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Growth of Massive Black Holes

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Abstract

Observational constraints on the growth of massive black holes (BHs) in galactic nuclei and material sources for BH growth are discussed in this paper. Using recent observational results on early-type galaxies, QSOs and BH demography, we find that the total local BH mass density is consistent with the total density accreted during optically bright QSO phases if QSOs have a mass-to-energy conversion efficiency $\epsilon \simeq 0.1$. Including the effect of BH mergers, we find relations between the local BH mass function and the QSO luminosity function. Comparison of the predicted relations with observations suggests that luminous QSOs ($L_{\rm bol} \gtrsim 10^{46}\,{\rm erg\,s^{-1}}$) have a high efficiency (e.g. $\epsilon \sim 0.2$) and the growth of high-mass BHs ($\gtrsim 10^8\,{\rm M_\odot}$) comes mainly from accretion during optically bright QSO phases. Less luminous QSOs must accrete with a low efficiency < 0.1; alternatively, they may accrete with high efficiency, but a significant fraction should be obscured. The mean lifetime of luminous QSOs ($L_{\rm bol} \gtrsim 10^{46}\,{\rm erg\,s^{-1}}$) is estimated to be $(3\text{–}13)\times 10^7$ yr, which is comparable to the Salpeter time. The mass released by stellar collisions and the stellar mass tidally disrupted by massive BHs are not sufficient to account for the present BH mass in galactic centers, especially in bright galaxies. The material for BH growth can only come from other sources, for example, the mass released by stellar evolution in the initial 1 Gyr of the galaxy's lifetime, or gas that sinks to the galactic center in a galaxy merger.

1.1 Introduction

QSOs are believed to be powered by accretion onto massive black holes (BHs) in faraway galaxies. According to the cosmological principle that the universe is homogeneous and isotropic on large scales, we believe that faraway galaxies represent the history of nearby galaxies. Thus, some nearby galaxies should have experienced bright QSO phases and contain massive BHs at their centers (Sołtan 1982; Rees 1984). Observations in the past two decades have shown that massive BHs indeed exist in the centers of most nearby galaxies (Kormendy & Richstone 1995; Kormendy & Gebhardt 2001). The questions we will discuss are as follows. How do the BHs become so massive? Is it mainly due to accretion during optically bright QSO phases or other mechanisms? What is the material source for BH growth?

1.2 Total BH Mass Densities

The simplest and most elegant argument relating the properties of QSOs to BHs in nearby galaxies is due to Sołtan (1982), who pointed out the luminosity function of QSOs as a function of redshift traces the accretion history of remnant BHs in nearby galaxies. The BH mass density due to bright QSO phases can be estimated directly from the local energy density in QSO photons and an assumed mass-to-energy conversion efficiency ϵ. We define $\Psi(L,t)$ as the QSO luminosity function so that $\Psi(L,t)\mathrm{d}L$ gives the comoving number density of QSOs with luminosity in the range $[L, L+\mathrm{d}L]$ at cosmic time t, and define $n_{M_\bullet}(M_\bullet,t)$ as the BH mass function so that $n_{M_\bullet}(M_\bullet,t)\mathrm{d}M_\bullet$ gives the comoving number density of BHs with mass in the range $[M_\bullet, M_\bullet+\mathrm{d}M_\bullet]$ at t. Defining t_0 as the present time, $n_{M_\bullet}(M_\bullet,t_0)$ gives the local BH mass distribution. Sołtan's argument can be encapsulated in the equation below:

$$\int_0^\infty M_\bullet n_{M_\bullet}(M_\bullet,t_0)\mathrm{d}M_\bullet = \int_0^{t_0}\mathrm{d}t\int_0^\infty \mathrm{d}L\frac{(1-\epsilon)L_{\rm bol}}{\epsilon c^2}\Psi(L,t), \tag{1.1}$$

