MODELING THE COUNTS OF FAINT RADIO LOUD QUASARS: CONSTRAINTS ON THE SUPERMASSIVE BLACK HOLE POPULATION AND PREDICTIONS FOR HIGH REDSHIFT

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ABSTRACT

We use a physically motivated semi–analytic model, based on the mass function of dark matter halos, to predict the number of radio–loud quasars as a function of redshift and luminosity. Simple models in which the central BH mass scales with the velocity dispersion of its host halo as $M_{\rm bh} \propto \sigma_{\rm halo}^5$ have been previously found to be consistent with a number of observations, including the optical and X–ray quasar luminosity functions. We find that similar models, when augmented with an empirical prescription for radio emission, overpredict the number of faint ($\sim 10\mu$Jy) radio sources by 1–2 orders of magnitude. This translates into a more stringent constraint on the low–mass end of the quasar black hole mass function than is available from the Hubble and Chandra Deep Fields. We interpret this discrepancy as evidence that black holes with masses $\lesssim 10^7$ M$_\odot$ are either rare or are not as radio-loud as their more massive counterparts. Models that exclude BHs with masses below 10^7 M$_\odot$ are in agreement with the deepest existing radio observations, but still produce a significant tail of high–redshift objects. In the 1-10GHz bands, at the sensitivity of $\sim 10\mu$Jy, we find surface densities of ~ 100, ~ 10, and ~ 0.3 deg^{-2} for sources located at $z > 6$, 10, and 15, respectively. The discovery of these sources with instruments such as the *Allen Telescope Array (ATA)*, *Extended Very Large Array (EVLA)*, and the *Square Kilometer Array (SKA)* would open a new window for the study of supermassive BHs at high redshift. We also find surface densities of ~ 0.1 deg^{-2} at $z > 6$ for mJy sources that can be used to study 21 cm absorption from the epoch of reionization. We suggest that, although not yet optically identified, the FIRST survey may have already detected $\sim 10^3 - 10^4$ such sources.

1. INTRODUCTION

The past few years have seen significant progress in probing the ultra–high redshift universe, with both galaxies (e.g. Spinrad et al. 1998; Hu et al. 2002; Rhoads et al. 2003; Kodaira et al. 2003) and quasars (Fan et al. 2000, 2001, 2003) being discovered in increasing numbers around and beyond redshift $z = 6$ (see recent reviews by Spinrad 2003 and Taniguchi 2003). In hierarchical structure formation scenarios in cold dark matter (CDM) cosmologies, the first baryonic objects appear at still higher redshifts: at $z \approx 20-30$, when the first high–σ peaks collapse near the Jeans scale of $\sim 10^5$ M$_\odot$ (Haiman, Thoul & Loeb 1996; see Barkana & Loeb 2001 for a recent review). Radiative cooling is efficient in the dense gas that has collapsed on these scales, and in principle, it can facilitate efficient formation of stars and black holes (BHs). Indeed, significant activity must have taken place at high redshifts, in order to reionize the intergalactic medium (IGM) by $z \sim 15$ (Spergel et al. 2003).

The deepest detections of galaxies and quasars to date have been obtained at optical or near infrared (NIR) wavelengths, where the objects were identified in broad–band filters by their continuum, or in narrow–band imaging observations by their Lyman–α emission. The expected number of faint sources in future, deep NIR observations have been studied extensively in the context of hierarchical structure formation, using simple semi–analytic models. Haiman & Loeb (1997; 1998) showed that if halos collapsing at high redshifts have reasonable star or BH formation efficiencies, they can be detected in the NIR continuum in great numbers, with surface densities possibly reaching ~ 1000 sources per arcmin^{-2} out to redshifts $z \gtrsim 10$. Similar models predict that a few $z > 6$ quasars per ~ 100 arcmin^{-2} could be visible in soft X–ray bands at the flux limits already accessible to deep *Chandra* and *XMM* observations (Haiman & Loeb 1999; Wyithe & Loeb 2003).

Predictions analogous to those above, based on physically motivated structure formation models, are currently lacking in the radio bands. Observations of $z \lesssim 6$ quasars have established that a significant fraction ($\sim 10\%$) of these objects are bright in the radio. Although some of the detailed physics responsible for this emission remains elusive, it is known to be a direct consequence of outflows generated by accretion onto a central massive BH. In this scenario, one would expect that the population of radio loud quasars extends to $z \gg 6$, to the epoch when the first BHs appeared and started to accrete. In fact, if the radio–loudness distribution does not evolve strongly at high redshift (Ivezic et al. 2002; Petric et al. 2003), and if high redshift supermassive BHs (SMBHs) radiate close to their Eddington limit, then black holes with masses as small as $M \sim 10^6$M$_\odot$ should have radio flux densities that are already being reached by the deepest existing observations ($\sim 10\mu$Jy at $\sim$ GHz frequencies). *The purpose of this paper is to confront simple models of the radio-loud quasar population with current observations and to put forward predictions for the counts at redshift and flux thresholds that are beyond the current observational limits.* While such extrapolations are necessarily uncertain, the detection of these objects would provide important constraints on the formation and growth of the first SMBHs (see Haiman & Quataert 2004 for a recent review).

