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FERMILAB-Pub-98/343-A

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March 1999

Submitted to *Astrophysical Journal Letters*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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Submitted to Ap.J. Letters
Preprint typeset using LaTeX style emulateapj

COSMOLOGICAL EVOLUTION OF THE ACCRETION RATE IN QUASARS

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Submitted to Ap.J. Letters

ABSTRACT

We derive the mass accretion rate $\dot{M}$ onto quasar black holes (BHs), and its redshift evolution between $0 \lesssim z \lesssim 4$, using the observed optical and X–ray quasar luminosity functions (LFs). We make the following assumptions: (i) the mass–function of dark matter halos follows the Press–Schechter theory, (ii) the BH mass scales linearly with the halo mass, (iii) quasars have a constant universal lifetime, and (iv) the optical luminosity is modeled as a thin disk, and the X–ray/optical flux ratio is calibrated from a sample of observed quasars. We show that the accretion rate in Eddington units, $\dot{m} \equiv \dot{M}/\dot{M}_{\rm Edd}$, inferred from either the optical or X–ray data under these assumptions generically decreases as a function of time from $z \simeq 4$ to $z \simeq 0$. For a typical quasar lifetime of $\simeq 10^7$ yr, the value of $\dot{m}$ inferred is independent of halo mass and, near $z \simeq 0$, drops to substantially sub-Eddington values at which advection–dominated accretion flows (ADAFs) exist. This decline of $\dot{m}$, possibly followed by a transition to low radiative efficiency ADAFs near $z \simeq 0$, could be the origin of the absence of bright quasars in the local universe and the faintness of accreting BHs at the centers of nearby galaxies. We argue that a decline of the accretion rate of the quasar population is indeed expected in cosmological structure formation models.

Subject headings: cosmology: theory – quasars: general – black hole physics – accretion, accretion disks

1. INTRODUCTION

The population of quasars as a whole exhibits a characteristic cosmological evolution: the number density of quasars rises monotonically by two orders of magnitude from redshift $z \simeq 0.1$ to an apparent peak at $z_{\rm pk} \simeq 2.5$. The evolution at redshifts exceeding $z_{\rm pk}$ is still unclear: the number density of optically bright quasars declines from $z_{\rm pk} \simeq 2.5$ to $z \simeq 4.5$ (Pei 1995), but recent ROSAT data has not shown any evidence for a similar decline in X–rays (Miyaji et al. 1998). The massive accreting black hole model (see Rees 1984) produces the bolometric luminosity of an individual quasar, and provides a framework that has successfully accounted for some properties of the observed quasar spectra (Frank et al. 1992; Laor & Netzer 1989). However, the reason behind the evolution of the quasar luminosity function must involve some additional physics, likely related to the cosmological growth of structures.

Several ideas have been put forward to explain the cosmic evolution of quasars, including activation by mergers (Carlberg 1990); intermittent accretion (Small & Blandford 1992); association with dark halos using a nonlinear (Haehnelt & Rees 1993) or linear (Haiman & Loeb 1998) scaling of the BH mass $M_{\rm bh}$ with halo mass $M_{\rm halo}$; a relation to the individual quasar light curves (Siemiginowska & Elvis 1997) or spectral shapes (Caditz et al. 1991); and a transition to ADAFs (Yi 1996). However, these ideas are still poorly constrained by present data, and a conclusive understanding has not yet been achieved.

The main ingredients in modeling the quasar LF is the BH formation rate and the light–curve of each BH in the relevant wavelength band. The usual approach taken is to specify these ingredients with several parameters, and fit the LF by a "trial and error" procedure. We emphasize here that the least understood ingredient in these attempts is the mass accretion rate onto the quasar black holes. Indeed, the key to understanding the cosmic evolution of quasars probably lies in their accretion history. In this *Letter*, we propose to invert the problem and infer the accretion rates of quasars directly from their observed LF, while using a set of reasonable assumptions for the other model ingredients. We show that the inferred accretion rate of the quasar population generically decreases as a function of time. Although we focus on optical and X-ray data, the method to infer $\dot{m}$ described here is applicable to any wavelength at which a LF and a reliable emission model exist. In this *Letter* we adopt the concordance cosmology of Ostriker & Steinhardt (1995), i.e. a flat ΛCDM model with a slightly tilted power spectrum $(\Omega_0, \Omega_\Lambda, \Omega_{\rm b}, h, \sigma_{8h^{-1}}, n)$=(0.35, 0.65, 0.04, 0.65, 0.87, 0.96). We have verified that our conclusions below regarding the decline in the accretion rate do not change significantly in other cosmologies.

