: the quasar bias increases much more sharply with luminosity.

The difference between the bias in these models is easy to understand. In the case of the ‘light bulb’ scenario, there is a one-to-one relation between luminosity and halo mass. The range of luminosities shown in the plot thus corresponds to a wide range in halo mass. The quasar bias, which depends strongly on halo mass, increases sharply with luminosity. Considering a pure exponential light curve gives an essentially identical result, as the implied peak luminosity distribution has nearly the same shape (Hopkins et al. 2005c). In the case of our models based on realistic quasar light curves, however, the entire range in luminosity corresponds to only a relatively small range in halo mass. As a result, the variation of quasar bias with luminosity is relatively poorly constrained by current luminosity function measurements.

One might wonder about the implications of these results for attempts to infer the lifetimes of quasars from their clustering properties (Martini & Weinberg 2001; Haiman & Hui 2001). The usual view is that quasar clustering makes it possible to distinguish whether quasars are numerous yet short-lived, or are rare but long-lived sources. Here we merely echo the sentiment of Adelberger & Steidel (2005): quasar lifetimes depend strongly on the instantaneous luminosity of quasar activity and the ‘duty cycle’ is larger for faint objects than bright ones. By ‘duty cycle’, we mean the ratio of the abundance of quasars in a given luminosity range to the abundance of the dark matter halos that host them (Martini & Weinberg 2001; Haiman & Hui 2001; Adelberger & Steidel 2005). Indeed, let us consider our model in which the characteristic halo mass at $z = 2$ is $\sim 1.3 \times 10^{13} M_{\odot}$, and the dispersion in halo mass is $\Delta M \sim 0.75$. In this case, the duty cycle for quasars with instantaneous B-band luminosity in the range $10^{10} - 10^{11} L_{\odot}$ is quite large, $\sim 0.3$. On the other hand, quasars with luminosity in the range $10^{13} - 10^{14} L_{\odot}$ have a duty cycle of only $\sim 8 \times 10^{-4}$. In other words, the quasar lifetime derived from quasar clustering should depend strongly on the luminosity of the sources considered, and should not be interpreted as an intrinsic lifetime (Hopkins et al. 2005a,e).

Finally, we note that our model predicts only the relative duty cycles of faint and bright quasars, since we do not attempt to predict the absolute normalization of the peak luminosity distribution. Although the bias as a function of luminosity is independent of this normalization, future work, incorporating theoretical estimates of the merger rates of gas rich galaxies, will be necessary to test whether these models can produce the large faint-quasar duty cycle implied by our best fit case. Alternatively, the $f_{\text{on}}(M)$ distribution may be less narrow than assumed above.

4. REDSHIFT EVOLUTION

It is also interesting to consider the redshift evolution of quasar clustering. The luminosity dependence of quasar clustering is poorly determined at each redshift we consider (although see Croom et al. 2005; Adelberger & Steidel 2005), and hence measurements (integrated over all luminosities) at different redshifts do not currently provide a strong test of our contention that bright and faint quasars reside in similar mass host halos. However, it does provide a consistency test regarding our assertion that the observed break in the quasar luminosity function corresponds to a turnover in the peak luminosity distribution, and of our assumed correlation between peak luminosity and halo mass. Moreover, from Fig. 2, we expect that quasar host halos may have a well defined characteristic mass. It is natural then to ask how this characteristic mass evolves with redshift (e.g., Porciani et al. 2004; Croom et al. 2005, Wyithe & Loeb 2005).

