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A Scenario for the Coevolution of an Elliptical Galaxy and a QSO

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Abstract

Based on the radiation hydrodynamic model for the 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 the 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 10^8yr. The former phase corresponds to the early stage of a growing BH and can be regarded as a "proto-QSO" phase. Also, by considering theoretical predictions for the observable properties in proto-QSO phase, we conclude that radio galaxies at high redshifts are a possible candidate for proto-QSOs.

1.1 Introduction

Recent X-ray and optical observations indicate that active galactic nuclei (AGN) are divided into two subclasses by the rate of black hole (BH) growth; one is a rapid-growth phase, and the other is a slow-growth phase (e.g., Pounds et al. 1995). This possibility has been pointed out primarily for the Seyfert 1 galaxies (Sy1s), which are divided into two subclass according to the width of the broad emission lines, $V_{\rm BLR}$. The Sy1s with $V_{\rm BLR}$ less than 2000km/s are called narrow line Sy1s (NLSy1s), whereas those with 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 (e.g., Pounds et al. 1995). Also, it is pointed out that the BH-to-bulge mass ratio is smaller than that in elliptical galaxies (Mathur et al. 2001). These all suggest that NLSy1s are in the rapid-growth phase of BH, in contrast to BLSy1s which are explained by conventional mild accretion onto a large BH. According to these observations, it has been suggested that NLSy1s may be Sy1s in the early stage of their evolution (Mathur 2000). On the analogy of 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 further high quality observations of galactic centers have shown 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 galactic bulges; the mass ratio of the BH to the bulge is 0.001-0.006 as a median value (e.g., Kormendy & Richstone 1995) . (Note that for an elliptical galaxy the bulge means a whole galaxy.) In addition, a lot of recent efforts have revealed that QSO host galaxies are mostly luminous and well-evolved early-type galaxies (e.g.,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 is physically related to each other. But, the link between the formation of a supermassive BH and the formation and evolution of a host galaxy is an open question. Also, the physical relationship among ultraluminous infrared galaxies (ULIRGs), radio galaxies, and QSOs is an issue of long standing.

Recently, as a potential mechanism to build up a supermassive BH in a spheroidal system, Umemura (2001) has considered the effects of radiation drag, and it has been found that this mechanism really works efficiently in a clumpy interstellar medium (ISM) (Kawakatu & Umemura 2002). But, in these works the effect of the realistic chemical evolution of the host galaxy has not been considered. Thus, it has been hard to compare theoretical predictions with observations. Hence, in order to clarify what objects correspond to the early growing phase of BH, it is important to investigate observable properties of the system. 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 early-type host galaxy. The purpose of this paper is to elucidate the physical relationship between BH growth and the evolution of host galaxy and to predict the observable properties of proto-QSOs.

1.2 Coevolution Model

First, we construct the BH growth model. Here, we suppose a simple two-component system that consists of a spheroidal stellar bulge and inhomogeneous optically-thick ISM within it. In the radiation drag model, it is likely that optically thin surface layers are stripped from optically thick clumpy clouds by the radiation drag, and the stripped gas losing angular momentum accretes on to a central massive object. Then, the mass of an MDO, $M_{\rm MDO}$, which is the total mass of dusty ISM assembled to the central massive object, is given by

$$M_{\rm MDO} = \eta_{\rm drag} \int_{t_{\rm thin}}^{t_{\rm w}} \frac{L_{\rm bulge}(t)}{c^2} dt, \tag{1.1}$$

where $L_{\rm bulge}$ is the bulge luminosity, $\eta_{\rm drag}$ is found to be maximally 0.34 in the optically thick limit (Kawakatu & Umemura 2002), $t_{\rm w}$ is a galactic wind timescale, and $t_{\rm thin}$ is a time before which the optical depth is less than unity.

In this model, we should distinguish BH mass from the mass of an MDO although the mass of an MDO is often regarded as BH mass from an observational point of view. Supposing the mass accretion driven by the viscosity on to the BH horizon is limited by an order of Eddington rate, the BH mass grows according to

$$M_{\rm BH} = M_0 e^{\nu t/t_{\rm Edd}}, \tag{1.2}$$

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, and $t_{\rm Edd}$ is the Eddington timescale, $t_{\rm Edd} = 1.9 \times 10^8$yr. Here M_0 is the mass of a seed BH, which could be a massive BH with $\sim 10^5 M_\odot$ formed by the collapse of a rotating supermassive star (Shibata & Shapiro 2002).

Next, we construct the model for QSO evolution. 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. Then, we employ the galactic wind model because it can reproduce the color-magnitude relation of a present-day elliptical galaxy (Arimoto & Yoshii 1987). Thereby, we can estimate the evolution of the physical properties of QSO host, such as mass, luminosity, color and metallicity.