Our predictions are especially timely in light of recent data on the reionization history of the intergalactic medium (IGM). On the one hand, SDSS quasar spectra imply that we may have reached the neutral epoch at $z \sim 7$ (e.g. Fan et al. 2002). On the other hand, observations of the cosmic microwave background (CMB) anisotropies suggest that the universe was significantly ionized as early as $z \sim 15$ (Kogut et al. 2003; Spergel et al. 2003). This behavior is a challenge to reionization models. Pinning down the value of the neutral fraction just beyond $z \sim 6$ would be of great value in elucidating these models (see, e.g. Haiman 2003 for a recent review). One promising probe of neutral hydrogen at high redshift is to study redshifted 21cm absorption and emission features. Background density fluctuations from the "21cm forest", both in absorption (Carilli et al. 2002) and in emission (Madau et al. 1997); absorption (Furlanetto & Loeb 2002) or emission (Iliev et al. 2002) from neutral gas in discrete minihalos; and a sharp step–feature analogous to the Gunn-Peterson trough (Shaver et al. 1999) could all, in principle, be detected against a bright enough background source. Such observations would provide a powerful probe of the amount and distribution of neutral hydrogen in the high–redshift IGM. These studies will obviously depend critically on the number of available radio sources (although 21 cm features can also be studied against the CMB; e.g., Tozzi et al. 2000).

The rest of this paper is organized as follows. In § 2 we summarize the phenomenology of radio–loud quasars, and in § 3, we briefly discuss the model we adopt to describe their abundance and evolution. In § 4, we compare this model to existing observations and in § 5 we present our predictions for even higher redshift. In § 6 we conclude with a discussion of our results and their implications. Throughout this paper, we adopt the background cosmological parameters as measured by the *WMAP* experiment, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $\Omega_b = 0.044$, $h = 0.71$, $\sigma_{8h^{-1}} = 0.9$ and $n_s = 1$ (Spergel et al. 2003).

2. RADIO-LOUD QUASARS

Radio emission from a relativistic outflow is a ubiquitous feature of accretion onto a central BH, from X-ray binaries (e.g., Fender 2001) and Seyferts (e.g., Ho & Peng 2001), to radio galaxies and quasars (e.g., Urry & Padovani 1995). In the context of active galactic nuclei, the emission can include both an unresolved component near the nucleus (e.g., the "core") and a spatially extended component such as radio lobes. The former is probably due to dissipation in the jet (by, e.g., internal shocks or MHD instabilities) while the latter is due to the interaction of the jet with the ISM or IGM (e.g., Begelman, Blandford, & Rees 1984). Since jet production is determined by local physics near the BH – e.g., via a collimated wind originating in the disk or via the Blandford-Znajek mechanism – it is reasonable to expect that jets will be launched from very high redshift BHs as well. Moreover, although the extended emission from jets might be expected to evolve with redshift as the conditions in the IGM change, the nuclear emission is determined by relatively local physics and so is likely to be much less sensitive to the ambient environment around the BH. Indeed there is already suggestive evidence that the fraction of radio-loud quasars does not evolve significantly even out to $z \approx 6$ (Ivezic et al. 2002; Petric et al. 2003).

3. MODELING THE HIGH REDSHIFT POPULATION

Our semi–analytical approach is a simplified version of the Monte–Carlo merger–tree models for the evolution of the AGN population found in the literature of hierarchical galaxy formation (Kauffmann & Haehnelt 2000; Menou et al. 2001; Volonteri et al. 2003). Its main ingredients are (1) the mass function of dark matter halos; (2) the ratio $M_{\rm bh}/M_{\rm halo}$ of black hole to halo mass as a function of $M_{\rm halo}$ and redshift z; (3) the probability distribution of radio loudness (defined here as the ratio of the radio to optical flux density); and (4) the duty cycle of quasar activity. Note that our simple model is not applicable at $z \lesssim 2$, where a single dark matter halo may host more than one quasar.

(1) Halo mass function. We assume that SMBHs populate dark matter halos, whose abundance $dN/dM_{\rm halo}(M_{\rm halo}, z)$ follows the form derived from cosmological simulations (Jenkins et al. 2001, equation 9). The cosmological power spectrum is computed from the fitting formulae of Eisenstein & Hu (1999).

(2) Black Hole Mass. We then assume that each halo harbors a central massive black hole of mass

$$M_{\rm bh} = 10^6 \left(\frac{M_{\rm halo}}{1.5\times 10^{12}{\rm M}_\odot}\right)^{5/3} \left(\frac{h}{0.71}\right)^{5/3} (1+z)^{5/2}\,{\rm M}_\odot. \quad (1)$$

The scaling with $M_{\rm halo}$ and z in this equation is equivalent to $M_{\rm bh} \propto \sigma_{\rm halo}^5$, where $\sigma_{\rm halo}$ is the velocity dispersion of the dark matter halo.[1] This scaling is consistent with the locally measured relation between the central velocity dispersion σ_c and BH mass in nearby galaxies, when the conversion between σ_c and $\sigma_{\rm halo}$ is taken into account using models for the DM halo profile (Ferrarese 2002, equation 6). Finally, equation (1) is also consistent with a physical picture in which feedback from the quasar's radiation and outflows determines the size of the black hole (by shutting off accretion once its cumulative energy output has reached the binding energy of the accreting gas; Silk & Rees 1998; Haehnelt et al. 1998; Wyithe & Loeb 2003). We chose the normalization in equation (1) by requiring the model to predict the luminosity function of optical quasars at $z \gtrsim 3$ for the duty cycle of 2×10^7 years (see Haiman & Loeb 1998 for more details of the method). The normalization we obtain is very close to the value found in a recent, more elaborate model by Wyithe & Loeb (2003, equation 4) and implies that $\sim 10\%$ of the quasar's energy output is deposited in the surrounding gas.