There are several factors that might drive redshift evolution in the characteristic mass of quasar host halos. In scenarios in which black hole growth is self-regulated by feedback, the final black hole mass is partly set by the depth of the gravitational potential well of the host halo. In this case, one expects the normalization of the relation between black hole mass and circular velocity to remain constant with redshift. The same is not true, however, for the relation between halo mass and black hole mass: high redshift halos of a given mass have deeper gravitational potential wells and can grow larger black holes than halos of the same mass at lower redshift (e.g. Wyithe & Loeb 2003). More specifically, from the scaling $M_{\text{bh}} \propto v_c^3$, and connecting circular velocity to halo mass, we have $M_{\text{bh}} \propto \frac{\Omega_m(z)}{\Omega_m(0)} \left(1 + 2 z \right)^{3/2} L_c^{4/3}$ (Wyithe & Loeb 2003), where $\Omega_m(z) = \frac{H(z)^2}{H_0^2}$, and $L_c(z) = 18 \pi^2 + 82 (\Omega_m(z) - 1) - 39 (\Omega_m(z) - 1)^2$. Here, $\Omega_m(z)$ denotes the matter density at redshift $z$ in units of the critical density, and $\Delta_c$ is the collapse overdensity according to the fitting formula of Bryan & Norman (1998). We further assume that the relation between peak luminosity and final black hole mass does not evolve with redshift, in which case the redshift evolution of the peak luminosity-halo mass relation is the same as that of the black hole mass-halo mass relation. These assumptions are further confirmed in numerical simulations at different redshifts, or more accurately, simulations in which we vary the properties of the merging galaxies to mimic redshift evolution (Robertson et al. 2005). Moreover, the peak quasar luminosity, $L_*$, evolves with redshift (e.g. Boyle et al. 2000), as does the shape of the halo mass function.

We aim, then, to piece together each of these evolving ingredients, and determine the evolution of quasar clustering with redshift, employing the same methodology as in §2 and §3. To this end, we adopt the pure luminosity evolution (PLE) double power law model of Boyle et al. (2000) in which the break magnitude varies quadratically with redshift, $M_*(z) = -22.65 + 1.35 z - 0.27 z^2$. For simplicity, we will further assume that the scatter in the relation between peak quasar luminosity and halo mass is independent of redshift. We can then infer the distribution of quasar peak luminosities (Eq. 3) and determine which dark matter halos host active quasars ($f_{\text{on}}(M)$ in Eq. 5) at each of several redshifts. At each redshift, we try to determine the $f_{\text{on}}(M)$ that provides the best fit to the quasar luminosity function, noting that current luminosity function measurements tolerate a wide range of values for $f_{\text{on}}(M)$, as illustrated in Fig. 2. We expect
The kink in the model prediction is the best fit measurement from Croom et al. (2005), beyond the redshift extent of their measurement. The blue dotted line shows the best fit measurement from Croom et al. (2005), while the blue dashed lines indicate the allowed 1-σ range implied by their measurement. The bottom panel shows the corresponding characteristic mass of dark matter halos that host active quasars as a function of redshift.

In what follows, we choose the redshift evolution of the typical quasar bias, we then consider a luminosity-averaged quasar bias defined by

$$\bar{b} = \left[ \int_{L_{\text{min}}}^{L_{\text{max}}} \frac{d\Phi}{dL} \right]^{-1} \int_{L_{\text{min}}}^{L_{\text{max}}} dL \, b(L) \frac{d\Phi}{dL}. \quad (9)$$

In what follows, we choose $L_{\text{min}} = 0.1 L_*(z)$, and $L_{\text{max}} = 10 L_*(z)$. Although this does not correspond precisely to the quasar bias that is measured observationally (e.g., Croom et al. 2005), our results are not very sensitive to our choices for $L_{\text{min}}$ and $L_{\text{max}}$. After all, the bias in our model depends only weakly on luminosity.

