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COSMOLOGICAL LUMINOSITY EVOLUTION OF THE QSO/ACTIVE GALACTIC NUCLEUS POPULATION

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ABSTRACT

We apply the observed optical/X-ray spectral states of the Galactic black hole candidates (GBHCs) to the cosmological QSO luminosity evolution under the assumptions that QSOs and GBHCs are powered by similar accretion processes and that their emission mechanisms are also similar. The QSO luminosity function (LF) evolution in various energy bands is strongly affected by the spectral evolution, which is tightly correlated with the luminosity evolution. We generate a random sample of QSOs born nearly synchronously by allowing the QSOs to have redshifts in a narrow range around an initial high redshift, black hole masses according to a power law, and mass accretion rates near Eddington rates. The QSOs evolve as a single long-lived population on the cosmological timescale. The pure luminosity evolution results in distinct luminosity evolution features caused by the strong spectral evolution. Most notably, different energy bands (optical/UV, soft X-ray, and hard X-ray) show different evolutionary trends, and the hard X-ray LF in particular shows an apparent reversal of the luminosity evolution (from decreasing to increasing luminosity) at low redshifts, which is not seen in the conventional pure luminosity evolution scenario without spectral evolution. The resulting mass function of black holes (BHs), which is qualitatively consistent with the observed QSO LF evolution, shows that QSO remnants are likely to be found as BHs with masses in the range 10^8–$5 \times 10^{10}\ M_\odot$. The long-lived single population of QSOs are expected to leave their remnants as supermassive BHs residing in rare, giant elliptical galaxies.

Subject headings: accretion, accretion disks — cosmology: theory — galaxies: active — galaxies: nuclei — X-rays: galaxies

1. INTRODUCTION

QSOs first appear at high redshifts ($z > 3$), and their peak activities are reached at $z \sim 2$–3 (e.g., Peterson 1997). The general evolutionary trend is that the number of bright QSOs rapidly decreases at $z < 2$. Such an observationally established fact has been interpreted in terms of two drastically different theoretical models. In the pure luminosity evolution (PLE) model (e.g., Mathez 1976; Boyle et al. 1993; Mathez et al. 1996; Page et al. 1996), a single generation of long-lived (e.g., $\sim 10^9$ yr) QSOs form at high z and evolve mainly by decreasing their luminosities. In the other model (density evolution model), a multiple of QSO populations rise and fall successively and conspire to result in the observed evolutionary trend. In the latter, the evolution is largely determined by the QSO number density evolution (Haehnelt & Rees 1993; Haehnelt, Natarajan, & Rees 1998, and references therein). In the PLE model, because of the longevity of the QSOs, the massive black hole (BH) remnants as massive as $\sim 10^9$–$10^{10}\ M_\odot$ are expected in a small number of massive galaxies with quiescent nuclei. The density evolution model suggests that a massive BH is a normal feature of the central region of essentially every nearby galaxy (e.g., Magorrian et al. 1998; Salucci et al. 1999). It is to be further studied whether both the luminosity evolution and the density evolution coexist in the observed QSO evolution (e.g., Miyaji, Hasinger, & Schmidt 1998). It is also unclear in the density evolution model why QSOs forming at low redshifts have lower luminosities than their high-z counterparts. Therefore, it is still interesting to see whether the PLE model can be further probed using some testable predictions.

If QSOs are powered by massive accreting BHs, the QSO luminosities are essentially determined by the black hole masses and their mass accretion rates (e.g., Frank, King, & Raine 1992). In this sense, the QSO luminosity evolution has to be related to the evolution of BH masses or the evolution of the mass accretion rates or both. In most of the previous studies in the context of the PLE model, the QSO luminosities have been interpreted loosely as bolometric luminosities or some band luminosities simply proportional to the bolometric luminosities (e.g., Yi 1996, and references therein). However, as observed in some Galactic black hole candidates (GBHCs), luminosities are strongly correlated with spectral states (e.g., Rutledge et al. 1998). That is, as luminosities vary, emission spectra change so much that some energy bands' luminosities no longer reflect the bolometric luminosity changes (see also Narayan, Mahadevan, & Quataert 1998; Esin et al. 1998). In the case of QSOs, direct spectral changes correlated with luminosities in an individual QSO have not been established. However, given the striking similarities in accretion flows' emission properties between QSOs (or active galactic nuclei [AGNs] in general) and GBHCs, a correlation between luminosity and spectrum in QSOs is quite plausible. The Seyfert galaxies' X-ray spectral photon index (~1.5–1.7) is similar to that of the hard state in GBHCs (Rutledge et al. 1998). The soft X-ray emission in bright GBHCs (e.g., McClintock 1998) is reminiscent of the so-called optical/UV/soft X-ray "big blue bumps" in bright active galactic nuclei (Frank et al. 1992). It is quite reassuring that the recently observed Galactic superluminal sources appear to be a scaled-down version of the superluminal radio sources in extragalactic nuclei (Mirabel & Rodriguez 1998). Therefore, we assume that the QSO luminosity evolution is accompanied by a strong spectral evolution.