2. THE FORMATION OF QUASAR BLACK HOLES

Although there is no a–priori theory for the cosmic black hole formation rate, it is natural to expect that it is related to the formation of dark matter halos. The mass function of halos $dN_{\rm ps}/dM$ at any redshift is described

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by the Press–Schechter (1974) theory with an accuracy of $\sim 50\%$ when compared to numerical simulations at the mass–scales relevant here (Somerville et al. 1998). Note that the shape of the halo mass function has the desirable property of a steep decline with $M_{\rm halo}$, similar to the quasar LF. Recently, measurements of the black hole masses in 36 nearby galaxies provided evidence for a linear relation $M_{\rm bh} \propto M_{\rm bulge}$ between black hole and bulge mass (Magorrian et al. 1998). Assuming $M_{\rm bulge} \propto M_{\rm halo}$, this result further implies $M_{\rm bh} \propto M_{\rm halo}$. A simple scenario in which the latter relation is satisfied in the local universe is if the relation holds at every redshift, i.e. if the BH masses grow synchronously with the host halo masses, $\dot{M}_{\rm bh}/M_{\rm bh} = \dot{M}_{\rm halo}/M_{\rm halo} \Rightarrow M_{\rm bh}/M_{\rm halo} = {\rm const.}$ Note that if mergers are important (i.e. if they occur on a time–scale less than the Hubble time), then we must also suppose that black holes merge together whenever their halos do. In what follows, we assume that $M_{\rm bh}/M_{\rm halo} = 10^{-3.2}$, consistent with the value $M_{\rm bh}/M_{\rm bulge} = 0.006$ measured by Magorrian et al. (1998).

3. THE OBSERVED QUASAR LUMINOSITY FUNCTIONS

The quasar LF between redshifts $0.1 \lesssim z \lesssim 4.5$ has been measured in the optical; we use the fitting functions for the K–corrected rest–frame B–band (around $\nu = 10^{14.83}$) LF obtained by Pei (1995). More recently, the LF has also been measured in X–ray; we use the parametric fits constructed by Miyaji et al. (1998). Both the optical and X–ray LFs have a steep slope, and the abundance of quasars rises rapidly from $z \simeq 0.1$ to $z_{\rm pk} \simeq 2.5$. At redshifts exceeding $z_{\rm pk}$, the abundance of optically bright quasars turns over and slowly declines, while the recent X–ray data have revealed a LF that stays flat up to $z \simeq 4.5$.

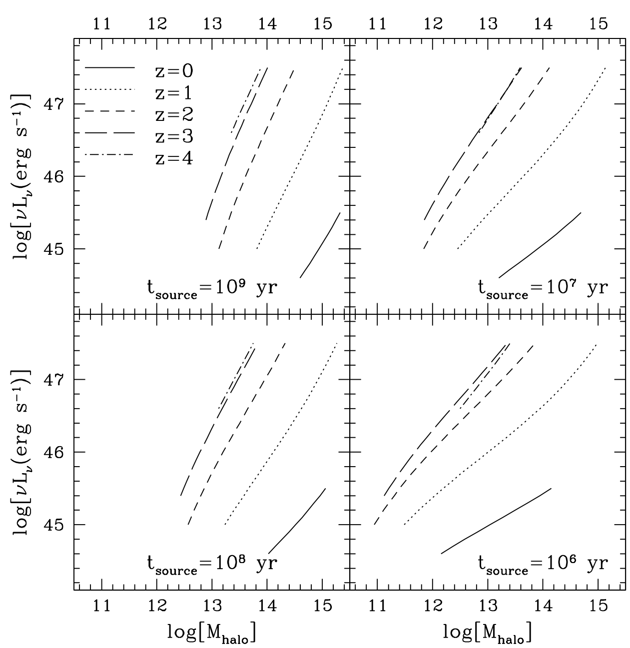

FIG. 1 – The relation between quasar luminosity (in the rest–frame B–band at $\nu_{\rm B} = 10^{14.83}$ Hz) and total halo mass, derived from the optical LF (Pei 1995) and the Press–Schechter mass function for 4 different quasar lifetimes.

