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$M_{\rm BH}-M_{\rm bulge}$ Correlation in AGNs: A Test of the Simple Unified Formation Scheme

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Abstract

A linear or non-linear property of the black hole (BH) to bulge mass correlation ($M_{\rm BH}-M_{\rm bulge}$) in Active Galactic Nuclei (AGNs) is intensively discussed recently, i.e. whether Seyfert galaxies follow the same relation as that of QSOs. This is not a question of the generality of this correlation, but an important test of the unified formation scheme of these two classes of AGNs. We present here a theoretical interpretation for $M_{\rm BH}-M_{\rm bulge}$ relation in AGNs and discuss a possibilty that a broad distribution of the ratio could be due to different velocity dispersion of the accreting gas from different environment or formation mechanism of their host galaxies. The mass ratio in bright QSOs is probably a limit case of BH evolution by merger enhanced accretion close to Eddington limit.

1.1 Introduction

A mass correlation of central BHs and their spheroids ~ 0.002 (within a factor of three) is suggested by Hubble Space Telescope and various ground-based CCD photometries of early type galaxies. The near-IR images of quasar hosts and the emission line measurements of Broad Line Region for bright QSOs present a similar correlation, which supports the speculation of an evolutionary linkage between the early active QSO phase and the central BHs in normal galaxies. Considering various observations, Wang & Biermann (1998) proposed a possible formation scenario for early type galaxies which are the products of major mergers between two comparable disk galaxies; the violent collision could destroy the original stellar disks and form the spheroidal component of merging galaxies after the relaxation; help to release the angular moment of the cold gas outside and drive them inwards; the starburst and QSO accretion in the central region will compete for the gas supply, feedback and drain the cold gas in a short time; possibly grow a supermassive BH during the spheroid formation, blow up the gas left probably by the nuclear wind when the central engine gets to be powerful enough; thus restrict the BH mass and the mass of the stellar component to a ratio of $\sim 10^{-3}$.

The model results show that the star formation approximately scales with the nuclear accretion during galaxy interactions, which can regulate $M_{\rm BH}-M_{\rm bulge}$ mass ratio to the observed level ~ 0.002 within a factor of three. In this scenario, a quasar BH is possibly formed at a cosmic time scale of $\sim 10^9$yr, corresponding to $z = 3 \sim 5$ in a flat Einstein-de Sitter world model with $\Omega = 1, H_0 = 50\,{\rm km\,s^{-1}\,Mpc^{-1}}$. Afterwards, when the quasar active phase has ceased and the spheroidal system gets relaxed in a comparable relaxation time scale, an elliptical or spiral bulge harboring a massive BH in the center with the mass in a factor $\sim 10^{-3}$ of the host spheroid may appear in the universe. We should mention the BH evolution in this model is assumed to reach the Eddington limit provided sufficient gas in the center.

However, recent studies of a combined sample of Seyfert 1 galaxies and bright QSOs suggests a non-linearity or a broad distribution of $M_{\rm BH}-M_{\rm bulge}$ mass ratio (Wandel 1999, Laor 2001). The mass ratio in Seyfert 1 galaxies is about one magnitude lower than the value in early type galaxies and bright QSOs. Although this discrepancy may in part be explained by systematic errors and selection or orientation effects, a significant difference probably remains, at least for the medium-bulge systems with masses similar to those of Seyferts (Wandel 2001). We present here a theoretical model to interpret the $M_{\rm BH}-M_{\rm bulge}$ correlation in AGNs, and discuss the dispersion of this ratio in QSOs and Seyferts within a simple unified formation scheme, where the bulge formation and nuclear activity are triggered by galaxy mergers or tidal interactions. We propose that different velocity dispersion of accreting gas could cause a range of distribution for the ratio, leading to a correlation of the nuclear BH mass and the gas velocity dispersion roughly as $M_{\rm BH} \propto v_{\rm e}^{4.7}$, within the slope suggested by recent work of Ferrarese & Merritt (2000) and Gebhardt et al. (2000).

1.2 $M_{\rm BH}-M_{\rm bulge}$ Correlation in AGNs, Model and Calculation

Within a unified formation scheme, QSOs and Seyferts are probably the products of galaxy mergers or tidal interactions. For Seyfert galaxies, the tidal perturbation of some satellites not only kinematically heat and thicken the host disks to form the central bulge, but may increase the self-gravity in the molecular disk and enhance the cloud-cloud collision. This can trigger the nuclear starburst and a considerable mass inflow to the central region on a relatively short time (Lin et al. 1988, Quinn et al. 1993, Walker et al. 1996, Veláquez & White 1999). Although we consider in our model the tidal interactions as a formation scheme for most Seyferts, we do not reject a possibility that some of AGNs with low $M_{\rm BH}-M_{\rm bulge}$ mass ratio could still be major mergers, but at the earlier evolutionary phase in which the BHs have not had time to reach the asymptotic value.