(3) Radio Loudness Distribution. The theory of radio emission from jets is not sufficiently well–understood to make reliable predictions for the radio flux of an accreting BH. We instead follow an empirical approach. We assume that each quasar shines at the Eddington luminosity for a timescale t_q (discussed below). We then compute the BH's flux F_i in the i–band using the template spectrum of Elvis et al. (1994). To make predictions in the radio, we use an observationally determined radio loudness distribution. Ivezic et al. (2002) compare the SDSS and FIRST surveys to infer the fraction of quasars with a given radio loudness R, where $R \equiv \log_{10}[F_{1.4}/F_i]$ is the 1.4 GHz radio flux density relative to the i–band optical flux density. An approximate fit to their results (Fig. 19) gives

$$N(R) = 0.5 f_l \exp[-(R-\bar{R})^2/\sigma^2] \quad (2)$$

where $f_l \approx 10\%$ is the fraction of quasars that are radio loud, $\sigma \approx 2/\sqrt{\pi}$, and $\bar{R} \approx 2.8$ is the average radio-loudness. Note that the ratio R defined by Ivezic et al. (2002) is for the *observed* 1.4 GHz and i–band (~ 8000Å) flux densities. However, the radio-loudness distribution described by equation (2) must physically arise between the emitted rest–frame luminosities of the sources. The mean redshift of the sources used to derive

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[1] There are additional cosmology– and redshift–dependent terms in the standard relation between $M_{\rm halo}$ and $\sigma_{\rm halo}$ obtained from the virial theorem (e.g. Iliev & Shapiro 2001), but these approach a constant value at the high redshifts considered here, $z \gtrsim 3$, and can be absorbed into the normalization of equation (1).

equation (2) is $\langle z\rangle \sim 1$ (see Fig. 21 in Ivezic et al. 2002); we therefore assume that $R \equiv \log_{10}[L_{2.8}/L_{i/2}]$, where $L_{2.8}$ and $L_{i/2}$ are the rest–frame luminosities at $1.4(1+\langle z\rangle)$ = 2.8 GHz and at $8000/(1+\langle z\rangle)$ = 4000Å, respectively. Note also that equation (2) has been normalized to f_l. The remaining 90% of radio-quiet quasars also produce radio emission, but the fluxes are too small to be of interest here. As mentioned above, there is no evidence for significant evolution in the radio loudness distribution with redshift (Ivezic et al. 2002; Petric et al. 2003), providing some support for extrapolating the locally–determined distribution to yet higher redshifts. Finally, for most of our calculations we assume that the radio spectrum is flat, i.e., $\alpha = 0$ where $F_\nu \propto \nu^{-\alpha}$. However, we also present results for a steeper spectrum, $\alpha = 0.5$, to illustrate the dependence on α.

(4) Duty cycle. We assume a fixed lifetime of $t_q = 2\times10^7$yr for the cumulative duration of the radio–loud phase(s) for each black hole. This value is consistent with the time–scale for Eddington limited accretion (Salpeter time), as well as with the quasar lifetimes obtained from other independent arguments (see Martini 2003 for a review, and Haiman & Loeb 1998 and Haehnelt et al. 1998 for discussions of how the lifetime can be uniquely related to the scalings assumed in equation [1] above). We approximate the duty cycle of activity, defined as the fraction of quasars that are active at a given time, as $f_{\rm duty} = t_q/t_H(z)$, where $t_H(z)$ is the age of the universe at redshift z. This simple assumption is justified by noting that the timescale for the formation of new BHs is approximately $t_{\rm form} \sim (dN/dM)/(d\dot{N}/dM) \sim t_H(z)$.

It is important to note that both t_q and $t_{\rm form}$ can, in general, be a function of both redshift and BH (or halo) mass. In particular, in extended Press-Schechter models, the typical halo age is a decreasing function of $t_H(z)$ at high redshift and high halo masses. For example, one may define the duty cycle as the fraction of all halos younger than t_q, with the halo age–distribution taken as the distribution of the half–mass assembly times in the extended Press–Schechter formalism (e.g., equation 2.26 in Lacey & Cole 1993). We find that using this definition would increase the number counts we predict at high redshift ($10 \lesssim z \lesssim 15$) by factors of $\approx 3-6$ (in Figures 3 and 5 below). On the other hand, if t_q were related to the dynamical time in the halo, rather than to the Salpeter time (as proposed in Wyithe & Loeb 2003), $t_q \propto (1+z)^{-3/2}$, which would nearly cancel this increase in counts at high redshift.

Given the above assumptions, the number of radio loud quasars per unit redshift and solid angle, with a flux density brighter than $F_{1.4}$ at redshift z, is given by

$$\frac{dN}{dzd\Omega}(F_{1.4},z) = \frac{dV}{dzd\Omega}\frac{t_q}{t_H(z)}\int_0^\infty dM\, f(>R[M,F_{1.4}])\frac{dN}{dM}, \quad (3)$$

where M is the halo mass, $dV/dzd\Omega$ is the cosmological volume element, $t_H(z)$ is the age of the universe at redshift z, and $f(>R) = \int_R^\infty dRN(R)$ is the fraction of sources with radio loudness R or higher. Inside the integral, $R = R(M, F_{1.4})$ is obtained by requiring that the BH residing in the halo of mass M, whose mass and optical flux are fixed by assumption, should have a given radio flux density $F_{1.4}$.

We have verified that the above model is consistent with the optical and X–ray quasar luminosity functions at $z \gtrsim 3$ (following Haiman & Loeb 1998; 1999). In addition, we have computed the number of high–redshift sources that should be detectable in the *Chandra* Deep Field North. Adopting the spectral template of Elvis et al. (1994), a $\sim 10^8 M_\odot$ BH with Eddington luminosity at redshift $z = 11$ will have a flux of 2×10^{-16} erg s^{-1} cm^{-2} in the soft X–ray band (see Fig.1 in Haiman & Loeb 1999). Using the same assumptions described above, we find that our model predicts ~ 6 quasars at $z > 3$ and ~ 1 quasar at $z > 5$; these numbers are consistent with the observed number of faint X–ray sources (Alexander et al. 2003; Barger et al. 2003).