The observed LF, $dN_{\rm obs}/dL$ can be compared directly with the Press–Schechter halo mass function $dN_{\rm ps}/dM$ to derive the luminosity $L(z,M)$ of each halo of mass M that satisfies

$$\frac{dN_{\rm obs}}{dL}(z,L) \times \frac{dL}{dM} = f_{\rm on}\frac{dN_{\rm ps}}{dM}(z,M). \tag{1}$$

Here $f_{\rm on}$ is the quasar "duty cycle", i.e. the fraction of BHs (assuming all halos contain BHs, cf. Magorrian et al. 1998) that are active at a given time around redshift z. This fraction is determined by the details of quasar light–curves and the distribution of formation times of BHs, and could be a function of several parameters, such as redshift, halo mass, etc. Here we simply assume that each quasar shines for a constant time $t_{\rm source}$, and we take the duty cycle to be $f_{\rm on} = t_{\rm source}/t_{\rm Hub}$, where $t_{\rm Hub}$ is the Hubble time. Our assumption is justified if the light–curve typically drops sharply a time $t_{\rm source}$ after the BH turns on (due to exhaustion of fuel, or shut–off due to a merger), or if intermittent activity adds up to a total duration $t_{\rm source}$ (e.g. if fueling is due to small but discrete clumps of gas). Note that independently of the ratio $M_{\rm bh}/M_{\rm halo}$, $f_{\rm on}$ must be $\ll 1$ to avoid unrealistically large masses of the quasar host halos.

The B–band luminosity associated with each halo mass obtained from equation (1) is shown for various redshifts and duty cycles in Figure 1. For a reasonable range of $t_{\rm source}$, observed quasars are associated with halos of $\sim 10^{11} - 10^{14} {\rm M}_\odot$. Note that this conclusion is based only on equating the observed and predicted space densities; the only assumption in Figure 1 (apart from adopting the Press–Schechter theory and the cosmological parameters) is the constancy of the duty cycle.

4. ACCRETION DISK MODELS

The optical/UV "Big Blue Bump" feature in the spectra of quasars is usually interpreted as emission from a thin accretion disk (e.g. Malkan 1983; Laor 1990). Here, we assume that, at any redshift, (i) the quasar luminosity in the B–band originates from a steady thin disk (Shakura & Sunyaev 1973; Frank et al. 1992) around a non–rotating BH, (ii) the disk is inclined at $i = 60^o$ from the line of sight and (iii) general relativistic effects, irradiation effects and possible complications due to radiation-pressure dominated zones in the disk can be neglected. We do not expect our main conclusions to depend crucially on these assumptions.

Figure 2 shows the luminosities $L_{\rm disk}$ predicted by these idealized disk models. The lines show $L_{\rm disk}$ for various accretion rates ($\log\dot{m} = 0$ to -3 with 0.5 intervals, in units of $\dot{M}_{\rm Edd}$) as a function of the central BH mass $M_{\rm BH}$. Note that here and in the remainder of this *Letter*, we use the Eddington accretion rate $\dot{M}_{\rm Edd} = 1.4 \times 10^{18}(M_{\rm BH}/M_\odot)$ g s^{-1} corresponding to a fiducial 10% radiative efficiency.

The essential feature of the disk emission used in our work is that there is a unique $L_{\rm disk}$ predicted in the B–band for a given $M_{\rm BH}$ and $\dot{m}$, as seen from Figure 2. The reduction of $L_{\rm disk}$ at high $M_{\rm BH}$ and low $\dot{m}$ in this figure appears because for this range of parameters the disk emission peaks at wavelengths longer than the B–band. We find that our conclusions do not depend crucially on this effect.