The main effect of the spectral evolution is that the luminosity evolution in different energy bands differs significantly. We therefore investigate the luminosity evolution trend in various energy bands (Choi, Yang, & Yi 1999). Our approach can eliminate some potentially serious uncertainties in the QSO

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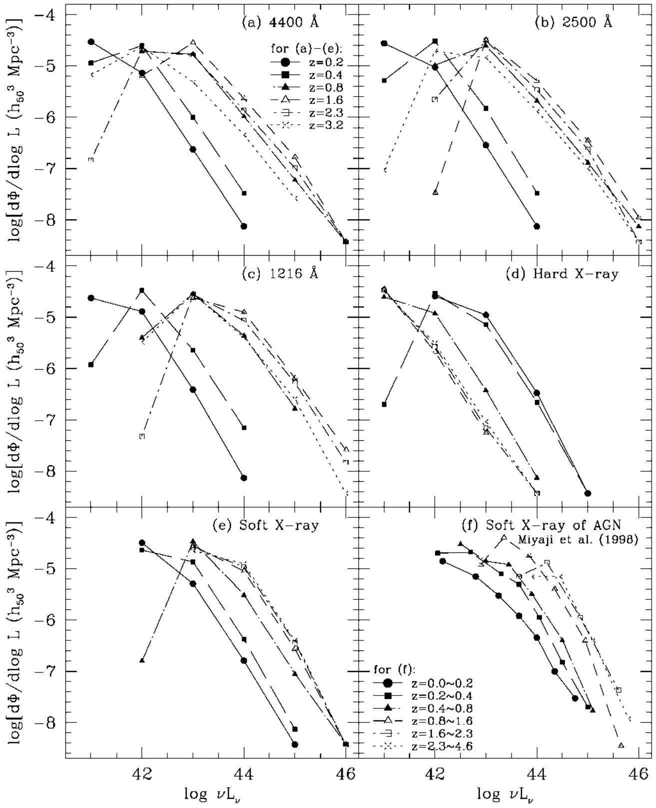

FIG. 1.—Redshift evolution of the QSO LF at different energy bands. The LF evolution has been obtained under the assumption that QSOs evolve as a single, long-lived population ($t_{\rm evol} \simeq 5 \times 10^9$ yr). The total number of randomly generated QSOs in the sample is 10^4. The comoving number density is normalized to match that of Miyaji et al. (1998). This figure shows that different energy bands show distinct LF evolution signatures. Especially, at hard X-ray energies, QSOs appear to experience a rather drastic turnaround at low *z*.

luminosity evolution models when only the bolometric luminosity evolution is considered (cf. Yi 1996). In this Letter, we attempt to explain the cosmological evolution of QSOs using a model in which the luminosity function (LF) of the QSO population is constructed from one generation of long-lived QSOs with an evolutionary timescale of ∼5 × 10^9 yr for a flat universe with no cosmological constant (Yi 1996).

2. LUMINOSITY FUNCTION EVOLUTION

We consider a single QSO population in terms of the LF which evolves in *z*. Each QSO is turned on at an initial *z* with an initial BH mass *M* and an initial mass accretion rate $\dot{M}$. An ensemble of QSOs evolve individually, while their luminosities and spectra evolve in a correlated manner (Choi et al. 1999), which is directly reflected in the LF evolution.