where c is the speed of light, the efficiency ϵ is assumed to be a constant, $L_{\rm bol}$ is the bolometric luminosity of QSOs and $(1-\epsilon)L_{\rm bol}/\epsilon c^2$ is the mass accretion rate onto the BHs in QSOs. The left-hand side of equation (1.1) gives the current total local BH mass density $\rho_{\bullet,\rm local}(z=0)$, and the right-hand side gives the total BH mass density accreted during QSO phases [until redshift $z=z(t_0)=0$] $\rho_{\bullet,\rm acc}(z=0)$. Note that the luminosity function $\Psi(L,t)$ of QSOs in equation (1.1) includes both unobscured and obscured QSOs (obscured accretion is suggested by the study of the X-ray background spectrum, see Fabian & Iwasawa 1999). Comparison of the local BH mass density with the density accreted during QSO phases provides considerable insight into the formation and growth of massive BHs (e.g. Yu & Tremaine 2002; Volonteri, Haardt & Madau 2003; Haehnelt & Kauffmann 2001 and references therein).

We use recent observation results on early-type galaxies, QSOs and BH demography to provide new estimates of the total local BH mass density and accreted BH mass density during optically bright QSO phases (Yu & Tremaine 2002). We use the velocity dispersions of nearby early-type galaxies obtained by the Sloan Digital Sky Survey (Bernardi et al. 2003), and the tight correlation between BH mass and velocity dispersion in Tremaine et al. (2002) to get the local BH mass function and BH mass density in early-type galaxies. We then correct the local BH mass density in early-type galaxies by the ratio of the total luminosity density of hot components (elliptical galaxies or bulges of spiral and S0 galaxies) to the luminosity density of hot components in early-type galaxies (Fukugita, Hogan & Peebles 1998), and get the total local BH mass density to be $\rho_{\bullet,\rm local}(z=0)=(2.5\pm0.4)\times10^5h_{0.65}^2\,\mathrm{M_\odot\,Mpc^{-3}}$, which is consistent with the mass density $\rho_{\bullet,\rm local}(z=0)=(2.0\pm0.7)\times10^5h_{0.65}^2\,\mathrm{M_\odot\,Mpc^{-3}}$ estimated by Aller & Richstone (2002). We use the QSO luminosity function obtained from the 2dF QSO redshift (Boyle et al. 2002) to get the total BH mass density accreted due to optically bright QSO phases $\rho^{\rm QSO}_{\bullet,\rm acc}(z=0)=2.1\times10^5(C_B/11.8)[0.1(1-\epsilon)/\epsilon]\,\mathrm{M_\odot\,Mpc^{-3}}$, where C_B is the bolometric correction of QSOs ($\simeq 11.8$ in Elvis et al. 1994), defined by $L_{\rm bol}=C_B\nu_BL_\nu(B)$ [$\nu_BL_\nu(B)$ is the energy radiated at the central frequency of the B band per unit time and logarithmic interval of frequency]. Here, we use the superscript "QSO" to represent optically bright QSOs, similarly below. We see that if QSOs have an efficiency $\epsilon\simeq0.1$, the two BH mass densities $\rho_{\bullet,\rm local}(z=0)$ and $\rho^{\rm QSO}_{\bullet,\rm acc}(z=0)$ are consistent. The growth history of the comoving massive BH mass density due to accretion during optically bright QSO phases is shown in Figure 1.1.

Study of the X-ray background spectrum suggests that a large number of obscured AGNs contribute to the total BH mass density (Fabian & Iwasawa 1999). The accreted BH mass