In order to ensure further that our model is consistent with

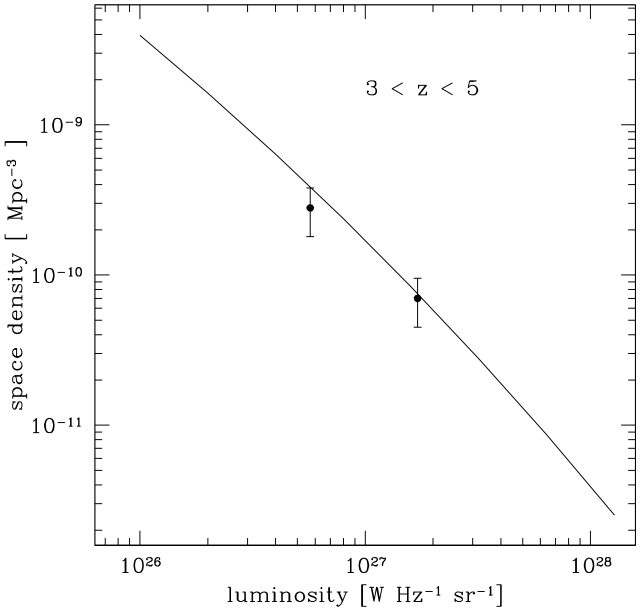

FIG. 1.— Predicted luminosity function of radio–loud quasars in the redshift bin $3 < z < 5$. The space density of all quasars brighter than a fixed luminosity is plotted against the luminosity at 5 GHz. The data points are taken from Hook, Shaver & McMahon 1998 (their Figure 4).

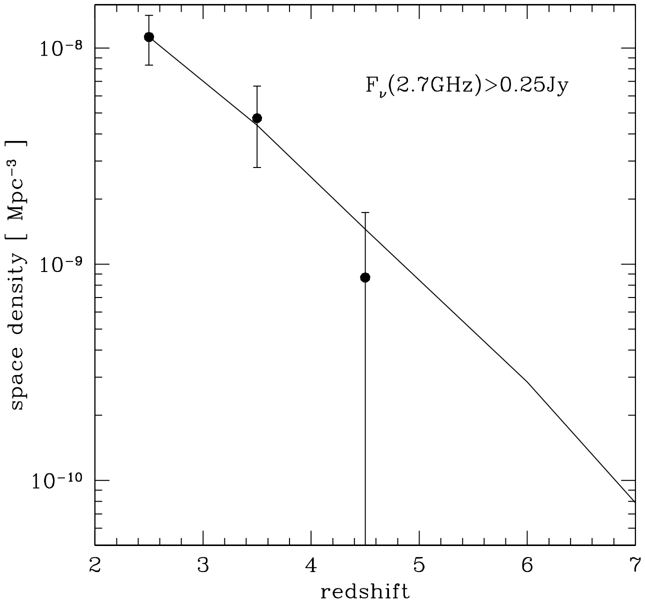

FIG. 2.— Predicted space density of radio–loud quasars as a function of redshift. A 2.7 GHz flux density limit of 0.25 Jy was assumed. The datapoints with error bars are taken from Hook, Shaver & McMahon 1998 (their Figure 6).

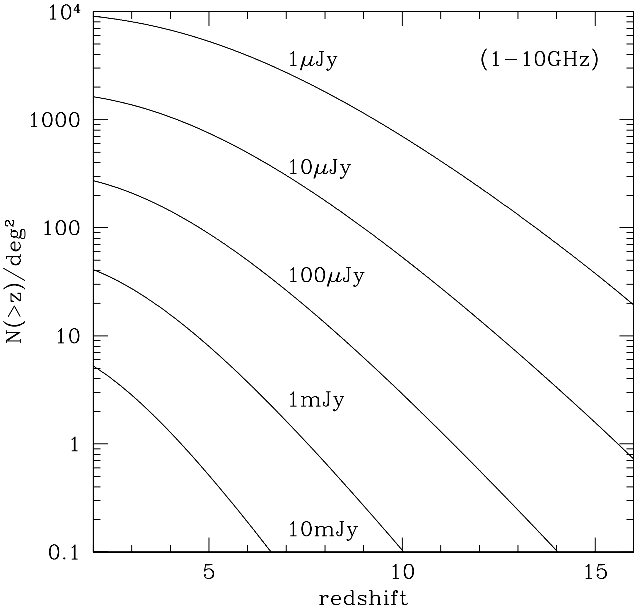

FIG. 3.— Predicted number of radio–loud quasars as a function of redshift (the counts are cumulative). A flat spectrum, $\alpha = 0$, is assumed, so the counts are the same at any frequency from $\approx 1-10$ GHz. Figure 6 shows the dependence on spectral index α.