1.3 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 1.1, 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 (1.2). The BH mass reaches $M_{\rm MDO}$ at a time $t_{\rm cross}$. As seen in Figure 1.1, during $t < t_{\rm cross}$, the BH mass fraction $f_{\rm BH} = M_{\rm BH}/M_{\rm bulge}$ increases with time. At $t > t_{\rm cross}$, almost all of the MDO matter has fallen onto the central BH, and therefore the BH mass is saturated. In the optically thick phase ($t_{\rm thin} < t < t_{\rm w}$), the BH fraction is $f_{\rm BH} \ll 0.001$. In the optically thin phase at $t > t_{\rm w}$, which is the dark gray area ($t_{\rm w} < t < t_{\rm cross}$) in Figure 1.1, 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 color-magnitude relation of bulges can be reproduced if a galactic wind sweeps away the gas at a wind epoch $t_{\rm w}$ of a few 10^8yr (Kodama & Arimoto 1997). The evolution of the bulge luminosity is shown in Figure 1.2 with the galactic wind model. Even after the galactic wind ($t > t_{\rm w}$), $M_{\rm BH}$ continues to grow until $t_{\rm cross}$ and therefore the AGN brightens with time if the Eddington ratio is constant. As seen in Figure 1.2, it is found that the area of $t_{\rm w} < t < t_{\rm cross}$ can be divided into two phases with a transition time $t_{\rm crit}$ when $L_{\rm bulge} = L_{\rm AGN}$; one is the host luminosity-dominant phase (*the dark gray area*), and the other is the AGN luminosity-dominant phase (*the light gray area*). Also, lifetimes of both phases are comparable to each other, which is about 10^8yr. The AGN-dominant phase is likely to correspond to ordinary QSOs, but host-dominant phase is obviously different from observed QSOs so far. We define this phase as "a proto-QSO". Objects corresponding to such host luminosity-dominant proto-QSOs have not been identified observationally yet. Hence, the detection of this type of QSOs could be a crucial test for the present picture. After the AGN luminosity ($L_{\rm AGN}$) exhibits a peak at $t_{\rm cross}$, it fades out abruptly. The later fading nucleus could be a low luminosity AGN (LLAGN). The phase ($t < t_{\rm w}$) is a bright and optically thick phase, which may correspond to a ultraluminous infrared galaxy (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 (See Kawakatu et al. 2003 for the details). As for the broad emission line width, which corresponds to the virial velocity, $V_{\rm BLR}$, is assessed by an empirical law for the size of broad line region (BLR), $r_{\rm BLR} = 15 L_{44}^{1/2}$light-days (Kaspi et al. 1997), where L_{44} is the luminosity at $0.1 - 1\mu$m in units of 10^{44}erg/s. As a result, the circular velocity of broad line clouds ($V_{\rm BLR}$) is given by

$$V_{\rm BLR} \simeq \left(\frac{GM_{\rm BH}}{r_{\rm BLR}}\right)^{1/2} = 1700 \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^{1/4} {\rm km/s}. \tag{1.3}$$

Then, it is found that $V_{\rm BLR}$ in the proto-QSO phase is less than ~ 1500km/s. This velocity is considerably small compared to normal QSOs.

Moreover, the colors of host galaxy at the observed bands with assuming the formation redshift of $z_{\rm f} = 4$ can be calculated. Here, we take into account the effect of dust extinction