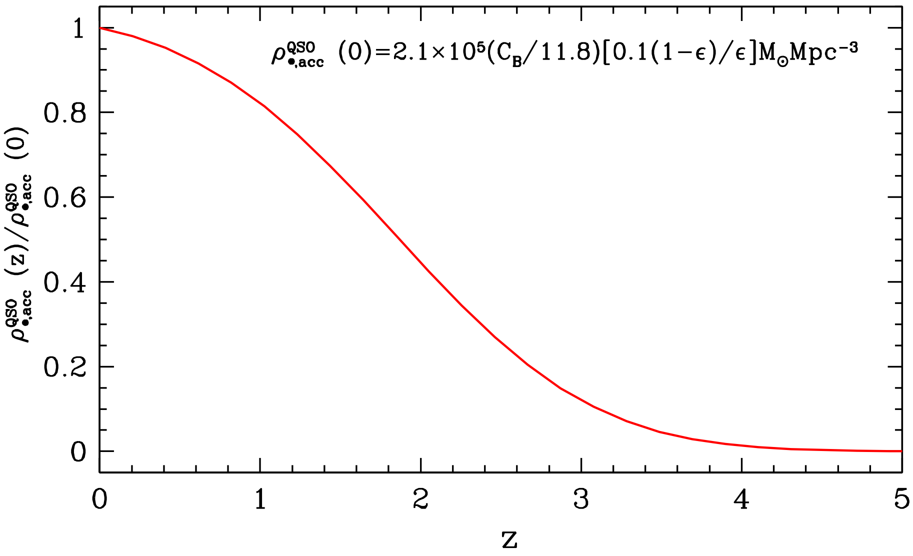

Fig. 1.1. The history of the comoving massive BH mass density due to accretion during optically bright QSO phases. The mass-to-energy conversion efficiency ϵ is assumed to be a constant.

density inferred from the X-ray background is larger, such as $\rho_{\bullet,\rm acc} = (6-9) \times 10^5 (0.1/\epsilon)\,{\rm M_\odot\,Mpc^{-3}}$ (Fabian & Iwasawa 1999), $\rho_{\bullet,\rm acc} = (7.5-16.8) \times 10^5 (0.1/\epsilon)\,{\rm M_\odot\,Mpc^{-3}}$ (Elvis, Risaliti & Zamorani 2002), and $\rho_{\bullet,\rm acc} = 9 \times 10^5 (0.1/\epsilon)\,{\rm M_\odot\,Mpc^{-3}}$ (Barger et al. 2001). However, there exist many uncertainties in the estimation of the above BH mass densities since the population of AGNs contributing to the X-ray background is not yet clearly understood, and is not necessarily the same as the optically bright QSOs.

If the local BH mass density comes mainly from optically bright QSOs, not only the total local BH mass density but also the local BH mass distribution should be consistent with the accretion history determined from QSOs. The latter comparison is the subject of the next section.

1.3 Partial BH Mass Densities

The evolution of the BH mass function is determined by both BH mergers and other physical processes (e.g. gas accretion). Here we update Soltan's argument and include the effects of BH mergers to get the relations between local BH mass density distribution and accreted mass density distribution due to QSO phases. Without considering BH mergers and assuming that the luminosity of QSOs is only a function of BH mass (e.g. the Eddington luminosity $L_{\rm Edd}$), we get the relation in partial mass densities simply by changing the lower integration limit in equation (1.1):

$$G_{\rm local}(M_\bullet,t_0) \equiv \int_{M_\bullet}^{\infty} (M'_\bullet - M_\bullet) n_M(M'_\bullet,t_0) {\rm d}M'_\bullet \tag{1.2}$$

$$= \int_0^{t_0} {\rm d}t \int_{L(M_\bullet)}^{\infty} {\rm d}L \frac{(1-\epsilon)L_{\rm bol}}{\epsilon c^2} \Psi(L,t) \equiv G_{\rm acc}(M_\bullet,t_0), \tag{1.3}$$