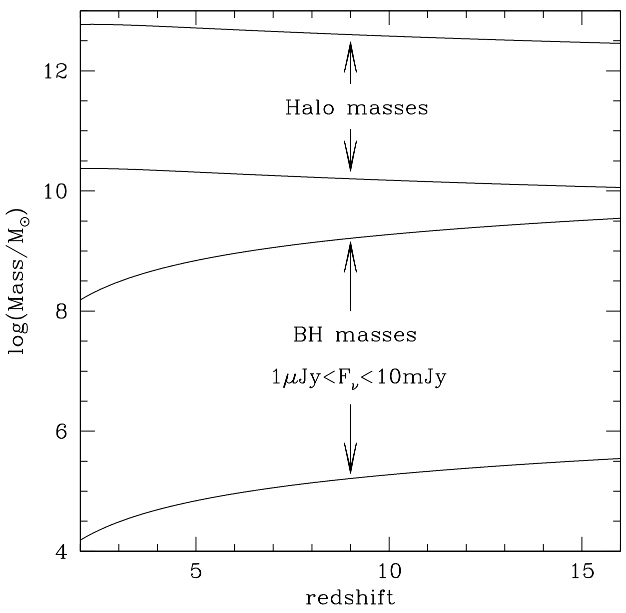

FIG. 4.— The mass of the BH (lower pair of curves) and halo (upper pair of curves) powering the typical radio–loud quasar, as a function of redshift, for the range of flux densities used in Figure 3.

existing observations of radio–loud quasars, in Figures 1 and 2 we show the results of our model for the luminosity function and its redshift evolution at the bright flux densities ($\sim$ 0.2Jy) at which it has been determined at $z \gtrsim 2$. In Figure 1, we show a luminosity range in the highest redshift bin $3 < z < 5$ that is used in Figure 4 of Hook, Shaver & McMahon (1998, reproduced by the points with error bars). In Figure 2 we show the redshift evolution at a 2.7 GHz flux density limit of 0.25 Jy, so that our numbers can be directly compared to the data in Figure 6 of Hook et al (reproduced by the points with error bars). As these two figures show, our simple model is in good agreement with the available data on the high-redshift radio LF.

4. A CONSTRAINT ON THE SMBH POPULATION FROM EXISTING SOURCE COUNTS

Figure 3 shows the predicted number counts in the radio as a function of redshift for five different choices of the threshold flux density. For this figure we took $\alpha = 0$, i.e., $F_\nu \approx$ constant (see Fig. 6 for results with $\alpha = 0.5$). The same number counts are thus predicted for any frequency in the $\approx 1-10$ GHz range; at sufficiently high frequencies ($\gtrsim 10-100$ GHz, depending on z), rest frame dust emission could become important and dominate over jet emission.

Figure 4 shows the mass of the typical BH at a given flux density and redshift (i.e., a BH with the mean radio–loudness ratio $R = \bar{R} = 2.8$). The upper pair of curves show the corresponding halo masses (whose range is reasonable). The important point revealed by this figure is that deep radio observations at flux densities $\lesssim 10\mu$Jy can probe the high-redshift population of SMBHs at $M_{\rm bh} \sim 10^4-10^6$ M$_\odot$, a range of masses that is not currently detectable in the optical/X–ray bands. In fact, it is not clear whether BHs as small as $\lesssim 10^{4-6}$M$_\odot$ exist at the centers of galaxies. Haiman, Madau & Loeb (1999) obtained an empirical lower limit of $\sim 10^6 M_\odot$ from the flattening of the optical quasar LF required to avoid over-predicting the number of faint, high–redshift quasars in the *Hubble* Deep Field. Moreover, the smallest directly measured mass for a central SMBH is just above 10^6 M$_\odot$ (e.g. Gebhardt et al. 2000; Merritt & Ferrarese 2001). If some holes as small as $10^4(10^5)$ M$_\odot$ do exist, our results suggest that they could have radio flux densities $\sim$ 1(10) μJy at $z = 4$ and $\sim$ 0.1(1) μJy at $z = 8$, and so could be detected in very deep radio observations.

The results shown in Figure 3 for the expected number counts can, in fact, be directly compared to existing observations. The FIRST survey (Becker et al. 1995) is using the Very Large Array (VLA) to map 10,000 deg^2 of the sky down to a point–source sensitivity of $\sim$ 1mJy. The survey is nearly complete, and at this flux density threshold, it has revealed a surface density for discrete sources of $\sim$ 75 deg^{-2}, implying a total of $\sim 7.5 \times 10^5$ sources over the entire survey area.[2] In a cross–correlation between SDSS and FIRST in a 1230 deg^{-2} region, Ivezic et al. (2002) identify $\sim$ 30% of the FIRST sources with SDSS sources; $\sim$ 17% of this matched sample are quasars. However, with the $N(R)$ distribution derived for the matched quasars (see eq. 2), the 1mJy FIRST flux density threshold corresponds to a typical magnitude $i = 23.4$, well below the detection threshold of SDSS ($i = 21.5$). This suggests that many FIRST sources must be quasars without SDSS counterparts. Ivezic et al. (2002; Appendix B) estimate the fraction of FIRST sources that could be quasars too faint for SDSS to detect. Taking a conservative count of optical quasars (from Pei 1995) down to a magnitude of $i = 23.5$, and combining it with the radio–loudness distribution $N(R)$, they find that for every FIRST quasar detectable by SDSS ($i < 21.5$), there should be at least $\sim$ six quasars at that are below the SDSS threshold. This implies that, overall, the fraction of quasars in the entire FIRST catalog should be $\sim 7 \times 0.17 \times 0.30 = 0.36$, or $\sim 270,000$ quasars in to-

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[2] For the status and results of the FIRST survey, see http://sundog.stsci.edu.

tal. This is in reasonable agreement with the $\sim 400,000$ sources we predict at $z > 2$ and > 1mJy in Figure 3 (note that Fig. 6 with $\alpha = -0.5$ predicts a comparable number of such sources, $\sim 300,000$).

The fraction of quasars in the FIRST survey can be determined directly by cross–correlating FIRST with optical surveys deeper than SDSS. To indicate the sensitivity of our results to model parameters, we note that a factor of 4 reduction in the average radio loudness (to $\bar{R} = 2.2$) of quasars near the FIRST threshold ($i \approx 23.5$) would reduce our predicted number of > 1 mJy quasars by a factor of $\approx 4-5$ in the range $2 < z < 10$. While there is no indication that the radio loudness decreases for fainter quasars in the SDSS-FIRST matched sample (to $i \approx 21.5$; see Ivezic et al. 2002), such a decrease is not currently well constrained at the faint end of the luminosity function that dominates our predicted mJy counts in Fig. 3 (at $i \approx 23.5$, corresponding to BH masses of a few $\times 10^7 M_\odot$).