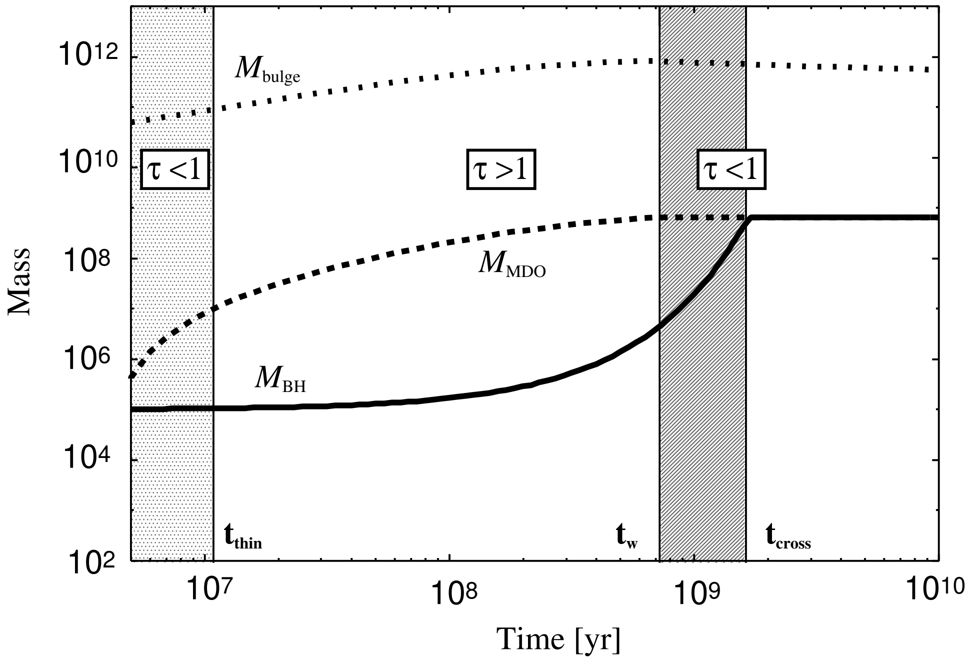

Fig. 1.1. BH growth, assuming $M_0 = 10^5 M_\odot$ and $\nu = 1.0$. The ordinate is mass in units of $M_\odot$. $M_{\rm bulge}$ is the mass of stellar component in bulge. $M_{\rm MDO}$ is the mass of MDO. $M_{\rm BH}$ is the mass of the supermassive BH. $t_{\rm w}$ is the galactic wind timescale. $t_{\rm cross}$ 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 the massive dusty disk ($10^{6-7} M_\odot$). In the optically thin phase, which is the dark gray area ($t_{\rm w} < t < t_{\rm cross}$), there can be a massive dusty disk ($> 10^8 M_\odot$) around a massive BH, and also the BH fraction is $f_{\rm BH} = M_{\rm BH}/M_{\rm bulge} \simeq 0.001$,which is just comparable to the observed ratio.

and K-correction, providing $H_0 = 70$km/s/Mpc and the Einstein-de Sitter universe. At the observed frame, it is found that the *V-K* color of the proto-QSO phase is about 0.5 magnitude bluer than that in the QSO phase, while the noticeable difference is not found in *U-B* and *B-V* colors between two phases. This may be an important photometric feature that discriminates the proto-QSO phase from the QSO phase.

1.4 Conclusions

Based on the radiation drag model for the BH growth, incorporating the chemical evolution of the early-type host galaxy, we have built up the coevolution model for a QSO BH and the 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 the lifetime comparable to the QSO phase timescale of a few 10^8 years. We have predicted the observable properties of proto-QSOs as follows: (1) The broad emission lines are narrower, which is less than 1500km/s. (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 of $(V-K)$ at observed bands are about 0.5 magnitude bluer than those of QSOs. (4) A massive dusty disk ($> 10^8 M_\odot$) surrounds a massive

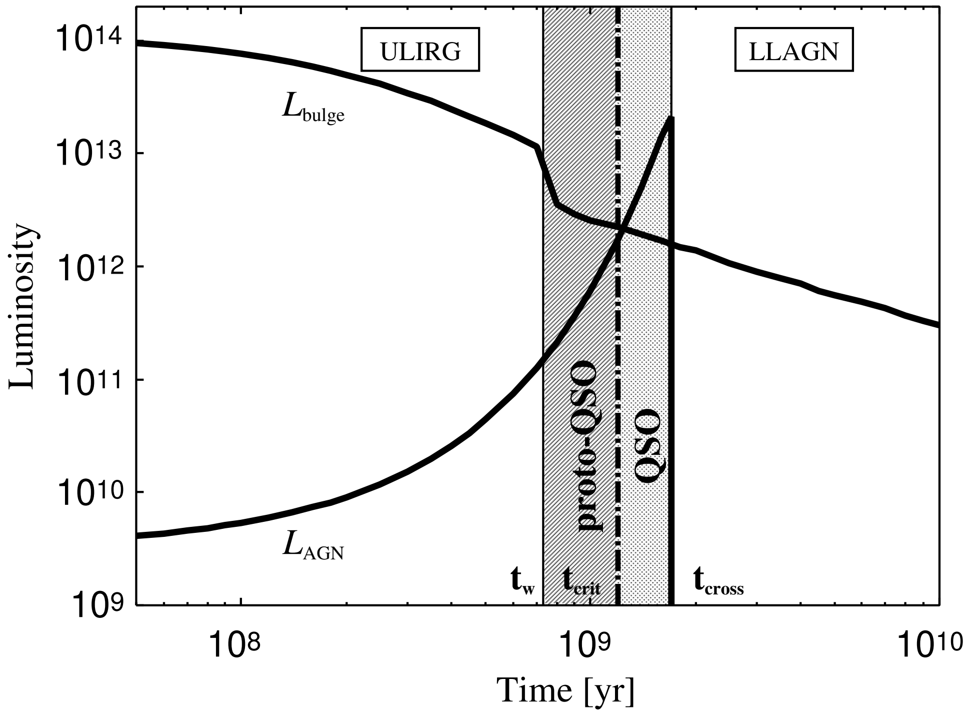

Fig. 1.2. AGN and bulge luminosity as a function of time. The ordinate is the luminosity in units of $L_\odot$. $t_{\rm crit}$ is the time when $L_{\rm bulge} = L_{\rm AGN}$. Here, we assume that $L_{\rm AGN}$ is the Eddington luminosity. The phase at $t < t_{\rm w}$ is a bright and optically thick phase, which may correspond to a ultraluminous infrared galaxy (ULIRG) 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 a low luminosity AGN (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 ($t_{\rm w} \leq t \leq t_{\rm crit}$) and the other is the AGN-dominant phase (QSO), which is the light gray area ($t_{\rm crit} \leq t \leq t_{\rm cross}$). The lifetime of both phases are comparable,$\approx 10^8$yr.

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 high redshift radio galaxies.

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