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PROTOQUASARS: PHYSICAL STATES AND OBSERVABLE PROPERTIES

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ABSTRACT

Based on the radiation hydrodynamic model for black hole (BH) growth and incorporating the chemical evolution of the early-type host galaxy, we construct the coevolution model of the quasar (QSO) BH and host galaxy. As a result, it is found that after a galactic wind epoch, the luminosity is shifted from the host-dominant phase to the active galactic nucleus–dominant phase (QSO phase) in the timescale of a few 10^8 yr. The former phase corresponds to the early stage of a growing BH and can be regarded as a "proto-QSO" phase. It has observable characteristic properties as follows: (1) The broad emission lines are narrower than those of ordinary QSOs and are typically less than 1500 km s^{-1}. (2) The BH-to-bulge mass ratio, $M_{\rm BH}/M_{\rm bulge}$, is in the range of $10^{-5.3}$ to $10^{-3.9}$. (3) Host galaxies are bluer than QSO hosts, by about 0.5 mag in the colors $B-V$ at the rest bands and $V-K$ at the observed bands, with assumed galaxy formation redshifts of $z_f = 3$–5. (4) The metallicity of gas in the galactic nuclei is $\sim 8\ Z_\odot$ and that of stars weighted by the host luminosity is $\sim 3\ Z_\odot$. (5) The central massive BH ($\simeq 10^7\ M_\odot$) is surrounded by a massive dusty disk ($>10^8\ M_\odot$), which may obscure the nucleus in the edge-on view and make a type 2 nucleus. By comparing these predictions with recent observations, radio galaxies are a possible candidate for proto-QSOs. Also, it is anticipated that the proto-QSO phase is preceded by an optically thick phase, which may correspond to ultraluminous infrared galaxies (ULIRGs). In this phase, $M_{\rm BH}/M_{\rm bulge}$ is predicted to be much less than 10^{-3} and to grow with metallicity. Moreover, as precursors of ULIRGs, optically thin star-forming galaxies are predicted. These may be in the assembly phase of Lyman break galaxies (LBGs) or Lyα emitters.

Subject headings: black hole physics — galaxies: active — galaxies: evolution — galaxies: formation — galaxies: nuclei — galaxies: starburst

1. INTRODUCTION

Recent X-ray and optical observations suggest the possibility that active galactic nuclei (AGNs) could be divided into two subclasses according to the rate of black hole (BH) growth; one is a rapid-growth phase and the other is a slow-growth phase (Pounds et al. 1995; Boller, Brandt, & Fink 1996; Mineshige et al. 2000; Mathur, Kurazkiewicz, & Czerny 2001; Wandel 2002). This possibility has been pointed out primarily for the Seyfert 1 galaxies (Sy1s), which are divided into two subclasses according to the width of the broad emission lines, $V_{\rm BLR}$. The Sy1s with $V_{\rm BLR}$ less than 2000 km s^{-1} are called narrow-line Sy1s (NLSy1s), whereas those with a broader line width are called broad-line Sy1s (BLSy1s). NLSy1s exhibit two distinctive X-ray properties, that is, rapid X-ray variability and strong soft X-ray excess. These properties can be explained in terms of the optically thick advection-dominated accretion flow onto a smaller BH, which is realized by a higher accretion rate compared to the Eddington limit (Pounds et al. 1995; Boller et al. 1996; Mineshige et al. 2000). Also, it is pointed out that the BH-to-bulge mass ratio is noticeably smaller than that in elliptical galaxies, $M_{\rm BH}/M_{\rm bulge} < 10^{-3}$ (Mathur et al. 2001; Wandel 2002). All of these suggest that NLSy1s are in the rapid-growth phase of a BH, in contrast to BLSy1s, which are explained by conventional mild accretion onto a large BH. In addition, Kawaguchi & Aoki (2001)[1] argue that NLSy1s have a high star formation rate (SFR). According to these observations, it has been suggested that NLSy1s may be Sy1s in the early stage of their evolution (Mathur 2000). By analogy to NLSy1s, QSOs are also expected to have a rapid-growth phase of QSO BHs. But it has not been elucidated so far what objects correspond to the early phase of QSOs.

On the other hand, recent high-resolution observations of galactic centers have revealed that the estimated mass of a central "massive dark object" (MDO), which is the nomenclature for a supermassive BH candidate, does correlate with the mass of a galactic bulge; the mass ratio of the BH to the bulge is 0.001–0.006 as a median value (Kormendy & Richstone 1995; Richstone et al. 1998; Magorrian et al. 1998; Loar 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Merritt & Ferrarese 2001; McLure & Dunlop 2001, 2002; Wandel 2002). (Note that for an elliptical galaxy the bulge means the whole galaxy.) In addition, it has been found that QSO host galaxies are mostly luminous and well-evolved early-type galaxies (McLeod & Rieke 1995; Bahcall et al. 1997; Hooper, Impey & Foltz 1997; McLoed, Rieke, & Storrie-Lombardi 1999; Brotherton et al. 1999; Kirhakos et al. 1999; McLure et al. 1999; McLure, Dunlop, & Kukula 2000). These findings, combined with the BH-to-bulge relations, suggest that the formation of a supermassive BH, an elliptical galaxy, and a QSO are physically related to each other. But the link between the formation of a supermassive BH and the evolution of a host galaxy is an open question. Also, the physical relationship among QSOs, ultraluminous infrared galaxies (ULIRGs), and radio galaxies has been an issue of long standing.

