A Coevolution Scheme for Supermassive Black Holes and Galactic Bulges

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The coevolution of a supermassive black hole (SMBH) and a bulge is considered based on a novel mechanism for BH formation, where the BH growth is promoted by the mass accretion driven by radiation drag which is exerted on dusty interstellar gas in radiation fields generated by bulge stars. It turns out that the resultant mass of a SMBH is predicted to be in proportion to the bulge mass, and the mass ratio is basically determined by the nuclear energy conversion efficiency from hydrogen to helium, $\varepsilon = 0.007$. In the present scenario, the bulge luminosity overwhelms the BH accretion luminosity in the growing phase of SMBH. This phase corresponds to a "proto-QSO", thereafter evolving to a QSO. Also, the proto-QSO phase is preceded by an optically-thick ultraluminous infrared galaxy (ULIRG) phase.

§1. Introduction

The recent compilation of the kinematical data of galactic centers in both active and inactive galaxies has shown that a central 'massive dark object' (MDO), which is the nomenclature for a black hole (BH) candidate, correlates with the properties of a hosting bulge (a bulge means a whole galaxy for an elliptical galaxy). The demography of MDOs has revealed the following relations:

1) The BH mass exhibits a linear relation to the bulge mass with the ratio of $f_{\rm BH} \equiv M_{\rm BH}/M_{\rm bulge} \approx 0.002$ as a median value (Kormendy and Richstone 1995; Richstone et al. 1998; Magorrian et al. 1998; Gebhardt et al. 2000a; Ferrarese and Merritt 2000; Merritt and Ferrarese 2001a; McLure and Dunlop 2002; Marconi and Hunt 2003).
2) The BH mass correlates with the velocity dispersion of bulge stars with a power-law relation as $M_{\rm BH} \propto \sigma^n$, $n = 3.75$ (Gebhardt et al. 2000b), 4.72 (Merritt and Ferrarese 2001a, b), or 4.02 ± 0.32 (Tremaine et al. 2002).
3) In disk galaxies, the mass ratio is significantly smaller than 0.01 if the disk stars are included. But, if the bulge is focused, the relation 1) still holds (Salucci 2000; Sarzi et al. 2001).
4) For quasars, the $f_{\rm BH}$ is at a similar level to that for elliptical galaxies (Laor 1998; Shields et al. 2002).

These correlations imply that the formation of a supermassive BH is physically linked to the formation of a galactic bulge which harbors a supermassive BH. In this paper, as a potential mechanism to build up SMBHs in a bulge, we consider the radiation drag exerted by the radiation from bulge stars. The radiation drag extracts angular momentum from interstellar gas and thus allows the gas to accrete onto the galactic center. Based on this BH formation mechanism, we propose a coevolution scheme for SMBHs and bulges.

§2. Formation of supermassive black holes

A radiation hydrodynamic model for the formation of SMBHs is recently proposed by Umemura (2001). In this model, the radiation drag extracts angular momentum from interstellar gas and allow the gas to accrete onto the center. For the total luminosity L_* of a bulge, the mass accretion rate is estimated to be

$$\dot{M} \simeq \eta_{\rm drag} \frac{L_*}{c^2}(1 - {\rm e}^{-\tau}), \tag{2·1}$$

where $\eta_{\rm drag}$ is the efficiency, c is the light speed and τ is the total optical depth. In an optically-thick regime, this gives simply $\dot{M} = \eta_{\rm drag} L_*/c^2$. Based on the numerical simulation by Kawakatu and Umemura (2002), $\eta_{\rm drag} = 0.34$ maximally. If $L_* \approx 10^{12} L_\odot$, this rate is comparable to the Eddington mass accretion rate for a black hole with $10^8 M_\odot$. The timescale of radiation drag-induced mass accretion is estimated to be

$$t_{\rm drag} \simeq 8.6 \times 10^7 {\rm yr} R_{\rm kpc}^2 \left(\frac{L_*}{10^{12} L_\odot}\right)^{-1} \left(\frac{Z}{Z_\odot}\right)^{-1}, \tag{2·2}$$

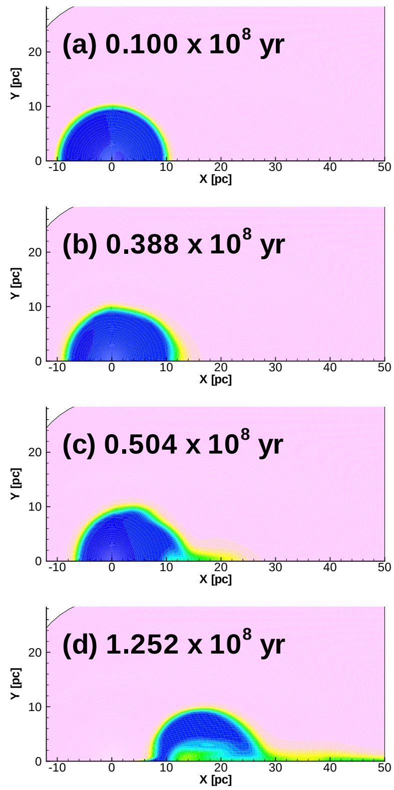

Fig. 1. Simulation of gas stripping by radiation drag. Density distributions are shown at each epoch. The density range is from 3.5×10^{-23} to 5.3×10^{-21}g cm^{-3}. It is shown that the optically-thin surface layer is stripped from an optically thick cloud and loses angular momentum.