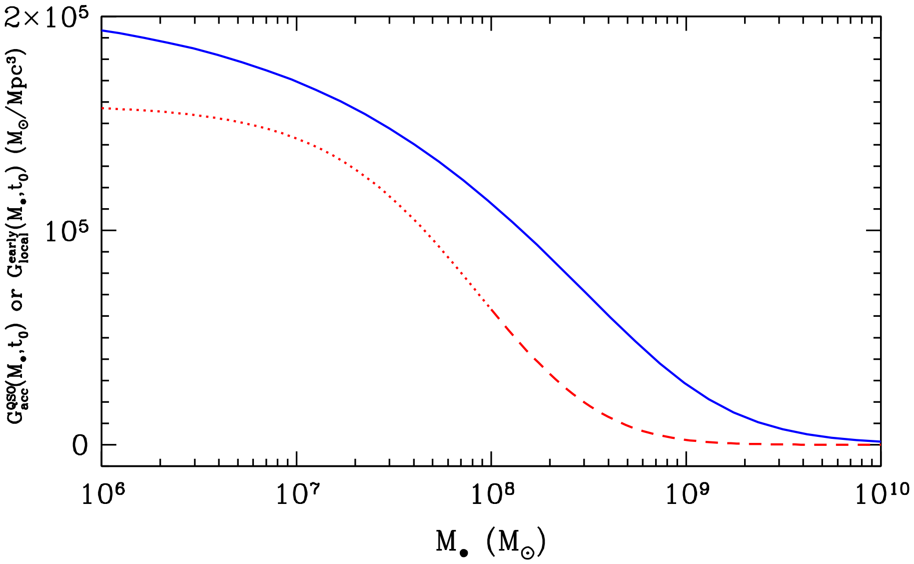

Fig. 1.2. Partial BH mass densities as a function of BH mass $M_\bullet$ (see eq. 1.5). The thick solid line shows the accreted partial BH mass density during optically bright QSO phases $G^{\rm QSO}_{\rm acc}(M_\bullet,t_0)$ (see eq. 1.3), where QSOs are assumed to have the Eddington luminosity and the mass-to-energy conversion efficiency ϵ is assumed to be 0.1. The dashed line ($M_\bullet \gtrsim 10^8\,{\rm M}_\odot$) and the dotted line ($M_\bullet \lesssim 10^8\,{\rm M}_\odot$) show the local partial BH mass density in early-type galaxies $G^{\rm early}_{\rm local}(M_\bullet,t_0)$ (see eq. 1.2). High-mass BHs are mostly in early-type galaxies, and we have $G^{\rm early}_{\rm local} \simeq G_{\rm local}$ at $M_\bullet \gtrsim 10^8\,{\rm M}_\odot$. In the dotted region, $G^{\rm early}_{\rm local}$ underestimates $G_{\rm local}$ because we have ignored the contribution from BHs in spiral bulges. For high BH masses ($M_\bullet \gtrsim 10^8\,{\rm M}_\odot$), inequalities (1.4) imply that the solid line should be equal to the dashed one if mergers are unimportant, and lower if mergers are important, which is inconsistent with the observations.

where we have the term $(M'_\bullet - M_\bullet)$ (rather than just $M'_\bullet$) in $G_{\rm local}(M_\bullet,t_0)$ because the accreted BH mass density represents an *increase* of the BH mass density. The physics of BH mergers is poorly understood. Here we consider an extreme case that BH mass is conserved during BH mergers, without gravitational radiation being emitted (relaxing this assumption will not significantly change our conclusions, see details in Yu & Tremaine 2002). In this case, considering that BH mergers always increase the total mass in high-mass BHs, equation (1.4) is changed to the inequality below:

$$G_{\rm local}(M_\bullet,t_0) \geq G_{\rm acc}(M_\bullet,t_0). \tag{1.4}$$

When $M_\bullet = 0$, we have Sołtan's argument $G_{\rm local}(M_\bullet,t_0) = G_{\rm acc}(M_\bullet,t_0)$. We also have the inequality for the normalized partial mass densities below:

$$g_{\rm local}(M_\bullet,t_0) \equiv \frac{G_{\rm local}(M_\bullet,t_0)}{G_{\rm local}(0,t_0)} \geq \frac{G_{\rm acc}(M_\bullet,t_0)}{G_{\rm acc}(0,t_0)} \equiv g_{\rm acc}(M_\bullet,t_0), \tag{1.5}$$

which is independent of the efficiency ϵ so long as it is constant.