The results of this calculation are shown in Fig. 4. The bottom panel of the figure shows the characteristic mass of quasar host halos – specifically, the center of the log-normal distribution $f_{\text{on}}(M)$ (Eq. 5) – for several redshifts. The figure clearly illustrates that the characteristic mass of quasar host halos evolves relatively little with redshift in our model. The reason for this is as follows. The characteristic mass of quasar host halos is primarily determined, within the context of our model, by the turnover in the distribution of quasar peak luminosities and the correlation between peak luminosity and halo mass. The turnover in the distribution of quasar peak luminosities is in turn set by the position of the break in the quasar luminosity function. The redshift evolution of the position of the break in the quasar luminosity function is, however, compensated by evolution in the peak luminosity-halo mass relation, and somewhat by changes in the shape of the halo mass function. Consequently, we find that our model produces the observed evolution in the break luminosity at close to fixed host halo mass: the characteristic host halo mass appears to vary by less than a factor of $\sim 2$ between $z = 0$ and $z = 3$. We note that the figure shows a turnover in the host halo mass near $z \sim 2.5$, which corresponds to a similar turnover in $L_*(z)$, but this is likely an artifact of extending the PLE model of Boyle et al. (2000) beyond the redshift extent of their measurement ($z \sim 2.3$). Finally, we remark that if the peak luminosity scales with halo mass as $L_p \propto M_\ast^{5/3}$ then the results are qualitatively similar, but the characteristic halo masses are a factor of $\sim 1.5 - 2$ times smaller.

The redshift evolution of the break luminosity is then a reflection of the self-regulated nature of quasar activity: halos that host quasars have deeper potential wells at high redshift and can thereby grow larger, more luminous black holes at high redshift than at low redshift. In this sense, black hole growth is anti-hierarchical: massive black holes form at higher redshifts than low-mass black holes (Cowie et al. 2003). In order to understand the physics that drives this anti-hierarchical growth in more detail, we need to understand what sets the characteristic mass of quasar host halos, a topic we briefly speculate on in the concluding section.

We show the resulting prediction for quasar bias as a function of redshift in the top panel of Fig. 4. We compare our theoretical predictions with the quasar bias measured by Croom et al. (2005). The figure illustrates that our theoretical predictions agree with the measured bias as a function of redshift, although our results are a bit higher the best fit measurements. This slight overprediction is somewhat sensitive to the assumed peak luminosity-halo mass relation, however, in the sense that assuming $L_p \propto M_\ast^{5/3}$ produces better agreement with the best fit measurements. The key qualitative feature of the figure is that, even though quasars at $z \sim 0$ and $z \sim 3$ reside in similar host halos, their clustering properties differ significantly. Specifically, quasars at $z \sim 0$ should be close to un-biased ($\bar{b} \sim 1$), while quasars at $z \sim 3$ are highly biased, with $\bar{b} > 5$. The reason for this is simply that halos of mass $\sim 7.5 \times 10^{12} M_\odot - 1.5 \times 10^{13} M_\odot$ correspond to rare, high-$\sigma$ peaks at $z \sim 3$, and are thus highly-clustered. On the other hand, the variance of the density field smoothed on the same mass scale is close to the collapse threshold at $z \sim 0$, $\sigma(M) \sim \delta_c$, and hence these halos faithfully trace the matter distribution (see also Croom et al. 2005, Wyithe & Loeb 2005) near $z \sim 0$. This trend is to be expected in the context of our model if mergers involving gas-rich galaxies occur mainly in dense environments at high redshifts, but in more isolated regions at $z \sim 0$.

5. CONCLUSION

Croom et al. (2005) derive the quasar bias assuming a slightly different cosmological model than we adopt here. The difference between the bias in our two models should, however, be small compared to the statistical errors in the measurement. In addition, the quantity Croom et al. (2005) measure is a little different from the luminosity-averaged bias we predict in Eq. 9. Again, the difference between our definitions of quasar bias should be small compared to statistical measurement errors.
In this paper, we have connected the properties of quasars, as determined from numerical simulations of galaxy mergers (Springel et al. 2005a, Di Matteo et al. 2005, Robertson et al. 2005), to the properties of the dark matter halos that host them. We find that bright and faint quasars reside in similar mass halos with characteristic masses close to $\sim 1 \times 10^{13} M_\odot$. As a result, we predict that quasar clustering should depend only weakly on quasar luminosity. Furthermore, we predict that the characteristic mass of quasar host halos should evolve only weakly with redshift. We note that Di Matteo et al. (2003) also found, using cosmological simulations with a simple model for black hole growth, that quasars at low and high redshift reside in similar mass host halos, although they associate quasars with less massive halos than we find presently. Our conclusions invite two obvious questions. The first question is of a theoretical nature: what physics sets the characteristic mass scale of quasar host halos? The second question is an observational one: what do observational measurements of the luminosity dependence of quasar clustering find?