We can also compare our model to recent radio observations at much fainter flux levels. One of the deepest radio images yet made is the Fomalont et al. (2002) observation of the VLA field SA 13 (65 arcmin^2), which was observed to a depth of $7.5\mu Jy$ ($5\ \sigma$). The calculations shown in Figure 3 predict 30 radio-loud quasars in such an observation. In contrast, Fomalont et al. find a total of 34 radio sources, only two of which are optically-detected quasars (10 & 26 micro-Jy; see their Table 1). In the remaining optically identified galaxies, there is no evidence for quasar activity (though some could be lower luminosity AGN).[3] Finally, although nine of their sources have no optical counterparts down to $I = 25.5$, and so in principle could be very high redshift quasars, these sources have steep radio spectra. This suggests that they are starbursts and not AGN (see also Richards 2000). A similar conclusion is reached in the observations of Richards et al. (1998), covering 65 arcmin^2 of the HDF and surrounding fields at the sensitivity of 9μJy ($5\ \sigma$). They find 29 sources in their statistically complete sample, but none of these are quasars. We are led to conclude that the simple model in Figure 3 over–predicts the number of faint radio sources by about an order of magnitude. Recall that this model is consistent with the available optical and X–ray data and the luminosity function and redshift evolution of bright radio-loud quasars (Figs 1 & 2).

This result implies that the radio LF has to flatten significantly at high redshift at flux densities of $10-100\mu$Jy. The simplest interpretation of this flattening is that there is a characteristic BH mass below which SMBHs either do not exist, are not accreting significant gas, or are much less efficient at producing radio emission. To address this possibility, we computed the total number of sources in a 65 arcmin^2 area down to the flux density threshold of 7.5(9)μJy. We ignored the counts from all BHs with masses below $M_{\rm crit}$ and varied $M_{\rm crit}$ until no more than 3 sources were predicted in either mock observation. We find that this requires $M_{\rm crit} = 10^7$ M$_\odot$, or, equivalently, a threshold velocity dispersion of 120 km s^{-1}. The resulting modified number counts, ignoring all BHs with $M < M_{\rm crit}$, are shown in Figure 5. As this figure reveals, ignoring the low–mass BHs has little effect on the number of bright sources ($\gtrsim 1$ mJy). Finally, an alternative way of stating this constraint is that the average radio flux for BHs with $M \lesssim 10^7$M$_\odot$ must decrease by a factor of $\gtrsim 15$ (i.e., from $\bar{R} = 2.8$ to $\bar{R} \lesssim 1.6$) in order to be consistent with the deep 10μJy observations.

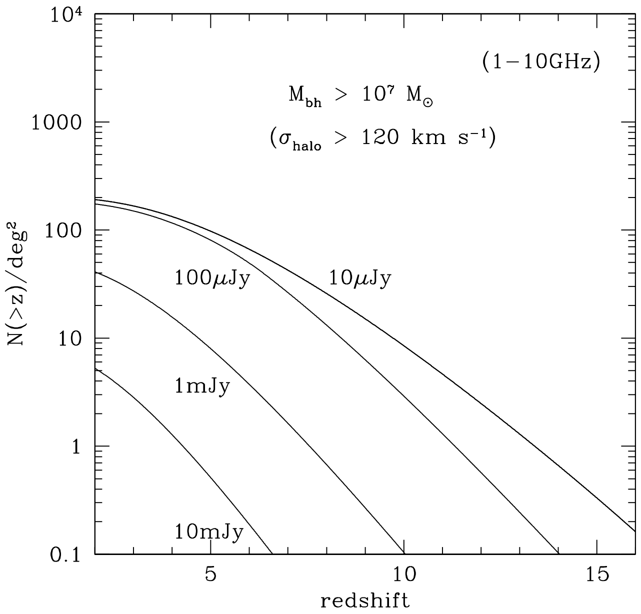

FIG. 5.— Predicted number of radio–loud quasars as a function of redshift with flux densities greater than the indicated levels, ignoring the contribution of black holes with masses below 10^7 M$_\odot$.

5. PREDICTIONS FOR HIGH–REDSHIFT COUNTS FOR FUTURE INSTRUMENTS

Figure 5 extends the predictions of our model to high redshift, for flux/counts combinations that could be probed by future instruments. For example, the Extended VLA (EVLA) will have a sensitivity about 10 times better than that of the current VLA.[4] The Low Frequency Array (LoFAr) will have $\sim$mJy sensitivity in the low frequency (10–240 MHz) range.[5] The Allen Telescope Array (ATA), expected to be fully operational in 2006, has a planned sensitivity similar to the VLA, but a significantly larger field of view.[6] It can achieve a sensitivity of 7.5μJy at 1.4 GHz over 10 deg^2 in about a week of observing. The Square Kilometer Array (SKA) will come online in about a decade.[7] Although its design is not yet final, SKA will likely have ~ 100 times the collecting area, but a ~ 5 times smaller field of view, than the ATA. As Figure 5 shows, imaging 10 deg^2 should reveal a few faint sources out to redshifts as large as $z \sim 15$.