Are these inequalities on partial BH mass densities consistent with the observations? Figure 1.2 shows the partial mass densities obtained from observations as a function of BH

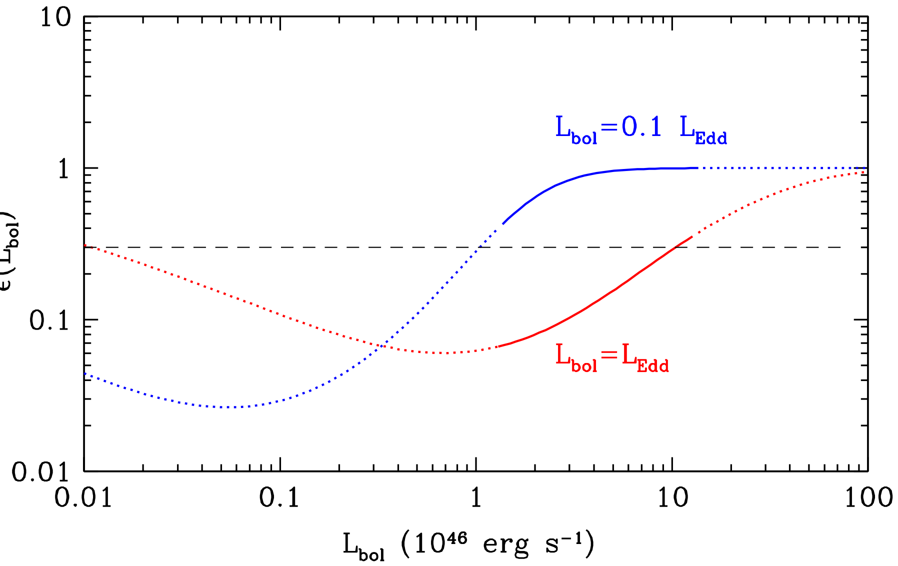

Fig. 1.3. The (bolometric) luminosity-dependent efficiency of QSOs $\epsilon(L_{\rm bol})$ if mergers are unimportant. The solid lines in the range $10^{46}\,{\rm erg\,s^{-1}} \lesssim L_{\rm bol} \lesssim 10^{47}\,{\rm erg\,s^{-1}}$ [corresponding to BH mass in the range $10^8(L_{\rm Edd}/L_{\rm bol})\,{\rm M_\odot} \lesssim M_\bullet \lesssim 10^9(L_{\rm Edd}/L_{\rm bol})\,{\rm M_\odot}$] show the region in which the observational constraints are fairly secure. The lower line represents the result obtained by assuming $L_{\rm bol} = L_{\rm Edd}$, and the upper one assumes $L_{\rm bol} = 0.1L_{\rm Edd}$. If $L_{\rm bol} = 0.1L_{\rm Edd}$, the efficiency is required to be higher than 0.3 (the maximum efficiency for thin-disk accretion onto BHs) or even approach 1.

mass. The solid line represents the BH mass density distribution accreted during optically bright QSO phases and the dashed line represents the local density distribution obtained from the SDSS early-type galaxy sample. It is assumed that QSOs have the Eddington luminosity and the efficiency is 0.1. The cosmological model used is $(\Omega_{\rm M},\Omega_\Lambda,h) = (0.3,0.7,0.65)$ (Wang et al. 2000). We only compare the distributions at the high-mass end ($M_\bullet \gtrsim 10^8\,{\rm M_\odot}$), because at the high-mass end the local BH mass function is dominated by the BHs in early-type galaxies. As shown in Figure 1.2, the partial mass density obtained from optically bright QSOs (solid line) is higher than that obtained from local galaxies (dashed line) which is not consistent with inequality (1.4) or (1.5).