where $R_{\rm kpc} = R/{\rm kpc}$ is the galaxy radius and Z is the metallicity of gas. Due to the mass accretion induced by the radiation drag, a massive dark object forms at the center of bulge, eventually evolving into a SMBH. Then, the mass of SMBH is estimated in terms of

$$M_{\rm BH} = \int_0^t \dot{M} dt \simeq \int_0^t \eta_{\rm drag} \frac{L_*}{c^2}(1 - {\rm e}^{-\tau}) dt. \tag{2·3}$$

In practice, optically-thin surface layers are stripped from optically-thick clumpy clouds by the radiation drag. The stripped gas loses angular momentum and therefore accretes onto the center (Sato et al. 2004). In Fig. 1, the results of numerical simulations on the gas stripping from an optically-thick cloud are demonstrated.

In this radiation hydrodynamic mechanism for BH formation, $f_{\rm BH}$ is tightly correlated with a bulge even in a disk galaxy (Kawakatu and Umemura 2004).

§3. Coevolution of SMBH and Bulge

Here, we construct a picture of the coevolution of SMBH and bulge based on the present mechanism for SMBH formation. In order to incorporate the chemical evolution of host galaxy, we use an evolutionary spectral synthesis code 'PEGASE' (Fioc and Rocca-Volmerange 1997), and also employ a galactic wind model with the wind epoch of $t_{\rm win} = 7 \times 10^8$yr to match the present-day color-magnitude relation. The system is assumed to change from optically-thick to optically-thin phase at $t_{\rm win}$.

At a time $t_{\rm cross}$, all the accreted materials are swallowed by the central BH. The resultant BH fraction becomes $f_{\rm BH}/ \simeq 0.001$, which is just comparable to the observed ratio. The accretion luminosity, $L_{\rm AGN}$, exhibits a peak at $t_{\rm cross}$, it fades out abruptly due to exhausting the fuel. The fading nucleus could be a low luminosity AGN (LLAGN).

It is found that the era of $t_{\rm win} < t < t_{\rm cross}$ 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. The 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, while the host-dominant phase is obviously different from observed QSOs so far. We define this phase as "a proto-QSO" (Kawakatu and Umemura 2003). The observable properties of proto-QSOs are predicted as follows: (1) The width of broad emission line is narrower, which is less than 1500 km/s. (2) $f_{\rm BH}$ rapidly increases from $10^{-5.3}$ to $10^{-3.9}$ in $\approx 10^8$ years. (3) The colors of $(B - V)$ at rest bands and $(V - K)$ at observed bands are about 0.5 magnitude bluer than those of QSOs. (4) In both proto-QSO and QSO phases, the metallicity of gas in galactic nuclei is $Z_{\rm BLR} \simeq 8Z_\odot$, and that of stars weighted by the host luminosity is $Z_* \simeq 3Z_\odot$. Such metallicity is consistent with the observations for QSOs and 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 quite similar to those of radio galaxies at high redshifts. Thus, high-z radio galaxies are a key candidate for proto-QSOs.

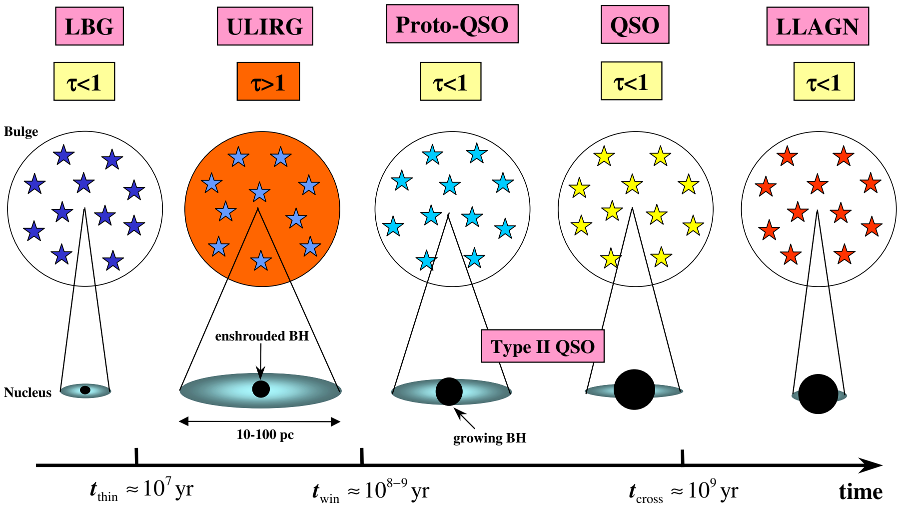

Fig. 2. Schematic sketch for the coevolution of SMBH and bulge.

The proto-QSO phase is preceded by a bright and optically thick phase, which may correspond to a ultraluminous infrared galaxy (ULIRG) phase. Also, the precursor of ULIRGs is an optically-thin and very luminous phase with the lifetime of $\sim 10^7$ years. This may correspond to the assembly phase of LBGs or Lyα emitters. In this phase, 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 $L_{\rm x} = 0.1 L_{\rm AGN}$. Such a coevolution scenario of a SMBH and the host is summarized in Fig. 2.

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