We adopt $\Sigma(R) = \frac{\Sigma_0 R_0}{R}$ as the initial surface density of protogalaxies with typical mass of $10^{11} M_\odot$ and disk scale of ~ 14 kpc, similar as the size of our Galaxy. The evolution of the surface density $\Sigma(R,t)$ of a differentially rotating disk with angular velocity Ω and viscosity ν is governed by (Lüst 1952, Pringle 1981)

$$\frac{\partial \Sigma}{\partial t} = -\frac{1}{R}\frac{\partial}{\partial R}\left\{\left[\frac{\partial (R^2\Omega)}{\partial R}\right]^{-1}\frac{\partial}{\partial R}\left(\nu \Sigma R^3 \frac{\partial \Omega}{\partial R}\right)\right\} - \frac{\Sigma}{t_*}(1-R_{\rm e}) \tag{1.1}$$

where $\nu = \beta_1 v_\phi r$ for a Keplerian selfgravitating disk (Duschl et al. 2000); the accretion time scale $t_{\rm acc} = r^2/\nu = r/\beta_1 v_\phi$; and the star formation time scale $t_* = \alpha t_{\rm acc} = \beta_2 r/v_\phi$ (Pringle 1981). Σ/t_* is the star formation rate in the disk with mass return rate $R_{\rm e} \sim 0.3$ (Tinsley 1974). In this case, the mass influx at the inner boundary $R_{\rm in}$ is $\mathrm{F} = 2\pi\beta_1 \mathrm{V}_0 \left[2\mathrm{R}\Sigma + \mathrm{R}^2 \frac{\partial \Sigma}{\partial \mathrm{R}}\right]_{\mathrm{R_{in}}} = 2\pi\beta_1 \mathrm{V}_0 \Sigma_0 \mathrm{R}_0$. We adopt $v_\phi \propto V_0$ for a flat rotation law for the protogalaxies in our calculation with $V_0 = 100\,\mathrm{km/s}$ as a normalization velocity. The justification of such simplification for a self-gravitating disk at parsec to kiloparsec region is discussed in detail by Wang & Biermann (1998).

The spheroidal Bondi accretion rate is given by $\dot{m} = 4\pi\lambda\rho R_{\rm acc}^2 v_{\rm e}$, where $R_{\rm acc}$ is the Bondi accretion radius defined as $R_{\rm acc} = \frac{GM_{\rm BH}}{v_{\rm e}^2}$ ($M_{\rm BH}$ is the mass of the central BH; $v_{\rm e}$ the effective relative velocity between seed BH and the ambient gas) (Bondi 1952). In the calculation, we start from a tiny BH $\sim 5M_\odot$, with the inner boundary of the accretion disk $R_{\rm in} \sim 0.1$pc which is usually thought to be the inner edge of a torus. At early time, $R_{\rm in} >> R_{\rm acc}$, we assume the mass shears inwards at the inner radius to form a uniform Bondi flow with the mass distribution $\frac{\triangle\rho(r)}{\triangle t} = \frac{2\pi\beta_1 V_0\Sigma_0 R_0}{4/3\pi R_{\rm in}^3}$ ($\triangle t$ is the time step of the calculation); afterwards, BH would grow and reach a stage of $R_{\rm acc} > R_{\rm in}$, we assume in this case BH accretes the mass shearing inwards within its influence at $R_{\rm acc}$ via a uniform Bondi flow with the mass distribution $\frac{\triangle\rho(r)}{\triangle t} = \frac{2\pi\beta_1 V_0\Sigma_0 R_0}{4/3\pi R_{\rm acc}^3}$.