What causes the discrepancy shown in Figure 1.2? We tested some assumptions we have made and considered some processes we have ignored, such as contributions by other accretion mechanisms, the uncertainty of the QSO luminosity function at the bright end, the uncertainty of the bolometric correction, the assumption of the Eddington luminosity for QSOs, emission of gravitation waves during BH mergers, incomplete merging of binary BHs etc. We find that in most cases the discrepancy cannot be solved or can only become worse. We may propose a possible solution to the discrepancy. To make the partial mass density accreted due to optically bright QSO phases $G_{\rm acc}^{\rm QSO}(M_\bullet,t_0)$ not higher than the partial local mass density $G_{\rm local}(M_\bullet,t_0)$ at the high-mass end ($M_\bullet \gtrsim 10^8\,{\rm erg\,s^{-1}}$), high efficiencies (e.g. $\epsilon \sim 0.2$) are needed for luminous QSOs ($L_{\rm bol} \gtrsim 10^{46}\,{\rm erg\,s^{-1}}$). Note that the required efficiency is close to the maximum efficiency allowed in thin-disk accretion mod-

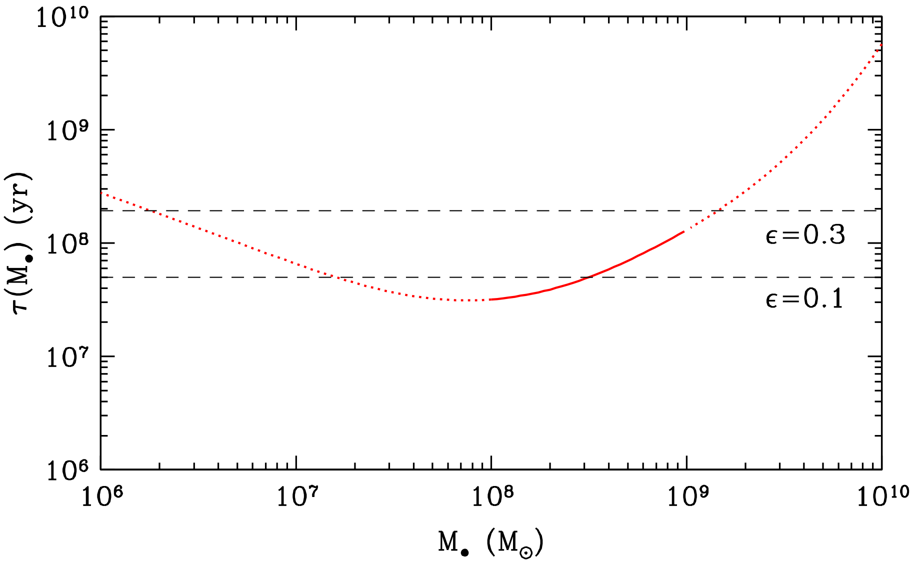

Fig. 1.4. The mean lifetime of QSOs with BH mass $\gtrsim M_\bullet$ as defined by equation (1.7). The solid line in the range $10^8\,M_\odot \lesssim M_\bullet \lesssim 10^9\,M_\odot$ shows the region in which the observational constraints are fairly secure. The horizontal dashed lines represent the Salpeter time (the time for a BH radiating at the Eddington luminosity to e-fold in mass) $\sim 4.5\times10^7\epsilon/[0.1(1-\epsilon)]$ yr.

