The Interplay among Black Holes, Stars and ISM in Galactic Nuclei
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QSO formation under coevolution of SMBH and bulge

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Abstract. The formation and growth of supermassive black holes (SMBHs) physically linked with bulges are considered. We focus on the radiation hydrodynamic process for the growth of SMBH in the optically thick starburst phase, where radiation from bulge stars drives the mass accretion on to a galactic center through radiation drag effect. In the present scenario, the AGN luminosity-dominant phase (QSO phase) is preceded by the host luminosity-dominat phase, which is called "proto-QSO phase". In this phase, there exists the massive dusty disks within younger bulges. Also, the proto-QSO phase is anticipated by an optically-thick ultraluminous infrared galaxy (ULIRG) phase. Furthermore, such radiation hydrodynamic model has been also applied to disk galaxies. It turns out that the mass of a SMBH primarily correlates with a bulge component even in a disk galaxy. Thus, by analogy to proto-QSOs, the BH growing phase in disk galaxies may have massive dusty disks within younger bulges.

1. Introduction

The paradigm that ultraluminous infrared galaxies (ULIRGs) could evolve into QSOs was proposed by pioneering studies by Sanders et al. (1988) and Norman & Scovill (1988). By recent observations, the X-ray emission (Brandt et a. 1997) or Paα lines (Veilleux, Sanders, & Kim 1999) intrinsic for active galactic nuclei (AGNs) have been detected in more than one third of ULIRGs. 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 0.002 as a median value (e.g., Marconi & Hunt 2003). In addition, it has been found that QSO host galaxies are mostly luminous and well-evolved early-type galaxies (e.g., McLure, Dunlope, & Kukula 2000). Comprehensively judging from all these findings, it is likely that ULIRGs, QSOs, Bulges, and SMBHs are physically related to each other.

2. Formation of Supermassive Black Holes

A radiation drag model for the formation of SMBHs is recently proposed by Umemura (2001). Here, we suppose a simple two-component system that consists of a spheroidal stellar bulge and inhomogeneous optically-thick interstellar medium (ISM) within it. In this model, radiation drag extracts the angular momentum from inhomogeneous optically-thick ISM and allow it to accrete onto the center. Then, the mass of an MDO, $M_{\rm MDO}$, which is the total mass of dusty ISM assembled to the central massive object, is

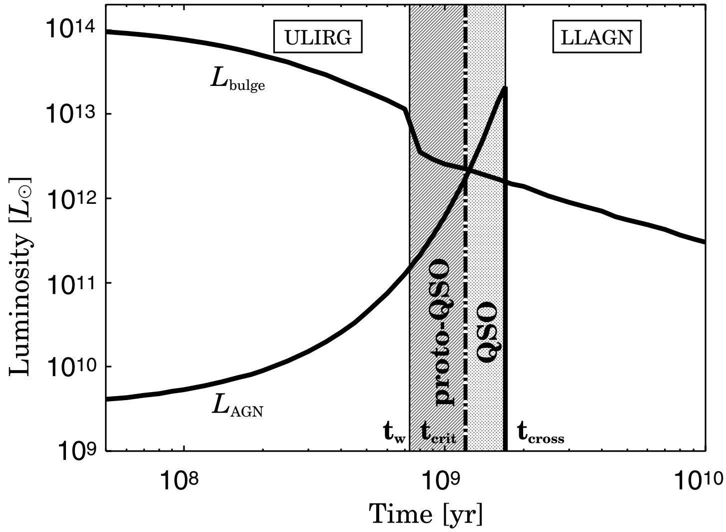

Figure 1. AGN and bulge luminosity as a function of time. The ordinate is the luminosity in units of $L_\odot$. $t_{\rm crit}$ is the time when $L_{\rm bulge} = L_{\rm AGN}$. Here, we assume that $L_{\rm AGN}$ is the Eddington luminosity. The phase at $t < t_{\rm w}$ is a bright and optically thick phase, 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 ($t_{\rm w} \leqslant t \leqslant t_{\rm crit}$) and the other is the AGN-dominant phase (QSO), which is the light gray area ($t_{\rm crit} \leqslant t \leqslant t_{\rm cross}$). The lifetime of both phases are comparable, $\approx 10^8$yr.

given by

$$M_{\rm MDO} = \eta_{\rm drag} \int_{t_{\rm thin}}^{t_{\rm w}} \frac{L_{\rm bulge}(t)}{c^2} dt, \tag{2.1}$$

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

In this paper, 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

$$M_{\rm BH} = M_0 e^{\nu t / t_{\rm Edd}}, \tag{2.2}$$

where ν is the ratio of BH accretion rate to the Eddington rate, 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).