[1] Electronic edition available at http://www.inaoep.mx/~ag00/posters.html.

Some theoretical models of BH growth have been considered to explain the BH-to-bulge correlations (Silk & Rees 1998; Ostriker 2000; Adams, Graff, & Richstone 2001). But little has been elucidated regarding the physics of the angular momentum transfer, which is requisite for BH formation. Recently, as a potential mechanism to remove angular momentum, Umemura (2001) has considered the effects of radiation drag, which is equivalent to a well-known Poynting-Robertson effect. The exact expressions for the radiation drag are found in the literature (Umemura, Fukue, & Mineshige 1997; Fukue, Umemura, & Mineshige 1997). In an optically thick regime, the efficiency of radiation drag is saturated as a consequence of the conservation of the photon number (Tsuribe & Umemura 1997). Thus, the angular momentum loss rate by radiation drag is given by $d\ln J/dt \simeq -(L_*/c^2 M_g)$, where J, L_*, and M_g are the total angular momentum of gaseous component, the total luminosity of the bulge, and the total mass of gas, respectively. Then the maximal rate of mass accretion is given by $\dot{M} = -M_g d\ln J/dt = L_*/c^2$ (Umemura 2001). Thus, the total accreted mass onto the MDO, $M_{\rm MDO}$, is estimated by

$$M_{\rm MDO} \simeq \int_0^\infty \frac{L_*}{c^2}\,dt\ .$$

In practice, the interstellar medium (ISM) is observed to be highly inhomogeneous in active star-forming galaxies (Sanders et al. 1988; Gordon, Calzetti, & Witt 1997). Kawakatu & Umemura (2002) have shown that the inhomogeneity of the ISM helps the radiation drag sustain maximal efficiency.

Thus, the final mass of the MDO is proportional to the total radiation energy from bulge stars, and the resultant BH-to-bulge mass ratio is basically determined by the energy conversion efficiency of the nuclear fusion from hydrogen to helium, i.e., 0.007 (Umemura 2001). So far, the realistic chemical evolution of the host galaxy has not been incorporated, but a simple evolutionary model was assumed. As for the relation between a QSO BH and the host galaxy, some phenomenological models have been proposed (Haehnelt & Rees 1993; Haiman & Loeb 1998; Kauffmann & Haehnelt 2000; Monaco, Salucci, & Danese 2000; Granato et al. 2001; Hosokawa et al. 2001; Romano et al. 2002), but little on the physics has been known. Hence, in order to reveal the formation and evolution of QSOs and clarify what objects correspond to the early phase of QSOs, it is important to investigate the physics of the rapid-growth phase of QSO BHs. Here based on the radiation drag model incorporating the realistic chemical evolution, we construct a physical model for the coevolution of a QSO BH and the early-type host galaxy. The purpose of this paper is to elucidate the physical relationship between BH growth and the evolution of the host galaxy and define a proto-QSO phase as an early stage of QSO evolution. Then we predict the observable properties of proto-QSOs. Also, we address a unified picture for the evolution of an elliptical galaxy nucleus.

The paper is organized as follows. In § 2, we build up a theoretical model for the coevolution of a QSO BH and the early-type host galaxy. In § 3, we investigate the time-dependent relation between a QSO BH and the early-type host galaxy and analyze the physical states of proto-QSOs, which correspond to the rapid-growth phase of a QSO BH. In § 4, we propose a unified picture for the evolution of an elliptical galaxy nucleus, and § 5 is devoted to the conclusions.

2. COEVOLUTION MODEL

First, we model the BH growth based on the radiation drag–driven mass accretion. Here we suppose a two-component system that consists of a spheroidal stellar bulge and inhomogeneous optically thick ISM within it.

The radiation drag efficiency increases with the optical depth τ in proportion to $(1 - e^{-\tau})$ (Umemura 2001). Thus, the mass of an MDO, $M_{\rm MDO}$, which is the total mass of the dusty ISM assembled to the central massive object, is given by

$$M_{\rm MDO}(t) = \eta_{\rm drag}\int_0^t \int_0^\infty \frac{L_{{\rm bulge},\,\nu}(t)}{c^2}(1 - e^{-\tau_\nu(t)})\,d\nu\,dt\ , \quad (1)$$

where τ_ν is defined as the optical depth of the bulge measured from the center. $\eta_{\rm drag}$ is found to be maximally 0.34 in the optically thick regime (Kawakatu & Umemura 2002). Here we estimate the evolution of τ_ν for U, B, V, and K band by using an evolutionary spectral synthesis code PEGASE (Fioc & Rocca-Volmerange 1997). In Figure 1, the evolution of τ_ν for all bands is shown. We define a time $t_{\rm thin}$ before which the optical depth is less than unity in the U band, which is most intensive in the early evolutionary phase. Before $t_{\rm thin}$, the radiation drag efficiency is low and the growth of MDO is quite slow. Furthermore, once a galactic wind occurs, the bulge becomes ISM-deficient and thus optically thin, so that the mass accretion via radiation drag is terminated. In this paper, after a wind epoch t_w of several 10^8 yr, τ_ν is assumed to drop abruptly to $\tau_\nu \ll 1$. Hence, the final mass of an MDO is given by

$$M_{\rm MDO} = \eta_{\rm drag}\int_{t_{\rm thin}}^{t_w} \frac{L_{\rm bulge}(t)}{c^2}\,dt\ , \quad (2)$$

where $L_{\rm bulge}$ is the bolometric luminosity of the bulge. It is found that escaping photons from the bulge in the optically thin phase of $0 < t < t_{\rm thin}$ is less than 5% of the total.