els, $\epsilon \simeq 0.31$ (Thorne 1974). Thus, we come to these conclusions: growth of high-mass BHs ($M_\bullet \gtrsim 10^8\,M_\odot$) comes mainly from accretion during optically bright QSO phases; and obscured accretion [or other accretion mechanisms, such as accretion by advection dominated accretion flow (ADAF) and accretion of non-baryonic dark matter etc., cf. Haehnelt, Natarajan & Rees 1998] does not significantly contribute to the high-mass BH growth. This conclusion is supported by recent observations on the X-ray background, which show that a significant fraction of sources contributing to the X-ray backgrounds come from low redshifts $z \lesssim 1$ (Hasinger 2003; Fabian 2004), rather than the usual assumption of $z \sim 2$ (thus the BH mass density contributed by obscured accretion significantly decreases, compared to early estimates), and is consistent with the scarcity of Type II QSOs. Less luminous QSOs ($L_{\rm bol} \lesssim 10^{46}\,{\rm erg\,s^{-1}}$) may either have a low efficiency ($\epsilon \lesssim 0.1$) to make the total local BH mass density consistent with the total accreted BH mass density; or they may have a high efficiency, but a significant fraction should be obscured. We stress that the arguments above are based on the assumption that all massive BHs reside in galaxy centers; however, BHs can be ejected from galaxy centers through either three-body encounters or gravitational radiation recoil during BH coalescence.

To make the local partial BH mass density match the accreted partial density during optically bright QSO phases, we estimate the efficiency of QSOs by ignoring BH mergers and assuming that the efficiency is a function of only BH mass or QSO luminosity. The result is shown in Figure 1.3. The solid lines in the interval $10^{46}\,{\rm erg\,s^{-1}} \lesssim L_{\rm bol} \lesssim 10^{47}\,{\rm erg\,s^{-1}}$ [corresponding to BH mass in the range $10^8(L_{\rm Edd}/L_{\rm bol})\,M_\odot \lesssim M_\bullet \lesssim 10^9(L_{\rm Edd}/L_{\rm bol})\,M_\odot$] denote the region where the observational constraints are fairly strong. The lower solid line represents the result obtained by assuming $L_{\rm bol} = L_{\rm Edd}$; and the upper one represents the result if $L_{\rm bol} = 0.1L_{\rm Edd}$. The fact that the efficiency is required to be higher than 0.3 (the maximum efficiency for thin-disk accretion onto BHs) or even approach 1 when $L_{\rm bol} = 0.1L_{\rm Edd}$ suggests that sub-Eddington luminosity for luminous QSOs is unrealistic.

If the duty cycle of QSOs with BH mass $M_\bullet$ is $\delta(M_\bullet, t)$ at time t, we may define the mean lifetime of QSOs as follows

$$\tau(>M_\bullet) \equiv \frac{\int_{M_\bullet}^{\infty} {\rm d}M'_\bullet \int_0^{t_0} \delta(M'_\bullet, t) n_{M_\bullet}(M'_\bullet, t){\rm d}t}{\int_{M_\bullet}^{\infty} n_{M_\bullet}(M'_\bullet, t_0){\rm d}M'_\bullet}. \tag{1.6}$$

With this definition, we have

$$\tau(>M_\bullet) \simeq \frac{\int_{L(M_\bullet)}^{\infty} {\rm d}L \int_0^{t_0} \Psi(L, t){\rm d}t}{\int_{M_\bullet}^{\infty} n_{M_\bullet}(M'_\bullet, t_0){\rm d}M'_\bullet}. \tag{1.7}$$

The lifetime $\tau(>M_\bullet)$ in equation (1.7) is independent of the assumed value of the efficiency. By inserting the QSO luminosity function and the BH mass function in local early-type galaxies in equation (1.7), and assuming that QSOs have the Eddington luminosity, we obtain the mean lifetime of luminous QSOs as a function of BH mass in Fig. 1.4 (see the solid line), which is $\tau(>M_\bullet) \sim (3\text{–}13) \times 10^7\,{\rm yr}$ in the range $10^8\,{\rm M}_\odot \lesssim M_\bullet \lesssim 10^9\,{\rm M}_\odot$ and is comparable to the Salpeter time $\sim 4.5 \times 10^7 \epsilon/[0.1(1-\epsilon)]\,{\rm yr}$ (the time for a BH radiating at the Eddington luminosity to e-fold in mass). Hence, accretion during optically bright QSO phases can significantly increase the mass of BHs, which is once again consistent with the argument that growth of high-mass BHs comes mainly from accretion during optically bright QSO phases.

