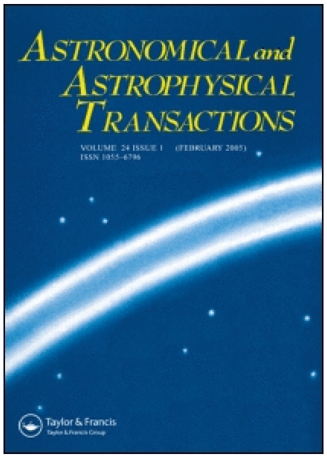

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ACCRETION EFFICIENCY AT THE EDDINGTON LUMINOUS STAGE IN QUASARS

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Non-steady and eruptive phenomena in quasars are thought to be associated with the Eddington or super-Eddington luminous stage. Although there is no lack of hypotheses about the total duration of such a stage, the latter remains essentially unknown. We calculate the duration of the quasar luminous stage as a function of the initial mass of a newborn massive black hole (MBH) by comparing the observed luminosity- and redshift distributions of quasars with the mass distribution of MBHs in normal galactic nuclei. It is assumed that, at the quasar stage, each MBH goes through a single (or recurrent) phase(s) of accretion with, or close to, the Eddington luminosity. The mass distributions of quasars is found to be connected with that of MBHs residing in normal galaxies by a single-valued relationship through the mass range 10^7–$10^{11}\,M_\odot$ of the inferred MBHs.

KEY WORDS Quasars, accreation, massive black holes

Recently for a sample of galaxies Kormendy and Richstone (1995) found an approximate relationship $M_h \simeq 0.003 M_b$ between the central MBH mass, M_h, and that of the galactic bulge, M_b. A similar relationship $M_h \simeq 0.006 M_b$ was found for a sample of 32 galaxies (Magorrian *et al.*, 1997). The relationship between absolute magnitudes of quasars and their host galaxies (Bahcall *et al.*, 1997) is reduced to the MBH to bulge mass relation in galaxies provided that (Ozernoy, 1998): (i) the central MBH shines at or near to the Eddington luminosity and (ii) the host galaxy undergoes through a starburst episode. This correlation, coupled with the known luminosity function of galaxies, can serve to obtain (Salucci *et al.*, 1998) the MBH mass distribution $\phi_1(M_h)dM_h$. The history of matter accretion onto a central MBH, thought to serve as a source of quasar activity, is linked to the present observable properties of each individual quasar, such as its luminosity, variability, and emission spectrum. If the bolometric luminosity of a quasar comprises a fraction λ of the Eddington luminosity, i.e. $\lambda = L/L_E$, $L_E = 4\pi G M_h m_p c/\sigma_T$, the underlying accretion is accompanied by an exponential growth of the MBH mass with the characteristic time $t_E = 4.5 \times 10^8 \eta/\lambda$ yrs, where η is the accretion efficiency of mass-to-energy transformation. The crucial problem is the duration, t_q, of such a nearly Eddington accretion phase. Usually an effective t_q, the same for the entire black hole mass range $M_h \sim 10^6$–$10^{10} M_\odot$, is calculated by comparing the global number density of normal galaxies and quasars: *e.g.* the effective t_q is in the range $10^6 \div 5 \times 10^8$ years (Haehnelt, *et al.*, 1997). Meanwhile the recent data on mass distribution of MBHs in galaxies provide an opportunity to solve this problem in a more detailed way, *viz.*, to calculate the dependence of t_q upon M_h, which is the major aim of this paper. We shall explore whether the distribution functions of quasars and MBHs in normal galaxies are consistent with each other, and we will do this locally in the vicinity of each mass, rather than in a global way.

It would be reasonable to assume that the duration of the Eddington phase t_q depends on the initial mass of a newborn MBH or, in other words, on the initial luminosity, L_i, of the quasar: $t_q = t_q(L_i)$. For simplicity, we also suppose that the transition into and out of the Eddington phase occurs instantaneously:

$$L = \begin{cases} 0, & \text{if } t < t_c; \\ L_i \exp[(t - t_c)/t_E], & \text{if } t_c < t < t_c + t_q(L_i); \\ 0, & \text{if } t > t_c + t_q(L_i), \end{cases} \tag{1}$$

where t_c is the instant of MBH formation. We use the observed (Boyle *et al.*, 2000) distribution $\phi_2(L, z)\, \mathrm{d}L\, \mathrm{d}z$ of quasars in bolometric luminosity L and redshift z.

Let $N(t, L)\, \mathrm{d}L$ be the number of active quasars at instant t per unit of comoving volume in the luminosity interval $\mathrm{d}L$, and $N_c(t, L_i)\, \mathrm{d}L_i$ be the number of MBHs formed before instant t per unit of comoving volume in the initial luminosity interval $\mathrm{d}L_i$. We also use the definition $T = \min\{t_q(L_i), t_E(L_i) \ln(L/L_i)\} \ll t$ with t_E depending on L_i via λ. At instant t, the number of active MBHs with luminosity $< L$ equals the total number of MBHs formed before t minus those MBHs which by the instant t either become inactive or have their luminosity above L. This balance condition can be written up as

$$\begin{aligned} N(t, L) &= \frac{\partial}{\partial L} \left\{ \int_0^L N_c(t, L_i)\, \mathrm{d}L_i - \int_0^L N_c(t - T(L, L_i), L_i)\, \mathrm{d}L_i \right\} \\ &\simeq \frac{1}{L} \int_{\tilde{L}}^{L} \frac{\partial N_c(t, L_i)}{\partial t} t_E(L_i)\, \mathrm{d}L_i, \end{aligned} \tag{2}$$