In this model, we should distinguish the BH mass from the mass of an MDO, although the mass of an MDO is often

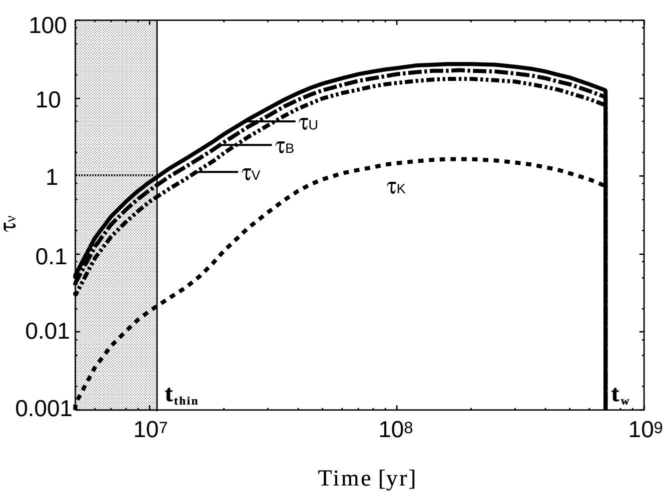

FIG. 1.—Optical depth (τ_ν) of the bulge measured from the center as a function of time. The abscissa is time in units of years. The ordinate is the optical depth for the U, B, V, and K bands. A time $t_{\rm thin}$ is defined so that the optical depth is less than unity in the U band. The optically thin phase ($\tau_U < 1$) is the gray area. The system is optically thick until the galactic wind timescale (t_w), at which time τ_ν is assumed to drop abruptly down to $\tau_\nu \ll 1$.

regarded as BH mass from an observational point of view. Supposing the mass accretion driven by the viscosity onto the BH horizon is determined by an order of Eddington rate, the BH mass grows according to

$$M_{\rm BH} = M_0 e^{\nu t/t_{\rm Edd}} , \tag{3}$$

where ν is the ratio of BH accretion rate to the Eddington rate, $\nu = \dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$, which is about 0.1 for QSOs (McLeod et al. 1999), and $t_{\rm Edd}$ is the Eddington timescale, $t_{\rm Edd} = \eta_{\rm BH} M_{\rm BH} c^2/L_{\rm Edd}$, where $\eta_{\rm BH}$ is the energy conversion efficiency and $L_{\rm Edd}$ is the Eddington luminosity. Recently, it has been shown by a full general relativistic calculation (Shibata & Shapiro 2002) that the collapse of a rotating supermassive star (SMS) results in the formation of a rotating BH with a Kerr parameter of 0.75. Hence, $\eta_{\rm drag}$ is assumed to be 0.42, which is the efficiency of a extreme Kerr BH. Then we have $t_{\rm Edd} = 1.9 \times 10^8$ yr, and M_0 as the mass of a seed BH, which could be an early formed massive BH with $\sim 10^5\ M_\odot$ (Umemura, Loeb, & Turner 1993) or a massive BH with $\sim 10^5\ M_\odot$ formed by the collapse of a rotating SMS (Baumgarte & Shapiro 1999; Saijo et al. 2002; Shibata & Shapiro 2002), which may result from the viscous runaway collapse of the MDO (Tsuribe 1999; Umemura 2002).

Next, we construct the model for the chemical evolution of the host galaxy. To treat the realistic chemical evolution, we use an evolutionary spectral synthesis code PEGASE (Fioc & Rocca-Volmerange 1997). In this paper, we consider an elliptical galaxy as a host galaxy to relate the formation of a QSO. Also, we select the model parameters so that the color-magnitude relation of present-day elliptical galaxies can be reproduced. In this model, we assume an initial mass function as $\phi = A(m_*/M_\odot)^{-0.95}$ for a mass range of [0.1, 60 $M_\odot$], where m_* is the stellar mass. The SFR per unit mass, $C(t)$, is assumed to be proportional to the fractional gas mass $f_g(t) \equiv M_g(t)/M_{g0}$, where M_{g0} is the initial gas mass, which is $10^{12}\ M_\odot$, and $M_g(t)$ is the total gas mass at time t. Incorporating a galactic wind model, the SFR is given by

$$\begin{aligned} C(t) &= kf_{\rm g}, (0 \le t < t_w) \\ &= 0,\ (t \ge t_w) , \end{aligned} \tag{4}$$

where a constant rate coefficient is set to $k = 8.6$ Gyr^{-1}. Here we assume $t_w = 7 \times 10^8$ yr from the fiducial wind model by Arimoto & Yoshii (1987). With this chemical evolution model, we can pursue the evolution of the physical properties of host galaxy, such as stellar mass, luminosity, color, and metallicity.