Our approach to the QSO evolution problem hinges on the hypothesis that the luminosity-correlated QSO emission spectra are physically similar to those of the GBHCs which show spectral transitions closely connected to luminosity levels (e.g., Rutledge et al. 1998; Narayan et al. 1998, and references therein). For instance, optical/UV/soft X-ray emission from geometrically thin, optically thick accretion disks around supermassive BHs contributes to the big blue bump postulated in QSOs (Frank et al. 1992). Based on the X-ray emission spectra observed in the GBHCs, QSOs spectral states are assumed to be directly related to luminosities. In this picture, hard X-ray emission generally requires a scattering corona with energetic electrons or advection-dominated accretion flows (ADAFs; e.g., Zdziarski 1998). Our main assumptions are as follows. (1) The QSOs are powered by massive accreting BHs with accretion flows. Therefore, emission properties directly reflect the underlying accretion flow structure, which is mainly determined by the mass accretion rate. We take the dimensionless accretion rate $\dot{m} \equiv \dot{M}/\dot{M}_{\rm Edd}$, which is defined as a physical accretion rate scaled by the mass-dependent Eddington accretion rate $\dot{M}_{\rm Edd} = 1.4 \times 10^{26} M_8$ g s^{-1}, where $M_8 = M/10^8\ M_\odot$ and the 10% radiative efficiency has been assumed. (2) The QSO emission is largely composed of four spectral states, defined by the X-ray spectral hardness: “soft/high” state (HS); “hard/low” state (LS); in addition, an “off” state (OS, which is included in LS); and “very high” state (VHS) deduced from the observed spectral states of GBHCs (Rutledge et al. 1998). Although direct evidence for QSO spectral changes in a single QSO does not exist (e.g., in part because of long physical timescales appropriate for QSOs and observational flux limits), it is plausible that QSOs have undergone considerable luminosity and spectral changes in the cosmological context.

We explain the cosmological evolution of QSOs using the spectral states discussed above, which are mainly determined by the dimensionless accretion rate $\dot{m}$ (Yi 1996; Narayan et al. 1998). (1) At high accretion rates, $\dot{m} > 1$, the spectral state of QSO corresponds to the VHS. While the HS, LS, and OS are well recorded in the GBHCs, the existence and the exact nature of VHS is less clear (e.g., Narayan et al. 1998). We assume that the X-rays emitted during the VHS originate in the scattering hot corona, which is thought to exist above the disk at high accretion rates. The main accretion flow itself contributes to thermal soft X-ray/UV/optical emission. We adopt a fraction ∼10% of the total luminosity for the X-ray luminosity, while the bolometric luminosity $L = \eta \dot{M} c^2$ (with $\eta \approx 0.1$, i.e., a high efficiency) is assumed. We identify the X-ray spectrum of this state with a power-law photon index $\Gamma \approx 3.2$ (Rutledge et al. 1998) and the optical/UV continuum with the thermal disk emission determined by a set of *M* and $\dot{M}$ (Frank et al. 1992). However, since the VHS is poorly understood, the X-ray and bolometric efficiencies remain largely unconstrained. This uncertainty is significant for the QSO evolution near the initial birth epoch near birth. Theoretically, the accretion flow could be in the form of the so-called slim disk with super-Eddington accretion rates (Szuszkiewicz, Malkan, & Abramowicz 1996). (2) At lower accretion rates, $0.01 \le \dot{m} \le 1$, the accretion flow corresponds to the geometrically thin disk radiating optically thick thermal emission (e.g., Frank et al. 1992) with a high efficiency ($\eta \approx 0.1$). The corresponding spectral state is the HS. X-ray luminosity of this state is also calculated in the same manner as in the VHS (i.e., 10% efficiency for the bolometric luminosity $L = \eta \dot{M} c^2$ with $\eta \approx 0.1$). The X-ray spectrum is identified with a single power law of photon index $\Gamma \approx 6.0$, deduced from the observed HS of the GBHCs (Rutledge et al. 1998). (3) As the accretion fuel is gradually exhausted, the accretion rate falls below the critical rate for the ADAFs, $\dot{m} < 0.01$. The corresponding spectral state is LS. When the accretion rate falls further, the OS, which is seen in nearby, X-ray–bright galactic nuclei, appears (Yi & Boughn 1998, 1999, and references therein). We assume that the OS is a direct extension of LS to lower luminosities for $\dot{m} < 0.001$. During LS/OS, the bolometric luminosity is adequately described by $L \approx 30 \dot{m}^x L_{\rm Edd}$ with $x \approx 2$ (e.g., Narayan & Yi 1995; Yi 1996; Yi & Boughn 1998, 1999). In this low-efficiency regime, the accretion flow becomes optically thin and radiates very weakly