5. EVOLUTION OF THE QUASAR ACCRETION RATE

The accretion rate in quasars as a function of redshift and BH mass can be found by equating the observed and predicted luminosities, $L_{\rm B}(M_{\rm bh}, z) = L_{\rm disk}(M_{\rm bh}, \dot{m})$. Here $L_{\rm B}$ is the B band luminosity associated with a halo of mass $M_{\rm halo}$ (Fig. 1), which harbors a black hole of mass $M_{\rm bh} = 10^{-3.2} M_{\rm halo}$; $L_{\rm disk}$ is the B–band luminosity of the quasar as shown in Figure 2. As an example, according to Figure 1 if the source lifetime is $t_{\rm source} = 10^7$ yr, at $z = 2$ a halo of mass $M_{\rm halo} = 10^{12.2}$ M$_\odot$ (with a black hole of mass $M_{\rm bh} = 10^9$ M$_\odot$) has a luminosity of $10^{45.5}$ erg s^{-1}. This luminosity and black hole mass, according to Figure 2, correspond to an accretion rate $\dot{m} = 0.1$ (third curve from top).

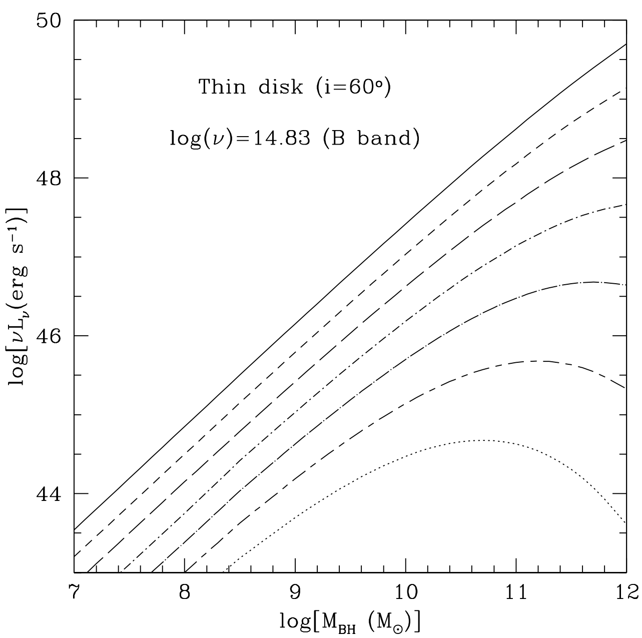

FIG. 2 – Predictions for the rest-frame B–band luminosity of an accretion disk inclined at $i = 60^o$ from the line of sight. The lines show the luminosities predicted for various accretion rates (from top to bottom, log $\dot{m} = 0$ to -3 with 0.5 intervals) as a function of the central black hole mass $M_{\rm bh}$.

In Figure 3, we show the inferred accretion rate $\dot{m}$ as a function of z for three different duty cycles ($t_{\rm source} = 10^{6,7,8}$ yr). In each case, we show the accretion rates for the halo mass range $10^{11} \leq M_{\rm halo}/{\rm M}_\odot \leq 10^{14}$. Figure 3 reveals that in all cases, the accretion rate decreases with decreasing redshift, and between $0 \lesssim z \lesssim 3$ follows the approximate relation $\log \dot{m} \simeq z - {\rm const}$. The inferred accretion rates are independent of halo mass for $t_{\rm source} = 10^7$ yr, as reflected by the grouping of the solid lines in Figure 3. For a longer lifetime $\dot{m}$ increases with increasing halo mass (long dashed curves); while for a shorter lifetime $\dot{m}$ decreases with increasing halo mass (short dashed lines). Note that in the latter case $\dot{m} > 1$ is predicted, meaning that the required luminosities can only be produced by BHs larger than we assumed. Although Figure 3 shows results only from the optical LF, we obtain qualitatively similar curves from the X–ray data, if we assume an X–ray/optical flux ratio of $\sim 20\%$. This value is based on the mean spectrum of a sample of 48 quasars, selected by Elvis et al. (1994) by the requirement that each quasar has a good spectrum both in the optical (from *IUE*) and X-ray (from *Einstein*). For $t_{\rm source} = 10^7$ yr, the accretion rate follows the simple relation $\log \dot{m} \simeq 0.9(1+z) - 3.7$ in the range $0 \lesssim z \lesssim 3$. This relation suggests that $\dot{M} \propto M$ at any given time, a scaling that would hold, for example, if each halo was undergoing isolated spherical self-similar infall (Bertschinger 1985). The apparent turnover of $\dot{m}$ at redshifts $z \gtrsim 3$ reflects the decline of the B–band LF at these redshifts, and may be caused by dust obscuration. This explanation is consistent with the recent X–ray data (insensitive to the presence or absence of dust) showing that the X-ray LF does not decline at $z \gtrsim 3$. Indeed, we find that the relation $\log \dot{m} \simeq 0.9(1+z) - 3.7$ allows a reasonable fit to the X–ray LF in the whole range $0 \lesssim z \lesssim 4$ for $t_{\rm source} \sim 10^7$ yr.