3. QSO BH–HOST RELATION

Based on the present coevolution model, the evolution of the mass of stellar component in the bulge ($M_{\rm bulge}$), the mass of MDO ($M_{\rm MDO}$), and the mass of the supermassive BH ($M_{\rm BH}$) are shown in Figure 2, assuming the constant Eddington ratio ($\nu = 1$). The mass accretion proportional to the bulge luminosity leads to the growth of an MDO up to $10^8\ M_\odot$, which is likely to form a massive dusty disk in the nucleus. However, the matter in the MDO does not promptly fall into the BH, because the BH accretion is limited by equation (3). The BH mass reaches $M_{\rm MDO}$ at a time $t_{\rm cross}$. As seen in Figure 2, during $t < t_{\rm cross}$ the BH mass fraction $f_{\rm BH} = M_{\rm BH}/M_{\rm bulge}$ increases with time. At $t > t_{\rm cross}$,

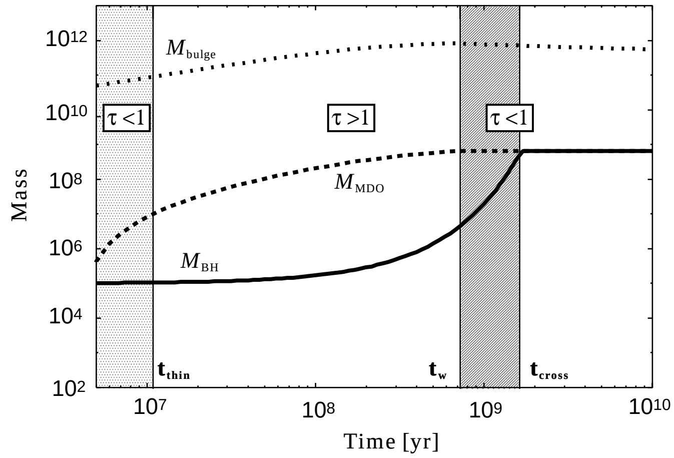

FIG. 2.—BH growth, assuming $M_0 = 10^5\ M_\odot$ and $\nu = 1.0$ (see eq. [3]). The ordinate is mass in units of solar mass. The mass of the stellar component in the bulge is $M_{\rm bulge}$, while $M_{\rm MDO}$ is the mass of MDO and $M_{\rm BH}$ is the mass of the supermassive BH. The galactic wind timescale is t_w, and $t_{\rm cross}$ is defined so that $M_{\rm MDO} = M_{\rm BH}$. The light gray area shows the initial optically thin phase in the timescale of $\sim 10^7$ yr. In this phase there can exist a massive dusty disk (10^6–$10^7\ M_\odot$). In the optically thick phase ($t_{\rm thin} < t < t_w$), the BH fraction $f_{\rm BH} = M_{\rm BH}/M_{\rm bulge} \ll 0.001$. In the optically thin phase, which is the dark gray area ($t_w < t < t_{\rm cross}$), there can be a massive dusty disk ($>10^8$ M$_\odot$) around a massive BH, and also the BH fraction is $f_{\rm BH} \simeq 0.001$, which is just comparable to the observed ratio.

almost all of the MDO matter has fallen onto the central BH, and therefore the BH mass is saturated. In the optically thick phase ($t_{\rm thin} < t < t_w$), the BH fraction is $f_{\rm BH} \ll 0.001$. In the optically thin phase at $t > t_w$, which is the dark gray area ($t_w < t < t_{\rm cross}$) in Figure 2, the BH fraction increases up to $f_{\rm BH} \simeq 0.001$, which is just comparable to the observed ratio.

It has been argued that the color-magnitude relation of bulges can be reproduced if a galactic wind sweeps away the gas at a wind epoch t_w of several 10^8 yr (Arimoto & Yoshii 1986, 1987; Kodama & Arimoto 1997; Mori et al. 1997). The evolution of the bulge luminosity is shown in Figure 3, with the galactic wind model. Even after the galactic wind ($t > t_w$), $M_{\rm BH}$ continues to grow until $t_{\rm cross}$, and therefore the AGN brightens with time if the Eddington ratio is constant. After the AGN luminosity ($L_{\rm AGN}$) exhibits a peak at $t_{\rm cross}$, it fades out abruptly because the fuel of the MDO is exhausted. As seen in Figure 3, it is found that the era of $t_w < t < t_{\rm cross}$ can be divided into two phases with a transition time $t_{\rm crit}$ when $L_{\rm bulge} = L_{\rm AGN}$; the earlier phase is the host luminosity–dominant phase (*dark gray area*), and the later phase is the AGN luminosity–dominant phase (*light gray area*). The lifetimes of both phases are comparable to each other, which is about 10^8 yr. The AGN-dominant phase is likely to correspond to ordinary QSOs, but the host-dominant phase is obviously different from the QSOs observed so far. We define this phase as "a proto-QSO." In this phase, $f_{\rm BH}$ rapidly increases from $10^{-5.3}$ to $10^{-3.9}$ in $\approx 10^8$ yr. Also, the central massive BH is surrounded by a massive dusty disk ($>10^8\ M_\odot$), which may obscure the nucleus in the edge-on view and make a type 2 nucleus. Objects corresponding to such host luminosity–dominant proto-QSOs have not yet been identified observationally. Hence, the detection of this type of QSO could be a crucial test for the present picture. The later fading nucleus could be a low-luminosity AGN (LLAGN; e.g., Kawaguchi & Aoki 2002; Awaki et al. 2001). The proto-QSO phase is