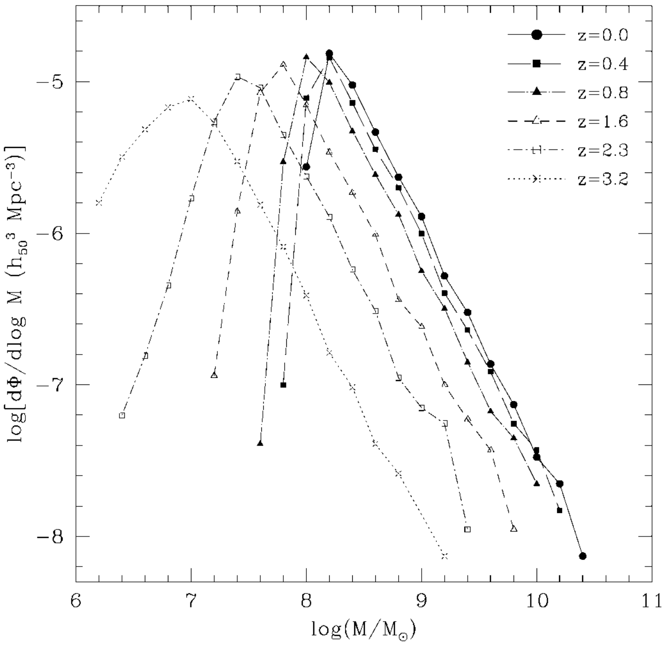

FIG. 2.—(*a*) Simplified spectral energy distributions of a QSO with a black hole mass of $10^8\ M_\odot$. From top to bottom, the decreasing $\dot{m}$'s correspond to the very high state (VHS) with $\dot{m} > 1$, the high state (HS) with $\dot{m} = 0.01$–1, and the low state and the off state (LS and OS) with $\dot{m} < 0.01$. The spectral and luminosity evolution is caused by the decrease of $\dot{m}$. (*b*) Differential mass function (comoving number density) of BHs at various redshifts. BHs form at high redshifts and grow through mass accretion during the QSO evolution. For simplicity, the initial mass function is assumed to have a power-law slope with index 2.5. The QSO remnants are likely to have BH masses in the range from 10^8 to $5 \times 10^{10}\ M_\odot$. The integrated comoving space density of QSOs is $\sim 4 \times 10^{-5}\ h_{50}^3$ Mpc^{-3}.

in optical/UV. The nonthermal emission dominates from optical/UV to X-rays (Narayan & Yi 1995). The spectral energy distribution roughly follows a power law with photon index $\Gamma \approx 1.7$, which is observed in GBHCs in LS. The simplified spectral shapes of the above-discussed states are displayed in Figure 2*a*. The similar spectral shapes for the GBHCs have been applied to several systems (Narayan et al. 1998; Esin et al. 1998).

We consider a population of QSOs that are born randomly within the prescribed parameter range. The initial birth occurs within such a narrow range of redshifts that the subsequent QSO evolution is largely synchronous. (1) First, we generate a QSO population that is large enough to avoid the small-number statistics problems. The total number of QSOs in the sample is 10^4. The LF evolution is obtained under the assumption that QSOs evolve as a long-lived single population with the cosmological evolution timescale, $t_{\rm evol} \simeq 5 \times 10^9$ yr (Yi 1996). QSOs' initial birth redshifts are randomly distributed following a Gaussian distribution with its center at $z = 4$ and width of 1. The initial BH masses are also randomly chosen from an initial mass function (MF), which is defined as a single power-law slope of 2.5 in the range 10^6–$10^9\ M_\odot$. The BHs are initially accreting at randomly chosen accretion rates around their respective mass-dependent Eddington rates, $\dot{m} \sim 1$. The accretion rates are assumed to be distributed as a Gaussian with its center at $\dot{m} = 1$ and width of 0.1. (2) Each QSO in the sample evolves as the mass accretion in the QSO decreases and the BH mass grows through mass accretion starting with the initial conditions. The evolutionary timescale $t_{\rm evol}$ is taken as a fraction of the cosmic time $t_{\rm age}$ for a flat universe ($q_0 = 0.5$) with no cosmological constant: $t_{\rm evol} = 0.5 t_{\rm age}$, $t_{\rm age} = 2t_{\rm H}/3 = 2/3H_0$, with $H_0 = 50$ km s^{-1} Mpc^{-1}. The mass accretion rate decreases exponentially with the characteristic *e*-folding timescale $t_{\rm evol}$ (e.g., Yi 1996). The remarkably synchronous birth and evolution of QSOs could indirectly support the global mass accretion evolution (e.g., Small & Blandford 1992; Turner 1991, and references therein for related discussions) assumed in the present study (Yi 1996 and references therein). As $\dot{m} \propto \dot{M}/M$ decreases during the course of the cosmological evolution (in part because of decreasing $\dot{M}$ and more importantly because of the growth of the BH mass), the luminosity and spectral state changes as described above. (3) We then construct the differential LFs in various energy bands at different z's. One of our major goals is to derive and compare LFs at various energy bands. The LFs are shown in the redshift range $0 < z < 4$ and the luminosity range $10^{41} < L < 10^{46}$ ergs s^{-1}. The LF and its evolution contains several free parameters: a slope of initial BH mass function, BH mass range, $t_{\rm evol}$, and initial $\dot{m}$ for a given cosmological model. The best-fit values for these parameters are chosen for qualitative and quantitative comparisons. The evolutionary timescale $t_{\rm evol}$ controls the overall evolution.