The Bondi parameter is assumed to be $\lambda = 1/2$ as a possible reduction factor due to the angular momentum. Thus the accretion rate $\dot{m}$ and the star formation rate Ψ in a time step $\triangle t$ is given by:

$$\dot{m} = \begin{cases} 3\,\lambda\,\beta_1\,V_0\,2\,\pi\,\Sigma_0\,R_0\,G^2\,M_{\rm BH}^2/R_{\rm in}^3\,v_{\rm e}^3 & \text{if } R_{\rm acc} < R_{\rm in} \\ \\ 3\,\lambda\,\beta_1\,V_0\,2\,\pi\,\Sigma_0\,R_0\,v_{\rm e}^3/GM_{\rm BH} & \text{if } R_{\rm acc} > R_{\rm in} \end{cases} \tag{1.2}$$

$$\Psi = \int_{R_{\rm in}}^{R_{out}} 2\pi\, r\, dr\, \frac{\Sigma}{t_\star} = \frac{(1-R_e)\,2\pi\Sigma_0 R_0\,V_0}{\beta_2}\, ln(R_{out}/R_{\rm in}) \tag{1.3}$$

From Eq. (1.2), we know the accretion rate $\dot{m} \propto 1/M_{\rm BH}$ when $R_{\rm acc} > R_{\rm in}$, which indicates that the nuclear activity would dim slowly as the central BH becomes massive enough. In this case, a critical BH mass would be reached when the nuclear accretion rate decreases to a level below Eddington rate $\dot{m}_{\rm edd} = 2.16\,10^{-4}\,(M_{\rm BH}/M_\odot)$ in units of $t_0 \sim 10^4$yr. Assuming $\dot{m} \sim \dot{m}_{\rm edd}$, we get an upper limit of the BH mass $\sim 2.6\,10^7 M_\odot$, with $v_{\rm e} \sim 50$km/s and $\beta_1 \sim 0.05$ corresponding to the viscous diffuse time scale of $\sim 10^9$yr (we will discuss these particular parameters later). Afterwards, the accretion rate would decrease quickly to be much less than Eddington rate, and the BH will not grow significantly. We say this is an upper limit, simply because we use the initial surface gas density $\Sigma(R) = \frac{\Sigma_0 R_0}{R}$ throughout the estimation. In this case, the BH growth would be locked up in a level of $\sim 10^7 M_\odot$ if there is no extra trigger for the nuclear accretion, such as mergers or tidal effects. We adopt $\beta_1\,\beta_2 \sim 1$ providing a unified formation scheme of AGNs, the critical BH mass $\sim 2.6\,10^7 M_\odot$ and $v_{\rm e} \sim 50$km/s as inputs to Eq. (1.2), a mass ratio about 0.001 would be approched. Choosing $v_{\rm e} \sim 50$km/s is based on the observations by Zylka et al. (1990) of molecular line emission in the central region of our Galaxy with the assumption that the velocity field of molecular clouds would be the low limit of the sound speed of hot gas (Linden et al. 1993, Garcia-Munoz et al. 1977, Reynolds 1989, 1990). We know from Eq. (1.2) and the numerical calculation, the variation of the velocity dispersion of accreting gas, $v_{\rm e}$, would cause a broad distribution of $M_{\rm BH} - M_{\rm bulge}$ correlation, which is actually shown by the observations. The ratio could reach ~ 0.06 when $v_{\rm e} \sim 180$km/s, close to the virial velocity of QSO hosts. We should mention the range ($0.001 \sim 0.06$) of $\frac{M_{\rm BH}}{M_{\rm bulge}}$ is a crude upper limit, since we could not include the surface density evolution in this estimation.

To numerically solve the partial differential Eq. (1.1), we introduce the dimensionless variables, $r' = r/r_0$, $t' = t/t_0$, $\Sigma' = \Sigma/\Sigma_0$ with the scale $r_0 = 1$pc, $t_0 \sim 10^4$yr. The general boundary conditions $lim_{r\to R_{out}}[\Sigma(r,t)] = 0$, and zero torque at the origin, $lim_{r\to R_{\rm in}}[G(r,t)] = 0$. The viscous torque G is given by Pringle (1981) as $G(r,t) = 2\pi\nu\Sigma R^3\frac{\partial\Omega}{\partial R}$, with the disk's outer radius $R_{out} \sim 14\,\mathrm{kpc}$ and the inner radius $R_{\mathrm{in}} \sim 0.1\,\mathrm{pc}$. This choice of boundary conditions guarantees zero viscous coupling between the disk and the central object, allows all mass reaching the inner boundary to flow freely inward.