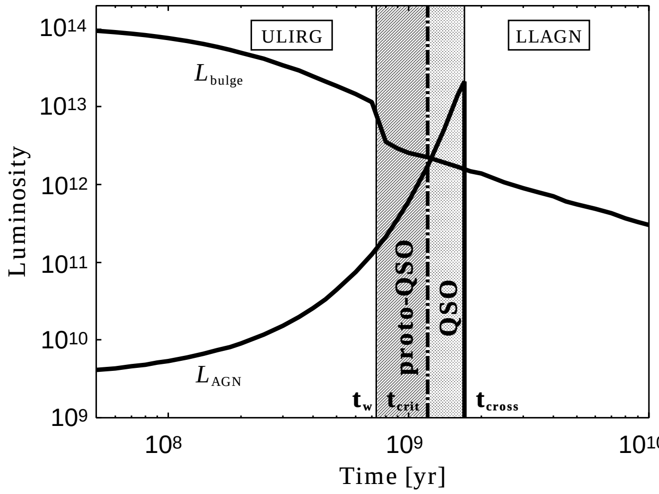

FIG. 3.—AGN and bulge luminosity as a function of time. The ordinate is the luminosity in units of solar luminosity; $t_{\rm crit}$ is the time when $L_{\rm bulge} = L_{\rm AGN}$. Here we assume that $L_{\rm AGN}$ is the Eddington luminosity. The phase at $t < t_w$ is a bright and optically thick phase, which may correspond to aULIRG phase. After the AGN luminosity ($L_{\rm AGN}$) exhibits a peak at $t_{\rm cross}$, it fades out abruptly. The later fading nucleus could be an LLAGN. The optically thin, bright AGN phase (*gray area*) can be divided into two phases; one is the host-dominant phase (proto-QSO), which is the dark gray area ($t_w \le t \le t_{\rm crit}$) and the other is the AGN-dominant phase (QSO), which is the light gray area ($t_{\rm crit} \le t \le t_{\rm cross}$). The lifetime of both phases are comparable, $\approx 10^8$ yr.

preceded by a bright and optically thick phase, which may correspond to a ULIRG phase.

The proto-QSO phase may be distinguishable in terms of several observable properties like the broad emission line width, the color of the host galaxy, and the metallicity. The time variations of these quantities are shown in Figures 4–6. The broad emission line width, which corresponds to the virial velocity, $V_{\rm BLR}$, is assessed by an empirical law for the size of the broad-line region (BLR), $r_{\rm BLR} = 15 L_{44}^{1/2}$ lt-days (Kaspi et al. 1997), where L_{44} is the luminosity at 0.1–1 μm

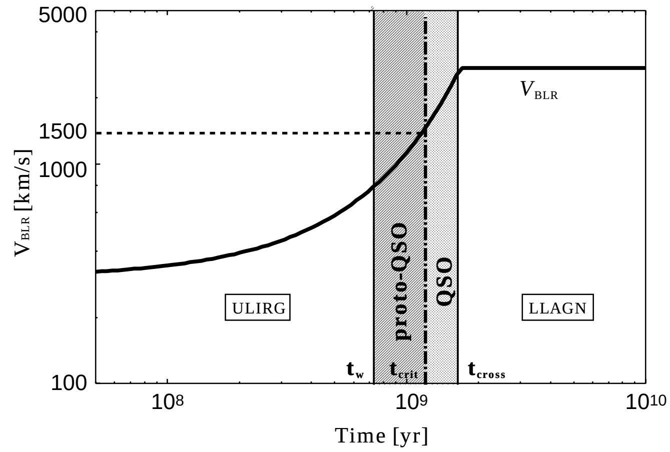

FIG. 4.—Broad emission line width, $V_{\rm BLR}$, as a function of time. The ordinate is $V_{\rm BLR}$ in units of kilometers per second. This line represents eq. (5). In the proto-QSO phase, $V_{\rm BLR}$ is less than $\sim$1500 km s^{-1}.

in units of 10^{44} ergs s^{-1}. In Seyfert galaxies, this relation holds not only for the slow-growth phase of AGN BHs, but also for NLSy1s (Peterson, McHardy, & Wilkes 2000). Provided that the broad line clouds are bound in the potential by central BH (Laor et al. 1997) and L (0.1–1 μm) is close to the Eddington luminosity, $L_{\rm Edd} \simeq 1.2 \times 10^{46} (M_{\rm BH}/10^8 M_\odot)$ ergs s^{-1}, the circular velocity of broad line clouds ($V_{\rm BLR}$) is given by

$$V_{\rm BLR} \simeq \left(\frac{GM_{\rm BH}}{r_{\rm BLR}}\right)^{1/2} = 1700 \left(\frac{M_{\rm BH}}{10^8\ M_\odot}\right)^{1/4} \text{km s}^{-1}. \quad (5)$$

The estimated widths of the broad emission lines are shown in Figure 4. It is found that $V_{\rm BLR}$ in the proto-QSO phase is less than $\sim$1500 km s^{-1}. This velocity is considerably smaller compared to ordinary QSOs.