The evolution of the LFs in different energy bands is shown in Figure 1.

1. In the observable luminosity range ($>10^{42}$ ergs s^{-1}), the QSO LFs show an apparent break from a simple power law (reflecting the initial BH mass function). That is, even for our simple single power-law initial mass function (and hence initial LF), the LFs at late times show that the steep power-law slope at the high-luminosity end turns over to a much flatter slope at the low-luminosity end, which is observed in the QSO samples (e.g., Boyle et al. 1993; Jones et al. 1997). This particular feature is surprisingly in good agreement with the trend of the observed LFs (e.g., the combined *ROSAT* and Extended Medium-Sensitivity Survey samples by Jones et al. 1997 and *ROSAT* samples by Miyaji et al. 1998). Our evolution model shows that LFs may appear to deviate from the pure luminosity evolution (in which only bolometric luminosity is considered) even when the QSO evolution is essentially driven by the luminosity evolution. This effect is obviously caused by the spectral changes accompanying the luminosity changes. We point out that this particular result implies that there is no strong evidence for cosmological evolution of the space density of low-luminosity AGNs, in contradiction to Miyaji et al. (1998).
2. The luminosity functions in X-ray bands are differently affected by the spectral changes caused by the transition of accretion flows. Most notably, the most significant spectral change occurs when the QSO spectrum changes from the HS (thin disk, $\Gamma \approx 6.0$) to LS (ADAF, $\Gamma \approx 1.7$), which to the lowest order induces a sudden luminosity decrease. However, since ADAFs are relatively hard X-ray bright (Yi & Boughn 1998, 1999), QSOs' hard X-ray LFs show a trend very different from other energy bands, as shown in Figure 1 (also see below). The QSOs undergo an accretion flow transition at a critical redshift $z_c \sim 1$, which corresponds to an epoch in which $\dot{m} = 0.01$ (Narayan & Yi 1995), as discussed above. Although the exact value of z_c depends on various model parameters (e.g., Yi 1996), it is plausible to identify z_c with the observed sudden decline of bright QSOs. For instance, $t_{\rm evol} \ll \sim 5 \times 10^9$ yr could drive much faster evolution than the observed one. Our model z_c is comfortably close to the observed break near $z \sim 1$–2 (Hewett, Foltz, & Chaffee 1993; Page et al. 1996).
3. Optical/UV (1216, 2500, and 4400 Å) LFs evolve much

faster than X-ray LFs at low z's. At high $z > z_c$, however, optical/UV luminosity evolution is very slow, which is in excellent agreement with the observed trend. There also exists a brief period of evolution during which the LF slightly moves to a higher luminosity range, although such a phenomenon is hard to detect observationally. In the case of the soft X-ray LF, the slow evolution is also seen at $z > z_c$. This is also in agreement with the results of Page et al. (1996).