6. DISCUSSION

We have presented a simple physically motivated model for the SMBH population and its evolution that fits the optical/IR and X-ray quasar luminosity functions out to $z \approx 5$, and the luminosity function and number counts of bright radio sources at high redshift. This model significantly overpredicts the counts

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[3] It is important to stress that our radio-source predictions assume that the bolometric luminosity of a BH is Eddington (for a time t_q). Thus the nuclear radio-sources would have optical counterparts that dominate the light of the host galaxy. In the calculations presented here, we do not attempt to model lower-luminosity AGN activity. We would expect such sources to be even more numerous than the bright quasars we focus on; it is thus possible that some of the Fomalont et al. sources could be moderate redshift lower-luminosity AGN.

[4] See http://www.aoc.nrao.edu/evla

[5] See http://www.lofar.org

[6] See http://www.seti.org/science/ata.html

[7] See http://www.skatelescope.org

at the $\approx 10\ \mu$Jy level in deep radio observations. This discrepancy can be reconciled by postulating the existence of a lower limit to the SMBH mass, below which SMBHs are either rare or do not produce as much radio emission as their more massive counterparts. We find that this lower limit is $\approx 10^7$ $M_\odot$, a constraint that is approximately an order of magnitude more stringent than that available from either the *Hubble* or *Chandra* deep fields (e.g., Haiman et al. 1999). This constraint is especially interesting since there are several SMBHs in local galaxies with dynamically determined masses $\lesssim 10^7 M_\odot$ (e.g. the central BHs in M32 – van der Marel et al. 1998 – and in the Milky Way – Schödel et al. 2002; Ghez et al. 2003). In addition, Filippenko & Ho (2003) argued for a $\sim 10^5 M_\odot$ BH for the Seyfert galaxy in the late type (bulgeless) spiral NGC 4395, and Barth et al. (2004) reached a similar conclusion for the dwarf Seyfert 1 Galaxy POX 52.

If indeed SMBHs with masses below $\approx 10^7 M_\odot$ are rare, this could be because it is difficult to form SMBHs in shallow potential wells (e.g., Haehnelt et al. 1998; Haiman et al. 1999). Alternatively, during the coalescence of SMBH binaries, the remnant BH receives a "kick" velocity of up to several hundreds of km s^{-1} due to the net linear momentum carried away by gravitational waves (e.g., Favata et al. 2004). This kick may be sufficient to unbind lower-mass BHs from their host galaxies, leading to a dearth of low-mass BHs in galactic nuclei (e.g., Madau & Quataert 2004; Merritt et al. 2004).

An alternative explanation for the discrepancy between our models and the number counts of faint radio sources is that their bright accretion phase (near Eddington) is significantly shorter than that of their high–mass counterparts (note, however, that the Salpeter time characterizing the growth of SMBHs is independent of BH mass), or that lower mass BHs with $M \lesssim 10^7 M_\odot$ are intrinsically less radio loud (we find that a reduction by a factor of ≈ 15, or changing $\bar{R} = 2.8$ to $\bar{R} \lesssim 1.6$, is needed). There are indeed some suggestions in the literature that very massive BHs are preferentially radio loud (e.g., Laor 2000; Lacy et al. 2001). However, other analyses suggest instead that the strongest correlation is between radio loudness and Eddington ratio (e.g., Ho 2002), consistent with the assumptions used here.

Our results also show that even in the presence of a low–mass cutoff in the distribution of radio-emitting SMBHs (which we assume is independent of redshift), a significant number of sources at redshifts as high as $z \sim 15$ could be detectable. In the 1-10GHz bands, at the sensitivity of $\sim 10\mu$Jy, we find surface densities of ~ 100, ~ 10, and ~ 0.3 deg^{-2} for sources located at $z > 6$, 10, and 15, respectively (Fig. 5). These predictions for the cumulative counts are insensitive to our choice of average radio loudness $\bar{R}$. The reason is that a typical $10^7 M_\odot$ BH radiating at Eddington at $z = 6$ produces $\approx 100\ \mu$Jy if $R \approx 2.8$ and $10\ \mu$Jy if $R \approx 1.8$. Thus even if we decrease the average radio flux by an order of magnitude, i.e., from $\bar{R} \approx 2.8$ to $\bar{R} \approx 1.8$, the total surface density of the faintest sources shown in Figure 5 does not change significantly (i.e., although the predicted fluxes for most of the sources decreases from $100\ \mu$Jy to $10\ \mu$Jy, the total number of sources with $F_\nu \gtrsim 10\ \mu$Jy is relatively unchanged). Figure 6 shows that, except at very high z, these predictions are also insensitive to the choice of the spectral index α.

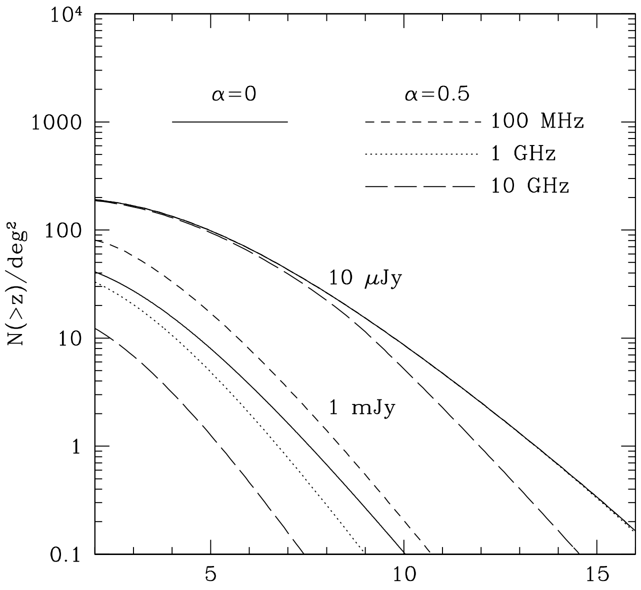

FIG. 6.— This figure shows the sensitivity of our predictions for the 10μJy and 1mJy counts to the assumed spectral slope α of the radio spectrum $F_\nu \propto \nu^{-\alpha}$. The counts for $\alpha = 0$ are independent of frequency. When $\alpha = 0.5$ is assumed, however, the counts increase with decreasing frequency, as shown by a comparison between the predictions at 100 MHz, 1GHz, and 10 GHz (short–dashed, dotted, and long–dashed curves, respectively).