The colors of the host galaxy at the rest bands and the observed bands, with assumed formation redshift of $z_f = 4$, are shown in Figures 5*a* and 5*b*, respectively. Here we take

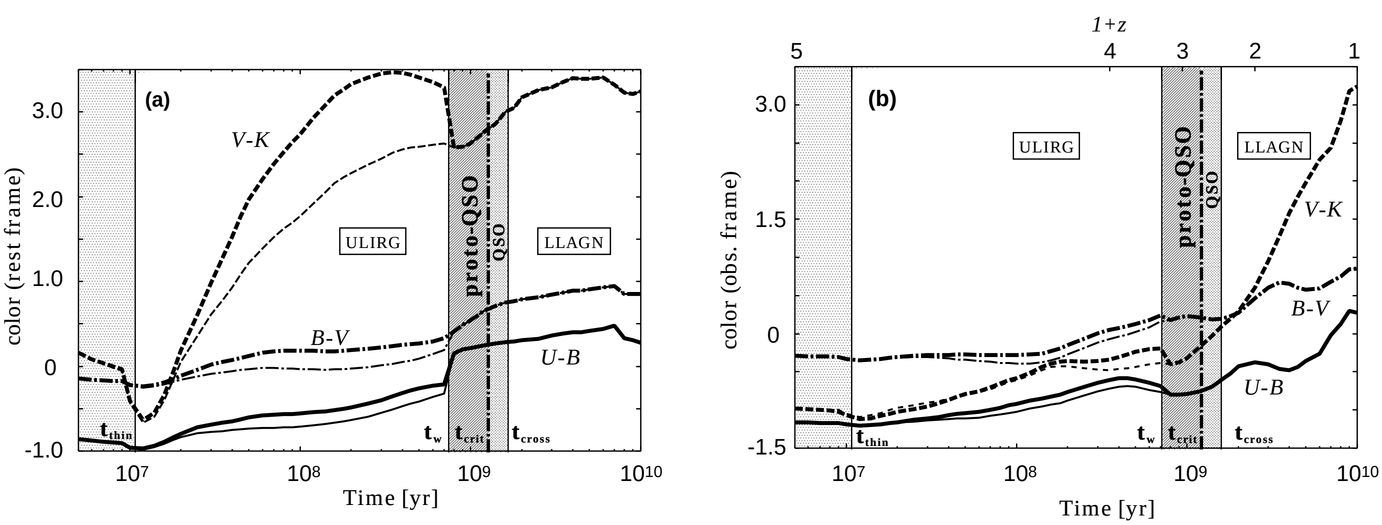

FIG. 5.—(*a*) $U-B$, $B-V$, and $V-K$ colors at the rest frame as a function of time. The ordinate is the $U-B$, $B-V$, and $V-K$ colors. The effects of dust extinction and K-correction are taken into account. The thick lines show the case with dust extinction. The thin lines denote the case without dust extinction. The $B-V$ color in the proto-QSOs is about 0.5 mag bluer than in that of the QSOs. Moreover, the $V-K$ color in the proto-QSOs is about 0.6 mag bluer than that of the QSOs. (*b*) $U-B$, $B-V$, and $V-K$ color at the observed frame as a function of time, assuming $H_0 = 70$ km s^{-1} Mpc^{-1}, a galaxy formation redshift of $z_f = 4$, and the Einstein–de Sitter model. The upper abscissa shows the redshift. The $V-K$ color in proto-QSOs is about 0.5 mag bluer than in the QSO phase.

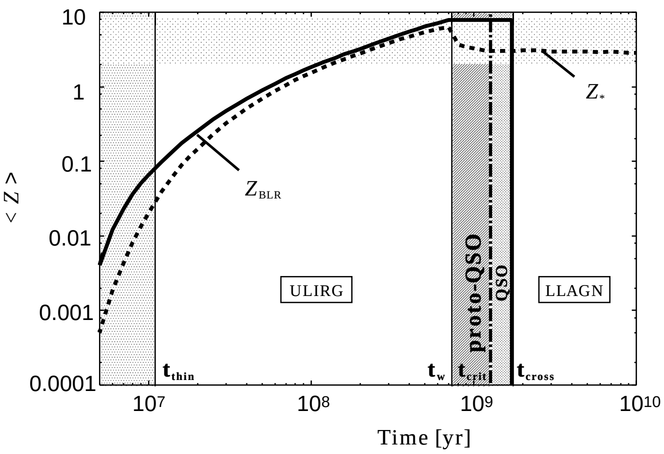

FIG. 6.—Mean metallicity $\langle Z \rangle$ as a function of time. The ordinate is the metallicity in units of $Z_\odot$. The solid line denotes the metallicity of gas in galactic nuclei, Z_{BLR}. The dotted line shows the metallicity of stars weighted by the host luminosity, Z_*. The top hatched area denotes the observable metallicity in QSO BLR and inferred metallicity in present-day elliptical galaxies (Dressler et al. 1984; Hamann & Ferland 1993; Shields & Hamann 1997; Dietrich & Wilhelm-Erkens 2000; Constantin et al. 2002; Becker et al. 2001).