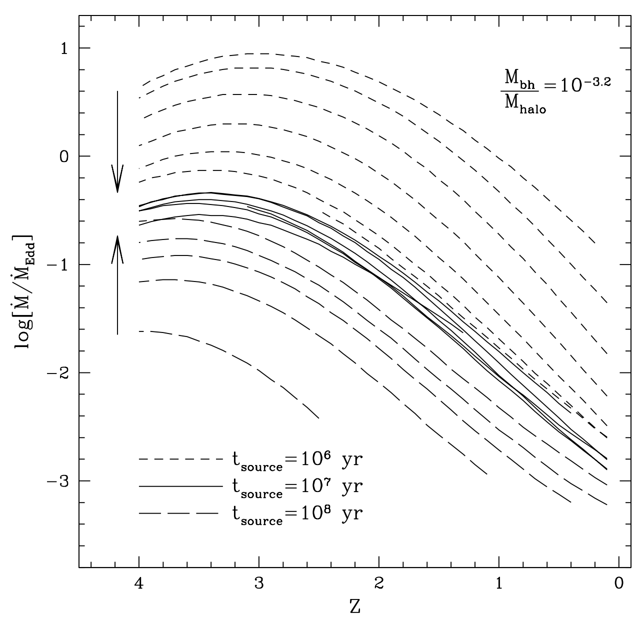

FIG. 3 – Accretion rates inferred from the quasar B–band LF and Press-Schechter theory, assuming a constant ratio $M_{\rm bh}/M_{\rm halo} = 10^{-3.2}$. The various lines correspond to halo masses in the range $10^{11} \leq M_{\rm halo}/{\rm M}_\odot \leq 10^{14}$, and the results are shown for three different values of the quasar lifetime. The arrows indicate the direction of increasing halo mass for the two cases $t_{\rm source} = 10^6$ and 10^8 yr.

6. PREDICTIONS FOR THE ACCRETION RATE

Is a declining accretion rate in the population of quasars indeed expected? A derivation of the accretion rate from first principles must necessarily address several complicated issues that are beyond the scope of this *Letter*, such as the role of mergers (which can presumably either provide fuel or shut off the accretion, depending on the mass ratio of the merging halos), angular momentum, and gas cooling. Here we will only put forward two general arguments for such a declining accretion rate.

First, assuming that each black hole grows as a central point mass in an isolated collapsing spherical cloud, the self–similar infall solutions of Bertschinger (1985) imply[2] that $M_{\rm bh} \propto t^{2/3}$ and $\dot{M}_{\rm bh}/M_{\rm bh} = 2/3t$. Although isolated spherical infall is likely to be a crude approximation at best for the formation of quasar black holes, the primary reason for the slow growth of the central mass is the cosmological expansion[3]. We therefore find it unlikely that departure from spherical symmetry, or interactions with other collapsing halos could considerably speed up the accretion relative to the power–law growth for an extended period of time (corresponding to $0 \lesssim z \lesssim 4$) in the entire quasar population. In Figure 4 we show the accretion rate as a function of redshift based on the Bertschinger (1985) solutions.

A second argument can be drawn directly from the Press–Schechter theory. Naively taking a time–derivative of the mass–function $dN_{\rm ps}/dM$ results in a quantity that is negative for small masses, and positive for large masses, with the sign changing at a critical value $M = M_*$. Sasaki (1994) argued that this behavior reflects a decreasing contribution of destructive mergers to the evolution of the mass function for $M > M_*$. In other words, the evolution of the mass function at large masses (the typical halo mass $M_{\rm halo}$ of interest here) is governed mainly by accretion, rather than mergers.