We model the effects of a tidal perturbation in a few kpc region by increasing the viscous friction. In fact, Lin et al. (1988) demonstrated that a tidal disturbance could propagate to the nucleus from a distance of a few kpc on a time scale shorter than the tidal interaction by "swing amplication", which induces a rapid increase in the effective viscosity and results in an increase in the rate of mass transfer and energy dissipation. The viscous diffuse time scale is $\sim 10^9$yr ($\beta_1 \sim 0.05$) in case of a tidal perburbation according to Lin et al. (1988). In this case, $\beta_2 \sim 20$ ($\beta_1 beta_2 \sim 1$), corresponding to a star formation rate $\sim 10 M_{\odot}/\mathrm{yr}$ in the central disk, which is at a reasonable level for the observed star formation rate in Seyferts. The initial seed BH in our model is tiny $\sim 5 M_{\odot}$. We know from the estimation that the BH grows by a rate $\propto M_{\mathrm{BH}}^2$ at the beginning till $R_{\mathrm{acc}} \sim R_{\mathrm{in}}$; afterwards, the accretion rate would decrease by $1/M_{\mathrm{BH}}$ and only a mediate BH of $\sim 10^6 M_{\odot}$ can be formed if there is no external trigger. In this case, a tidal perturbation around $5\,10^9\,\mathrm{yr}$ could help to grow a massive BH, which corresponds to $z \sim 0.8$ in an Einstein-de Sitter Universe with $\Omega = 1, H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Although the parameters, such as initial BH mass, the inner boundary of the accretion disk etc. could have certain influence on the finally ratio, we notice from the calculation and the illustrative estimation that velocity dispersion of the accreting gas is a key parameter besides the value of $\beta_1\beta_2$, which could cause a large dispersion of $M_{\mathrm{BH}} - M_{\mathrm{bulge}}$ in AGNs. Numerical calculation gives a rough proportionality of $M_{\mathrm{BH}}/M_{\mathrm{bulge}} \propto v_{\mathrm{e}}^{1.4}$. If the masses of the spheroidal systems scale with their luminosities as $M \propto L^{5/4}$ and the scale length $r \propto L^{1/2}$, we get the bulge velocity dispersion $\sigma^2 \propto \frac{M}{r} \propto \frac{M}{L^{1/2}} \propto \frac{M}{M^{2/5}} \propto M^{3/5}$ in a virial system (Faber & Jackson 1976, Faber et al. 1987, Peterson 1997). So, we obtain $M_{\mathrm{bulge}} \propto \sigma^{3.3}$. The assumption that the velocity dispersion of accreting gas is systematically proportional to the stellar velocity dispersion gives a correlation of $M_{\mathrm{BH}} \propto v_{\mathrm{e}}^{4.7}$, which is shallower than the slope of $M_{\mathrm{BH}} \propto \sigma^{5.2}$ given by Ferrarese & Merritt (2000), but steeper than the best-fit correlation ($M_{\mathrm{BH}} \propto \sigma^{3.75}$) by Gebhardt et al. (2000). It shows that variation of the velocity dispersion of accreting gas would cause a broad distribution of $M_{\mathrm{BH}} - M_{\mathrm{bulge}}$ correlation, where the accreting gas with higher velocity dispersion could lead to an accretion near Eddington limit, and form more massive BHs in QSOs. Therefore, $M_{\mathrm{BH}} - M_{\mathrm{bulge}}$ correlation in massive systems is close to an upper limit and much tighter than that in medium-bulges. The possible interpretation of a discrepancy in Seyferts and QSOs could be due to the different formation or evolution environments. The violent collision between two galaxies could trigger intense starburst i n the center, heat or shock the interstellar medium efficiently than tidal interaction, thus drive a Bondi flow fuelling the central BH with probably a higher sound speed and result in a higher accretion rate. In this case, it may enhance a QSO evolution with the accretion rate close to Eddington limit, form a massive BH, and lead to a ratio of M_{bh}/M_{bulge} higher than in case of Seyferts.

1.3 Summary

We present here a possible BH evolution scheme where BH accretes gas by a uniform Bondi flow. The numerical calculation gives a rough proportionality of $M_{\mathrm{BH}}/M_{\mathrm{bulge}} \propto v_{\mathrm{e}}^{1.4}$. Considering a virial equilibrium $M_{\mathrm{bulge}} \propto \sigma^{3.3}$, we get a relation $M_{\mathrm{BH}} \propto v_{\mathrm{e}}^{4.7}$, within the slope suggested by recent work of Ferrarese & Merritt (2000) and Gebhardt et al. (2000). It shows the mass ratio in such evolution scheme strongly depends on the velocity disper-

sion of the accreting gas. Within a simple unified formation scheme of AGNs, we think the intense starburst by violent mergers could heat or shock the interstellar medium (ISM) to a higher sound speed than by tidal interactions, result in a higher accretion rate close to Eddington limit and a higher ratio of $M_{\rm BH}/M_{\rm bulge}$ in QSOs and early type galaxies than in Seyferts. Thus, Wang & Biermann (1998) describes a limiting case for the BH evolution in QSOs, with the accretion close to Eddington limit.

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