A particularly interesting question is the redshift evolution of bright radio sources, which can be used to study redshifted 21cm absorption features and hence the reionization history of the universe. Carilli et al. (2002) find that a $\sim$ 6mJy source (at a few 100 MHz) is needed to achieve the S/N necessary for 21 cm absorption studies. For a flat spectrum ($\alpha = 0$), our results (Figure 5) imply that ~ 2.5 such sources should be available in a 10 deg^2 field at $z = 6-7$, with $\approx 2,000$ sources available over the full sky in the redshift range $8 < z < 12$. Figure 6 shows that the predicted counts are larger by a factor of few if we instead assume a steeper spectrum with $\alpha = 0.5$. It is also important note that since these bright mJy sources are produced by massive BHs, their counts are independent of the low-mass cutoff considered above. They are, however, sensitive to an evolution in the average radio–loudness $\bar{R}$ (in contrast to the counts of the faint sources). For example, decreasing $\bar{R}$ from $\bar{R} = 2.8$ to $\bar{R} = 2.3$ beyond $z > 6$ would decrease the number of 6mJy sources at $6 < z < 7$ and $8 < z < 12$ by a factor of 4.6, and 6.3, respectively. Another important point to note is that our fiducial results, obtained assuming $\bar{R} = 2.8$, predict that the FIRST survey may have already detected $\sim 10^3 - 10^4$ quasars at $\sim$ 1mJy from redshift $z \gtrsim 7$. The identification of these quasars is a challenge, but should, in principle, be feasible with deep optical/IR observations.

The extrapolation of the radio-source population to high redshifts is necessarily uncertain; nevertheless, the results presented here should serve as useful order of magnitude estimates. We also note that our assumption of $M_{\rm bh} \propto \sigma^5$ is somewhat conservative; a shallower relation would imply that the typical BHs reside in lower–mass halos (with shorter lifetimes; see Haiman & Loeb 1998 and Haehnelt et al. 1998); their abundance would then decrease less rapidly at high redshifts.

An important issue in designing future surveys is the relative merits of area vs. depth. The DM halo mass function has an approximate power–law shape at low masses $dN/dM \propto M^{-2}$, and the velocity dispersion scales as $\sigma \propto M^{1/3}$. As a result, if

$M_{\rm bh}$ scales as σ^α, and if the flux is proportional to $M_{\rm bh}$, then the number of sources will go as $Fdn/dF \propto F^{-3/\alpha}$. The number of detections scales linearly with the solid angle $\Delta\Omega$, and with the observation time as $t^{1.5/\alpha}$; area is therefore more important than depth for the empirically determined slopes of $\alpha \approx 4$ (Gebhardt et al. 2000; Merritt et al. 2001; Tremaine et al. 2002). In principle, at bright flux limits, corresponding to BH masses where the halo mass function turns over and drops exponentially, decreasing the flux threshold would result in a larger yield of sources. However, Figure 5 reveals that even at the brightest fluxes shown, the source counts increase linearly with the flux threshold, and it would therefore be more advantageous to cover a larger area.

To conclude, we briefly discuss how to identify the high redshift radio sources. At low flux densities ($\lesssim 30$ μJy), starbursts dominate over quasars in deep radio observations (e.g., Richards et al. 1998). There is also a contribution from moderate redshift low–luminosity AGN. AGN can be distinguished from starbursts by their flatter spectra and variability. Isolating the high redshift sources, however, will require optical/IR followup. Our typical 10 μJy source at $z \approx 6$ and $z \approx 10$ is powered by a $\approx 10^7 M_\odot$ BH (without the cutoff described above it would be $\lesssim 10^6 M_\odot$, but we would then overpredict the number of such sources). With the Elvis et al. (1994) spectral template, normalized to a bolometric Eddington luminosity, these sources would have a flux density of $\sim 0.3\mu$Jy at observed wavelengths of $\sim 1-5\mu$m, or an AB magnitude of ~ 25.5 (see, e.g., figure 1 in Haiman & Loeb 1998). They should be detectable in moderate integrations with the *Hubble* or *Spitzer Space Telescopes*.[8] The very bright $\sim$mJy sources at $z \approx 6-10$, relevant for 21 cm absorption studies, should have flux densities of $\sim 3\mu$Jy (or AB magnitudes of ~ 23 at $\sim 1-5\mu$m), and should be detectable in short exposures with *HST* or *Spitzer*, and potentially from the ground as well. The discovery and confirmation of even a few radio sources at $z > 10$ by instruments such as the *Allen Telescope Array (ATA)*, *Extended Very Large Array (EVLA)*, and the *Square Kilometer Array (SKA)* would open a new window for the study of supermassive BHs at high redshift, and of the pre–reionization universe. Of even more immediate interest is the prediction from our models that, although not yet optically identified, the FIRST survey may have already detected $\sim 10^3-10^4$ distant $z > 7$ quasars. Deep surveys, such as NOAO Deep Wide-Field Survey (NDWFS), VIRMOS and DEEP may cover the area necessary to identify a handful of these high-z FIRST sources.

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[8] The *Spitzer Space Telescope* has a point–source sensitivity of $\sim 3\mu$Jy in a 10-second exposure at 3.6μm, see http://ssc.spitzer.caltech.edu/irac/sens.html