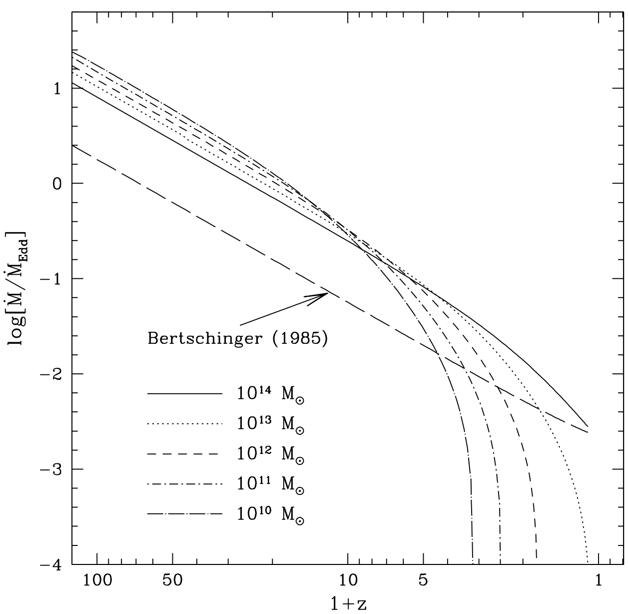

FIG. 4 – Accretion rates predicted by Press–Schechter theory for halos of various masses, assuming that the evolution of the PS mass function is driven by accretion only. Also shown is the accretion rate predicted by the self-similar collapse theory of Bertschinger (1985). The accretion rates for the central BHs are identical to those of the halos if the ratio $M_{\rm bh}/M_{\rm halo}$ is constant.

In the limit that $d^2N_{\rm ps}/dMdt$ merely reflects the growth in mass of each individual halo, the accretion rate of halos can be obtained by requiring that the total number density of halos does not change, $d/dt[MdN/dM] = 0$. This yields $\dot{m} = -(1/M) \times (d^2N/dMdt) \times [(dN/dM)/M + d^2N/dM^2]^{-1}$ for the halo mass accretion rate, which, by our assumption of constant ratio $M_{\rm bh}/M_{\rm halo}$, is identical to the BH accretion rate. In Figure 4 we show the accretion rates in this limit as a function of redshift. The accretion rates drop in all cases but unlike in the isolated spherical self-similar infall case, $\dot{m}(z)$ depends on the halo mass.

7. DISCUSSION AND CONCLUSIONS

In our picture, after their formation, the black holes grow synchronously with their dark matter halos, maintaining a constant $M_{\rm bh}/M_{\rm halo}$. We did not address the important question of consistency between the mass accretion rates inferred from the LFs and the individual black hole masses acquired by the end of the quasar phase ($M_{\rm bh} = \int dt\dot{M}_{\rm bh}$). This would require following the accretion and the merger history of individual halos (Lacey & Cole 1993; Kauffmann & White 1993) while our work concentrated on the quasar population as a whole. Related to this question is the interpretation of the duty–cycle, which could be caused either by short intermittent activity phases or one single luminous phase. We assumed that all halos have a central black hole, as suggested by observations (Magorrian et al. 1998); however the duty cycle could be partly interpreted as the fraction of halos harboring quasars.

It is important to note that, independent of the questions of interpretation above, our fit to the LF with a declining $\dot{m}(z)$ is not unique. An alternative possibility is if the ratio $M_{\rm bh}/M_{\rm halo}$ decreases rapidly towards low redshifts (Haehnelt, Natarajan & Rees 1998). In order to reconcile the small black hole masses predicted in this model with the Magorrian et al. (1998) data, the bulges must comprise a small fraction ($\lesssim 1\%$) of the total baryonic mass in galaxy–size halos. A second alternative to our scenario is a decrease of the duty–cycle with redshift. However, Figure 3 shows that keeping the accretion rate constant over the range $0 \lesssim z \lesssim 4$ would require very short lifetimes ($t_{\rm source} \ll 10^6$ yr) near $z \sim 0$.