1.4 Material Sources for the BH Growth

In an isolated stellar system, central BHs may accrete stellar mass from the following three sources: (i) gas released by tidal disruption of stars and stars swallowed whole by central BHs (mostly for stars on elongated radial orbits which may come close to central BHs), (ii) gas released by stellar collisions, and (iii) gas loss caused by stellar evolution (either by stellar winds or Type II supernovae). The first source in this list, tidal disruption of stars, was studied by Magorrian & Tremaine (1999), who showed that the total mass of stars that are tidally disrupted or swallowed whole over the lifetime of typical nearby galaxies is of the order of $10^6\,{\rm M}_\odot$, approximately independent of galaxy luminosity. Thus disrupted stars may contribute significantly to the present BH mass only in faint galaxies ($\lesssim 10^9\,{\rm L}_\odot$). The second source, gas released by stellar collisions, was studied by Yu (2003), who showed that the second source is also not sufficient to explain the BH mass in nearby galactic centers, especially in bright galaxies. Thus, the material for BH growth, especially in bright galaxies can only come from the following sources: the mass released by stellar evolution in the initial 1 Gyr of the galaxy's lifetime, or gas concentrated in the centers of interacting galaxies by galaxy encounters (see simulations on galaxy encounters in Barnes & Hernquist 1996). For both of the above possibilities, massive BHs form or grow rapidly, early in the universe's history. This scenario is also consistent with our argument in § 1.3 that growth of high-mass BHs comes mainly from accretion during optically bright QSO phases.

1.5 Conclusions

Observational constraints on the growth of massive BHs in galactic nuclei and material sources for BH growth are discussed in this paper.

We use the early-type galaxy sample obtained by the Sloan Digital Sky Survey and the relation between BH mass and velocity dispersion to estimate the total local BH mass density to be $\rho_{\bullet,\mathrm{local}}(z=0) \simeq (2.5 \pm 0.4) \times 10^5 h_{0.65}^2\,\mathrm{M}_\odot\,\mathrm{Mpc}^{-3}$. We also use the QSO luminosity function from the 2dF Redshift Survey to estimate the BH mass density accreted during optically bright QSO phases. The local BH mass density is consistent with the density accreted during optically bright QSO phases if QSOs have a mass-to-energy conversion efficiency $\epsilon \simeq 0.1$. Including the effect of BH mergers, we find relations between the local BH mass function and the QSO luminosity function. Comparison of the predicted relations with the observations suggests that luminous QSOs ($L_{\mathrm{bol}} \gtrsim 10^{46}\,\mathrm{erg\,s^{-1}}$) have a high efficiency (e.g. $\epsilon \sim 0.2$) and the growth of high-mass BHs ($\gtrsim 10^8\,\mathrm{M}_\odot$) comes mainly from accretion during optically bright QSO phases, rather than obscured accretion, accretion by ADAF, accretion of non-baryonic dark matter etc. Luminous QSOs must accrete with a low efficiency < 0.1; alternatively, they may accrete with high efficiency, but a significant fraction should be obscured. We estimate that the mean lifetime of luminous QSOs ($L_{\mathrm{bol}} \gtrsim 10^{46}\,\mathrm{erg\,s^{-1}}$) is $(3\text{–}13)\times 10^7$ yr, which is comparable to the Salpeter time.

The mass released by stellar collisions and the stellar mass tidally disrupted by massive BHs are not sufficient to account for the present BH mass in galactic centers, especially in galaxies brighter than $10^9\,\mathrm{L}_\odot$. The material for BH growth can only come from other sources, for example, the mass released by stellar evolution in the initial 1 Gyr of the galaxy's lifetime, or gas that sinks to the galactic center in a galaxy merger.

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