where $\tilde{L}$ is the root of equation $t_q(\tilde{L}) = t_E(\tilde{L}) \ln(L/\tilde{L})$. In the limiting case of $t_q = \mathrm{const} \ll t_E$, from Eq. (2) follows the obvious relationship $N(t, L) = t_q \partial N_c(t, L)/\partial t$. By using the distribution functions of MBHs and quasars, ϕ_1 and ϕ_2 correspondingly, we may rewrite Eq. (2) as

$$\int_0^\infty dz (1 + z)^{-3/2} L \cdot \phi_2(L, z) \simeq \frac{t_E(L)}{t_0} \int_{M(L)}^{M(L)X} \phi_1(M_h)\, \mathrm{d}M_h. \tag{3}$$

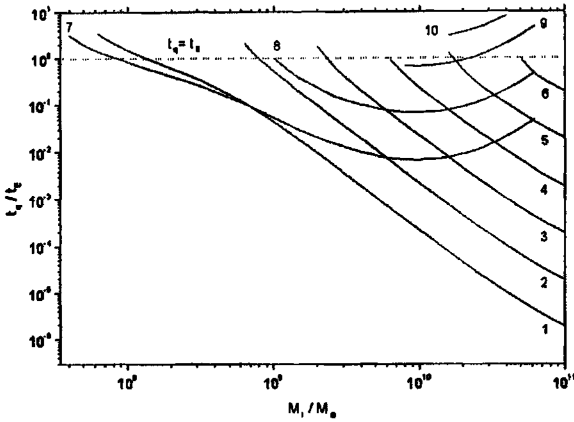

Figure 1 The ratio $t_q(M_i)/t_E$ as a function of the initial MBH mass M_i. Curves labeled 1 to 6 are based on the distribution A for $\eta = 10^{-1}$, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} 10^{-6}, respectively. Curves 7 to 10 are based on the distribution B for $\eta = 10^{-1}$, 10^{-2}, 10^{-3}, 5×10^{-4}, respectively.

Here $X = \exp[t_q(L)/t_E]$ with $M(L)$ determined by the equation $L = \lambda L_E$ and the relationship $t = t_0/(1+z)^{3/2}$ for the flat cosmological model is used. While obtaining Eq. (3), we have also taken into account that t_E very slowly varies with respect to $\phi_1(M_h)$. Eq. (3) defines t_q as an implicit function of L_i, which can be translated into a relationship between t_q and the initial BH mass M_i using equation $L = \lambda L_E$.

The numerical solution of Eq. (3) is found by adopting the mass distribution of MBHs $\phi_1(M_h)\,\mathrm{d}M_h$ (Salucci *et al.*, 1998), derived with the use of three relationships, *viz.*, (i) a recently found correlation $\log(M_h) = \log(M_b) - 2.6 \pm 0.3$ between the MBH mass M_h and the bulge mass M_b; (ii) the mass-luminosity relation for galaxies and (iii) the Schechter luminosity function. In Figure 1 we employ two somewhat different distributions in MBH mass (Salucci *et al.*, 1998) and name them distribution A (dotted lines) and distribution B (solid lines), which correspond respectively to the power-law and constant dispersion forms (Salucci, *et al.*, 1998). Figure 1 presents the results of our numerical calculation of the ratio $t_q(M_i)/t_E$ for different values of η and MBH mass distributions A and B.

It should be noted that a solution does not exist for all values of M_i and η. The existence region for the solution is defined by the condition that the r.h.s of Eq. (3) exceeds its l.h.s. if one puts $X = +\infty$. For those M_i which lead to the opposite condition, the number of galactic nuclei with MBHs is not enough to explain, in the framework of our model, the distribution function of quasars in L and z, even if these MBHs stay in an active quasar state during the maximum possible time $t_q \sim 3t_E$. The solution only exists at $\eta > 3 \times 10^{-7}$ for BH distribution A and at $\eta > 5 \times 10^{-4}$ for distribution B. Figure 1 demonstrates the main result of this work: ***the distribution of MBHs and quasars locally (in mass) connected by a single-valued relation through some mass and η ranges.*** Nevertheless, jumps of the η value are not excluded on the boundary of the region of solution existence. Similar jumps seem to be quite natural if MBHs in the different mass ranges are formed in different ways (e.g., by collapse of massive gas clouds, stellar clusters, etc.) and so there are various accretion regimes with different values of η. If such jumps indeed take place, transitions between the curves of each of distributions A and B are possible. These transitions must be smoothed because MBHs formed in different ways would coexist in some mass range(s).

If accretion onto a black hole were nearly spherical, the efficiency of mass-to-energy transformation, determined by the physical state of the infalling matter and deviations from the spherical symmetry (such as magnetic field), would be very low, $\eta \ll 1$. In reality, the matter in galactic nuclei possesses angular momentum (possibly, acquired in the process of formation) and therefore accretion disks must have been formed around the central MBHs. The efficiency of disk accretion onto a Schwarzschild black hole is $\eta \simeq 0.06$ and reaches $\eta \simeq 0.42$ for an extremely rotating Kerr black hole. As we find in this paper, the comparison of the MBH mass distribution function in quasars with those in normal galaxies demonstrates that most favorable agreement is achieved for large $\eta \sim 0.1$ and therefore, in the galactic nuclei, disk accretion seems to be more justifiable than spherical.

Acknowledgments

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