3. Coevolution of BH Growth and Bulge

Here, we construct a scenario of the coevolution of SMBH and bulge based on the radiation drag model for SMBH formation. In order to treat the realistic chemical evolution of host galaxy, we use an evolutionary spectral synthesis code 'PEGASE'(Fioc &

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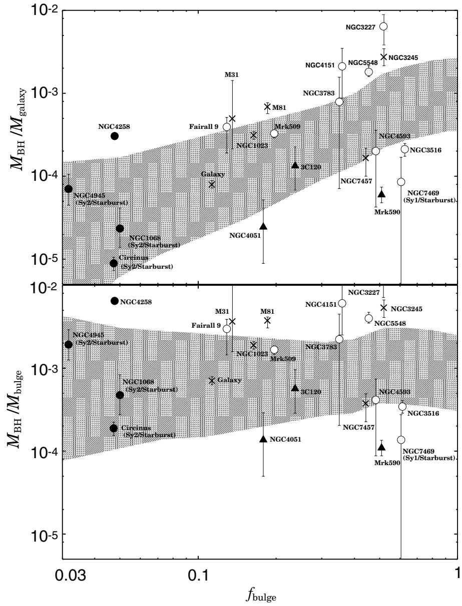

Figure 2. Comparison between the theoretical prediction and the observational data on BH mass for disk galaxies. The upper panel shows the BH-to-galaxy mass ratio ($M_{\rm BH}/M_{\rm galaxy}$) and the lower panel shows the BH-to-bulge mass ratio ($M_{\rm BH}/M_{\rm bulge}$) against the bulge fraction ($M_{\rm bulge}/M_{\rm galaxy}$). The hatched area is the prediction of the present analysis. The observational data are plotted by symbols. The data points are categorized into four types. *Crosses* – disk galaxies which do not possess AGNs, *open circles* – Seyfert 1 galaxies (Sy1s), *filled triangles* – narrow line Seyfert 1 galaxies (NLSy1s), and *filled circles* – Seyfert 2 galaxies (Sy2s). Seyfert galaxies accompanied by starburst activities are specified like Sy1/starburst or Sy2/starburst.

Rocca-Volmerange 1997). Also, we employ a galactic wind model with the wind epoch of $t_{\rm w} = 7 \times 10^8$yr because it can reproduce a present-day color-magnitude relation. In this model, the system is assumed to change from optically-thick to optically-thin phase at $t_{\rm w}$. Also, we assume the star formation rate is in proportion to gas fraction and initial gas mass is $10^{12} M_\odot$. Thereby, we can estimate the evolution of the physical properties of QSO host, such as mass, luminosity, color and metallicity.

Based on the present coevolution model, the mass accretion proportional to the bulge luminosity leads to the growth of an MDO, 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 (2.2). The BH mass reaches $M_{\rm MDO}$ at a time $t_{\rm cross}$ because almost all of the MDO matter has fallen onto the central BH. The resultant BH fraction becomes $f_{\rm BH} \simeq 0.001$, which is just comparable to the observed ratio. The evolution of bulge luminosity ($L_{\rm bulge}$) and AGN luminosity ($L_{\rm AGN}$) are shown in Figure 1, assuming the constant Eddington ratio ($\nu = 1$). 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. After $L_{\rm AGN}$ exhibits a peak at $t_{\rm cross}$, it fades out abruptly to exhaust the fuel. The fading nucleus could be a low luminosity AGN (LLAGN).

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 $L_{\rm bulge} = L_{\rm AGN}$; the earlier phase is the host luminosity-dominant phase, and the later phase is the AGN luminosity-dominant phase. 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" (Kawakatu,

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Umemura, & Mori 2003). We have predicted the observable properties of proto-QSOs as follows: (1) The broad emission lines are narrower, which is less than 1500km/s. Thus, proto-QSO can be regarded as a "Narrow line Type I QSO (NLQSO)" (2) 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. (3) 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. (4) The colors of $(V - K)$ at observed bands are about 0.5 magnitude bluer than those of QSOs. The predicted properties of proto-QSOs are similar to those of high redshift 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 that the BH fraction is anticipated to be much less than 0.002 and grows with metallicity in the ULIRG phase.

4. Growth of SMBH in Disk Galaxies

We have hitherto applied the radiation drag model to elliptical galaxies, but it could been also applied to disk galaxies. Thus, we recently elucidate the efficiency of the radiation drag in disk galaxies (Kawakatu & Umemura 2004). As seen in Figure 2, it is found that the SMBH should be smaller in a disk galaxy, but correlate with the bulge component in a similar way to an elliptical galaxy. In addition, the observational trends in disk galaxies are broadly consistent with the theoretical prediction. Hence, by analogy to proto-QSOs, a growing BH phase in a disk galaxy (e.g., NLS1) possibly have a massive dusty disk within a younger bulge.

5. 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 yr. 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. The proto-QSO phase is preceded by an optically-thick ultraluminous infrared galaxy (ULIRG) phase. Furthermore, the present model could be applied to disk galaxies. We found that the mass of a SMBH correlates with that of a bulge even in disk galaxies. Thus, by analogy to proto-QSOs, a growing BH phase in a disk galaxy (e.g., NLS1) may have a massive dusty disk within a younger bulge. In summary, the present model could be a physical picture of evolution of ULIRGs (LIRGs) to QSOs (Sy1s).

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