into account the effects of dust extinction and K-correction, providing $H_0 = 70$ km s^{-1} Mpc^{-1} and the Einstein–de Sitter universe. In Figure 5, the thick lines show the cases with dust extinction, whereas the thin lines denote the cases without dust extinction. At the rest frame, as seen in Figure 5*a*, it is found that the $U-B$ color is almost identical between the proto-QSO and QSO phases because the massive stars responsible for the $U-B$ color of the host galaxy disappear before $\sim 10^9$ yr. However, the $B-V$ color in the proto-QSO phase is about 0.5 mag bluer than that in the QSO phase. Moreover, the $V-K$ color in the proto-QSO phase is about 0.6 mag bluer than that in the QSO phase. At the observed frame, as seen in Figure 5*b*, the $V-K$ color of the proto-QSO phase is about 0.5 mag bluer than that in the QSO phase, while a noticeable difference is not found between two phases in the $U-B$ and $B-V$ colors. We confirm that the results do not change significantly for different redshifts of galaxy formation (e.g., $z_f = 3$ and 5). This may be an important photometric feature that can discriminate the proto-QSO phase from the QSO phase.

As for the metallicity, Figure 6 shows that no appreciable difference is found between proto-QSO and QSO phases. The average metallicity of gas in galactic nuclei, Z_{BLR} (*solid line*), is $\sim 8\ Z_\odot$, and the average metallicity of stars weighted by the host luminosity, Z_* (*dashed line*), is $\simeq 3\ Z_\odot$. These results are consistent with the observed metallicity in QSO BLRs and the inferred metallicity in present-day elliptical galaxies (Dressler et al. 1984; Hamann & Ferland 1993; Shields & Hamann 1997; Dietrich & Wilhelm-Erkens 2000; Constantin et al. 2002; Becker et al. 2001).

4. A UNIFIED EVOLUTIONARY SCENARIO FOR AN ELLIPTICAL GALAXY NUCLEUS

Based on the results shown in the above sections, we attempt to provide an evolutionary picture for an elliptical galaxy nucleus. The present radiation-hydrodynamic model is grounded on two key conditions, that is, the starburst event and the optically thick ISM. Obviously, starburst galaxies including ULIRGs satisfy these two conditions. Starbursts are observed to be often triggered by galaxy mergers or interactions (e.g., Borne et al. 2000), and also numerical simulations of galaxy mergers actually demonstrate this possibility (e.g., Mihos & Hernquist 1996). Thus, the present model can be considered in the context of galaxy mergers. On the other hand, the recent discovery of high-redshift quasars with $z > 6$ (Fan et al. 2001) indicates that the formation of supermassive BHs proceeded in an appreciably short timescale of less than 10^9 yr. In these cases, there may not be enough time for well-evolved galaxies to merge to form massive elliptical galaxies. However, the present model is still valid if QSO hosts satisfy the above two conditions.

Recent high-quality observations suggest that radio galaxies, ULIRGs, Lyman break galaxies (LBGs), and Lyα emitters could be precursors of spheroidal galaxies at high redshifts. As for the radio galaxies, they are categorized as radio-loud AGNs. Radio galaxies are thought to have massive BHs ($\sim 10^8\ M_\odot$), which are comparable to that of the radio-loud QSOs, but the ratio of the AGN luminosity to the host luminosity (L_{AGN}/L_{bulge}) is less than unity (Dunlop et al. 2002). In addition, by the analysis of the spectral energy distribution of high-redshift ($z > 2$) radio galaxies, the galactic age is estimated to range from ~ 0.1 to 2 Gyr (Mazzei & Zotti 1996; Pentericci et al. 2001). Furthermore, a large amount of dust is detected (e.g., Papadopoulos et al. 2000), and the gas extended over several tens of kiloparsecs has solar or supersolar metallicity (Vernet et al. 2001, Villar-Martin et al. 2001). It is intriguing that all these properties of radio galaxies are quite similar to the predicted properties of proto-QSOs. In that sense, radio galaxies could be a key candidate for proto-QSOs.

As for ULIRGs, the X-ray emission (Brandt et al. 1997) or Paα lines (Veilleux, Sanders, & Kim 1999) intrinsic for active nuclei have been detected in roughly one forth of ULIRGs. Also, recent X-ray observations have revealed that ULIRGs with AGN activity mostly have the lower ratio of the hard X-ray luminosity to the bolometric luminosity, which is $L_X/L_{bol} \leqslant 0.01$ (Imanishi & Ueno 1999; Braito et al. 2002). If the AGN luminosity is controlled by the Eddington limit, these results indicate that the BH mass is considerably smaller in a ULIRG phase. In the present model, if the optically thick phase ($t_{thin} < t < t_w$) is regarded as a ULIRG phase, the mass ratio M_{BH}/M_{bulge} is predicted to be much less than 0.001 in the ULIRG phase. Also, it is expected that M_{BH}/M_{bulge} grows with metallicity at the later phases of ULIRGs. The present model may be a physical picture of the evolution of ULIRGs to QSOs proposed by Sanders et al. (1988) and Norman & Scovill (1988).