We will largely defer answering the first question to future work, but a plausible explanation is that the most luminous quasars at a given redshift are triggered by the most massive gas rich galaxies merging at that time. The halos that host these objects will be determined by the evolution of merger rates, depending on environment, and the gas content of the galaxies they contain. We note that more precise luminosity function measurements will be helpful in obtaining tighter constraints on the width of the $L_p$ distribution, and on the mass range of halos that host active quasars. Observations of e.g. the Eddington ratio distribution and active black hole mass function can further constrain this distribution at faint luminosities where the observed luminosity function provides only weak limits (Hopkins et al. 2005e). Likewise, the distribution of host masses can be constrained by observations of the quasar host galaxy luminosity function; these find an approximately lognormal distribution with narrow width $\Delta L = \Delta M = 0.5$ ($\sim 0.6 - 0.7$ magnitudes) and a peak corresponding to the stellar mass of quasar hosts with $L_p \sim L_\star$ (Balogh et al. 1997; McLure et al. 1999; Hamilton et al. 2002), close to that predicted by our best-fit model. Further progress can be made theoretically with more detailed semi-analytic calculations incorporating galaxy merger rates (Kauffmann & Haehnelt 2002), or with cosmological simulations incorporating black hole growth and feedback.

We now address the second question. There have been two recent observational attempts to measure the luminosity dependence of quasar clustering. First, Croom et al. (2005) examine the luminosity dependence of quasar clustering from $\sim 20,000$ 2dF quasars, finding no evidence for any luminosity dependence. Their measurement, however, spans only a factor of $\lesssim 20$ in luminosity. Second, Adelberger & Steidel (2005) examine the luminosity dependence of quasar clustering using the galaxy–AGN cross-correlation function, rather than the quasar auto-correlation function. This approach, initially advocated by Kauffmann & Haehnelt (2002), takes advantage of the fact that galaxies are much more abundant than quasars: therefore, statistical measurements of the galaxy–AGN cross correlation function are correspondingly tighter than measurements of the quasar auto-correlation function. Furthermore, Adelberger & Steidel (2005) probe the luminosity dependence of quasar clustering with a much larger dynamic range, roughly a factor of 10 in magnitude, or a factor of $10^4$ in luminosity. Their result is, again, that quasar clustering is independent of luminosity. Specifically, they find that the correlation length for quasar sources with $-30 < \log (L_{1350} < -25$ is $r_0 = 4.7 \pm 2.3$, and $r_0 = 5.4 \pm 1.2$ for sources with $-25 < \log (L_{1350} < -19$, where $M_{1350}$ denotes an AB magnitude at a rest-frame wavelength of 1350Å. The statistical precision of these results is not high, but again, they are qualitatively consistent with our picture. We eagerly anticipate more precise measurements from SDSS and 2dF in the near future, which should provide a more definitive test of this picture for quasar formation and evolution.

Finally, we remark that in this paper we confined our theoretical calculations to large scales where linear biasing is an accurate description of clustering, but it would be interesting to extend calculations to smaller scales. Indeed, Henriawi et al. (2005) find that the quasar correlation function is an order of magnitude larger, at proper separations of $< 40$ kpc/h, than expected based on extrapolating clustering measurements from large scales. This is likely evidence that quasar clustering is associated with galaxy mergers in dense environments, but this should be quantified.

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