According to our results, the accretion rate of the population of quasar black holes decreases with time. A peak in the accretion rate near $z \simeq 3.5$ (Fig. 3) is inferred from the optical LF. A derivation using X–ray data does not show a similar turnover, suggesting that the peak inferred from optical is caused by dust obscuration (Heisler & Ostriker 1988). If quasars have a lifetime of $\sim 10^7$ yr and a constant ratio $M_{\rm bh}/M_{\rm halo} = 10^{-3.2}$, we find that the simple relation $\log \dot{m} \simeq 0.9(1+z) - 3.7$ provides a reasonable fit to the evolution of the quasar LFs at $0 \lesssim z \lesssim 3$. Note that the overall normalization of the inferred accretion rates depends on the 10% radiative efficiency assumed for the thin disk, and that a scatter around this relation is naturally expected for individual quasars. Our work suggests, however, that near $z = 0$, $\dot{m}$ drops to substantially sub–Eddington values ($\dot{m} \lesssim 10^{-2}$), at which ADAFs exist (Narayan et al. 1998). The combination of a decreasing $\dot{m}(z)$ and a possible transition to low radiative efficiency ADAFs near $z \sim 0$ could be the origin of the absence of bright quasars in the local universe and the faintness of accreting BHs at the centers of nearby galaxies.

[2]Although these relations are valid only for an Einstein–de Sitter universe, a similar behavior is expected in $\Omega + \Lambda$=1 models.

[3]For comparison, note that in a static medium the central mass would grow exponentially or faster, cf. Bondi (1952).

We thank A. Loeb, R. Narayan and M. Rees for useful discussions and comments. ZH was supported by the DOE and the NASA grant NAG 5-7092 at Fermilab. KM was supported by a SAO Predoctoral Fellowship, NASA grant NAG 5-2837, and a French Higher Education Ministry grant.

REFERENCES

Bertschinger, E. 1985, ApJS, 58, 39
Bondi, H. 1952, MNRAS, 112, 195
Caditz, D., Petrosian, V., & Wandel, A. 1991, ApJL, 372, 63
Carlberg, R. G. 1990, ApJ, 350, 505
Elvis, M. et al. 1994, ApJS, 95, 1
Frank, J., King, A. R., & Raine, D. J. 1992, Accretion Power in Astrophysics, 2nd ed., Cambridge Univ. Press, Cambridge
Haehnelt, M. G., Natarajan, P. & Rees, M. J. 1998, MNRAS, submitted, astro-ph/9712259
Haehnelt, M. G., & Rees, M. J. 1993, MNRAS, 263, 168
Haiman, Z., & Loeb, A. 1998, ApJ, 503, 505
Heisler, J., & Ostriker, J. P. 1988, ApJ, 332, 543
Kauffmann, G., & White, S. D. M. 1993, MNRAS, 261, 921
Lacey, C., & Cole, S. 1993, MNRAS, 262, 627
Laor, A. 1990, MNRAS, 246, 369
Laor, A., & Netzer, H. 1989, MNRAS, 238, 897
Magorrian, J., et al. 1998, AJ, 115, 2285
Malkan, M. A. 1983, ApJ, 268, 582
Maloney, A., & Petrosian, V. 1998, ApJ, submitted, astro-ph/9807166
Miyaji, T., Hasinger, G., & Schmidt, M. 1998, Proceedings of "Highlights in X-ray Astronomy", astro-ph/9809398
Narayan, R., Mahadevan, R. & Quataert, E. 1998, in "The Theory of Black Hole Accretion Discs", eds M.A. Abramowicz, G. Bjornsson & J.E. Pringle (Cambridge: Cambridge University Press), astro-ph/9803141.
Ostriker, J. P., & Steinhardt, P. J. 1995, Nature, 377, 600
Pei, Y. C. 1995, ApJ, 438, 623
Press, W. H., & Schechter, P. L. 1974, ApJ, 181, 425
Rees, M. J. 1984, ARA&A, 22, 471
Sasaki, S. 1994, PASJ, 46, 427
Shakura, N. I. & Sunyaev, R. A. 1973, A&A, 24, 337
Siemiginowska, A., & Elvis, M. 1997, ApJL, 482, 9
Small, T. A., & Blandford, R. D. 1992, MNRAS, 259, 725
Somerville, R. S., Lemson, G., Kolatt, T. S., Dekel, A, MNRAS, submitted, astro-ph/9807277
Yi, I. 1996, ApJ, 473, 645