The present picture also predicts the existence of the optically thin phase ($t < t_{thin}$) before the ULIRG phase, as shown in Figure 1. This phase has several characteristic properties: (1) The hard X-ray luminosity is relatively low $L_X = 5 \times 10^8\ L_\odot$ if $L_X = 0.1 L_{AGN}$. (2) The metallicity of the gaseous component is subsolar, $Z_{BLR} < 0.1\ Z_\odot$ (Fig. 6). (3) The massive dusty disk with $10^{6-7}\ M_\odot$ can surround the galactic center (Fig. 2). (4) The seed BH with $\sim 10^5\ M_\odot$ can form through the collapse of a rotating SMS. Then the gravitational wave is expected to be emitted, which may be detectable by the *Laser Interferometer Space Antenna* (*LISA*; de Arajo, Miranda, & Agular 2001; Saijo et al. 2002). As for the host galaxy, recently observed high-redshift LBGs or Lyα emitters may correspond to the beginning phase of a bulge (Friaca & Terlevich 1999; Matteucci & Pipino 2002). LBGs have the luminosity 10^{10}–10^{11} $L_\odot$, are observed to be optically thin, and have the metallicity of 0.1–1 $Z_\odot$. Also, they exhibit strong clustering at $z \sim 3$. In addition, the *Chandra X-Ray Observatory* has detected the hard X-ray of LBGs with the luminosity of $\sim 10^8$ $L_\odot$, although it is still uncertain whether the X-ray emission arises from AGNs or not (Brandt et al. 2001). Some LBGs have a light profile following an $r^{1/4}$ law over a large radial range (Giavalisco, Steidel, & Macchetto 1996). Moreover, it has been proposed that Lyα emitters may be the first 10^7 yr of the galaxy formation, and thereafter their luminosity fades rapidly by dust (Malhotra & Rhoads 2002). Therefore, the precursor of ULIRGs predicted in the present model may correspond to the assembly phase of LBGs or Lyα emitters.

5. CONCLUSIONS

Based on the radiation drag model for BH growth, incorporating the chemical evolution of the early-type host galaxy, we have built up the coevolution model for a QSO BH and a host galaxy. As a consequence, we have shown the possibility of the proto-QSO phase, which is optically thin and host luminosity–dominant and has a lifetime comparable to the QSO-phase timescale of a few 10^8 yr. We have predicted the observable properties of proto-QSOs as follows: (1) The broad emission lines are narrower, less than 1500 km s^{-1}. (2) The BH-to-bulge mass ratio, $M_{\rm BH}/M_{\rm bulge}$, rapidly increases from $10^{-5.3}$ to $10^{-3.9}$ in $\approx 10^8$ yr. (3) The colors $B-V$ at rest bands and $V-K$ at observed bands are about 0.5 mag bluer than those of QSOs. (4) In both proto-QSO and QSO phases, the metallicity of gas in the galactic nuclei is $Z_{\rm BLR} \simeq 8\ Z_\odot$ and that of stars weighted by the host luminosity is $Z_* \simeq 3\ Z_\odot$, values that are consistent with the observations for QSOs and the elliptical galaxies. (5) A massive dusty disk ($>10^8\ M_\odot$) surrounds a massive BH, and it may obscure the nucleus in the edge-on view to form a type 2 nucleus. The predicted properties of proto-QSOs are similar to those of radio galaxies.

The proto-QSO phase is preceded by an optically thick phase before the galactic wind, which may correspond to ULIRGs. The present model predicts a low-luminosity ratio of $L_{\rm AGN}$ to $L_{\rm bol}$, which is consistent with the observed ratio $L_{\rm X}/L_{\rm bol} \leqslant 0.01$ for ULIRGs. In addition, $M_{\rm BH}/M_{\rm bulge}$ is anticipated to be much less than 10^{-3} and $M_{\rm BH}/M_{\rm bulge}$ grows with metallicity in the ULIRG phase.

Finally, we can predict the precursor of a ULIRG, which is optically thin and its lifetime is $\sim 10^7$ yr. This may correspond to the assembly phase of LBGs or Lyα emitters. In this phase, the massive dusty disk of $\approx 10^6$–10^7 $M_\odot$ exists, the metallicity is subsolar ($Z_* < 0.1\ Z_\odot$), and the hard X-ray luminosity is $L_{\rm X} \sim 5 \times 10^8\ L_\odot$ if $L_{\rm X} = 0.1 L_{\rm AGN}$. In addition, the formation of a seed BH ($\sim 10^5\ M_\odot$) can occur as a consequence of the collapse of a rotating supermassive star in this phase. Thus, the gravitational wave may be detectable by the *LISA*.

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