4. At hard X-ray energies (2.0–10 keV), a dramatic turnaround in the LF evolution is identified at $z < z_c \sim 1$. That is, the hard X-ray LF as a whole gradually shifts to lower luminosities until $z \sim z_c$ is reached. Below z_c, the relatively X-ray–bright (especially in hard X-rays) ADAFs drive an increasing number of QSOs into higher hard X-ray luminosities. This results in reversal in the direction of the hard X-ray LF evolution as shown in Figure 1*d*. This rather surprising result is explained by the fact that QSOs have undergone an accretion flow transition from a thin disk (HS) to an ADAF (LS) as $\dot{m}$ decreases. Observationally, neither transition in hard X-ray luminosity nor luminosity evolution itself has been clearly seen. However, once 2–10 keV X-ray LFs become available (e.g., the *Chandra X-Ray Observatory*), this predicted trend should be testable.

5. At soft X-ray energies (0.5–2.0 keV), there is no apparent dramatic transition. The soft X-ray luminosity evolves roughly as $L \propto (1+z)^k$ with $k > 3$, up to z_c. This value is similar to but larger than those obtained by Boyle et al. (1993) and Page et al. (1996) based on the pure (bolometric) luminosity evolution model. The discrepancy could be resolved if spectral evolution is taken into account. For a quantitative comparison between model LFs and observed ones, we convert the space density per comoving volume in the *ROSAT* AGN soft X-ray LF estimated by Miyaji et al. (1998) to the QSO LF assuming $H_0 = 50\ h_{50}$ km s^{-1} Mpc^{-1}, $h_{50} = 1$, and $q_0 = 0.5$. On the whole, our model and the Miyaji et al. (1998) result agree quite well with each other. We consider this qualitative agreement as a support for the QSO luminosity evolution models.

The MF of BHs and its evolution can be naturally derived from our evolutionary calculation. As long as the model QSO LF agrees with the observed LF, the resulting MF has immediate consequences on the fate of the QSO remnants at the present epoch. Figure 2*b* shows the differential MF of BHs that have grown during the QSO evolution. The initial MF with a slope of power law $s = 2.5$ has been assumed. The BH MF suggests that the QSO remnants are likely to have BH masses in the range 10^8 to $\sim 5 \times 10^{10}\ M_\odot$. On average, remnant BH masses are bigger than the initial masses by a factor ∼100. BH remnants in the mass range 10^8–$10^9\ M_\odot$ are most likely to be found in some present-day galaxies' centers. This finding obviously suggests that it is difficult for our model to explain small BHs with masses in the range 10^5–$10^7\ M_\odot$ that are found in nearby, typical spiral L^* (e.g., Peebles 1993) galaxies with the comoving space density $\sim 10^{-2}\ h_{50}^3$ Mpc^{-3} (Magorrian et al. 1998). In the present single population scenario, the integrated comoving density of very massive QSO remnants is $\sim 4 \times 10^{-5}\ h_{50}^3$ Mpc^{-3}, which suggests that they are likely to be found in rare, giant elliptical galaxies. Our model inevitably points to massive BHs with masses $\geq 10^9\ M_\odot$ (e.g., Fabian & Canizares 1988; Mahadevan 1997) in elliptical galaxies as QSO remnants. It is possible that smaller mass black holes in galactic nuclei might have grown without experiencing the QSO phase.

3. DISCUSSION

Our model is largely consistent with the observed QSO evolution trend, which supports the possibility that the QSO evolution is accounted for by a single, long-lived QSO population. The evolution of the LF shows an apparent transition at a critical redshift caused by the accretion flow transition (Yi 1996). As far as we know, there is no other convincing explanation for this apparent break in the QSO evolution. The overall agreement between the observed LF evolution and our model implies that spectral states of QSOs may indeed be similar to those of GBHCs.

The accretion flow has undergone a transition as $\dot{m}$ has declined from ∼1 to less than 0.01 while the initial BH masses have evolved by a factor ∼100. The MF of BHs indicates that QSO remnants are likely to be found as massive BHs with masses in the range $\sim 10^8$–$5 \times 10^{10}\ M_\odot$, which are likely to be found as massive BHs of $\geq 10^9\ M_\odot$ residing in very rare elliptical galaxies.

The distinguishable evolutionary signature at hard X-ray energies is significant and also, in principle, testable. Future confirmation or rejection of our prediction by hard X-ray luminosity functions (e.g., by the *Chandra X-Ray Observatory*) could provide a crucial piece of information. It remains to be seen whether an alternative scenario, in which QSO evolution is composed of many short-lived populations, is also affected by the luminosity-spectrum correlation we have looked into. The QSO spectral evolution could result in some interesting consequences for the X-ray background, although the detailed analyses require rather sophisticated spectral calculations (e.g., Yi & Boughn 1998, and references therein).

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