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Unifying the Scaling Relations in Galactic Bulges – an Implication of Bulge Formation

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Author's contribution

This work was carried out by author CMH. Author CMH read and approved the final manuscript.

Research Article

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ABSTRACT

Aims: I present the derivation of some important scaling relations in galactic bulges by using a simple model of bulge formation.
Methodology: If the radiation pressure of the bulge suppresses its accretion of mass, together with the bulge luminosity-mass relation and the supermassive black hole (SMBH)- velocity dispersion relation, we can obtain a set of scaling relations such as those relating the mass of SMBH to bulge mass and luminosity, the Faber-Jackson and the fundamental plane relations.
Results: All these derived scaling relations agree with the empirical fittings from the observations.
Conclusion: All the scaling relations derived are consistent with the observational data. Therefore, the radiation pressure of the bulge provides a significant role to connect all the scaling relations together.

Keywords: Galaxies; galactic centre; supermassive blackholes; velocity dispersion.

1. INTRODUCTION

In the past decade, observations have led to some tight relations between the central supermassive blackhole (SMBH) masses MBH and the physical properties of bulges. A large

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number of the correlations have now been identified. The most spectacular correlation is linking the SMBH mass to velocity dispersion σ ($M_{BH} \propto \sigma^{\beta}$). The value of β has been estimated several times in the past 12 years: originally 3.75 ± 0.3 [1] and 4.80 ± 0.54 [2], then 4.02 ± 0.32 [3], and more recently 4.06 ± 0.28 [4], 4.24 ± 0.41 [5], 5.12 ± 0.36 [6] and 5.13 ± 0.34 [7]. These relations correspond to galaxies of all morphological types. One can separate the fittings into different groups such as the early-type and late-type galaxies. For example, McConnell et al. [6] obtain β = 4.53 and β = 4.58 for the early-type and late-type galaxies respectively if they are fitted separately. The slopes are shallower than the combined one (β = 5.12). Nayakshin et al. [8] suggest that the apparently large β may be due to the superposition of several $M_{BH} - \sigma$ relations for different galaxies vertically offset in mass. Therefore, the latest fitting indicates $\beta \approx 4.5$.

Other important correlations have also been demonstrated recently, such as those linking SMBH mass to host luminosity L_{bulge} ($M_{BH} \propto L_{bulge}^{0.9-1.2}$) [5,9,10] and bulge mass M_{bulge} ($M_{BH} \propto L_{bulge}^{0.7-1.1}$) [9,10,11,12]. In addition, some traditional relations such as the Faber-Jackson relation $L_{bulge} \propto \sigma^4$ [13] and the fundamental plane relation $R_e \propto \sigma^{1.24} I_e^{-0.82}$ [14] have been puzzling for many years, where R_e and I_e are the effective radius and the surface brightness within R_e respectively. Since these bulge properties are themselves correlated, it is not clear whether any one is in some sense more basic [15].

It is commonly believed that all the above relations may demonstrate a fundamental link between the galaxy formation and the growth of SMBH. The $M_{BH} - \sigma$ relation has been derived by recent theoretical models [8,16,17,18,19,20,21,22,23]. On the other hand, Power et al. [24] suggest a theoretical model to obtain $M_{BH} \propto \sigma^4$ and $M_{BH} \propto M_{bulge}$. However, recent empirical fittings from observations do not support these predictions [6,10]. Recent analysis based on observational data indicate that there exists some connections among the scaling relations [15,25,26], which may provide a useful ingredient to understand the bulge formation process. Therefore, a theoretical model is needed to account for all these inter-related scaling relations. Ciotti et al. [27] attempted to derive some scaling relations with the $M_{BH} - \sigma$ and the fundamental relation with old empirical fittings. However, it is not possible to derive all scaling relations from some more basic relations without any physical arguments or frameworks. For example, Renzini and Ciotti [28] deduced the mass to light ratio by using fundamental relation with an initial mass function (IMF). However, recent observations indicate that the IMF may have large deviations from universal in many galaxies [29,30]. Therefore, a universal theoretical physical framework should be considered in order to connect all the scaling relations together. In this article, I provide a theoretical framework, including a bulge formation model, to unify all the above scaling relations systematically. The derivations will be based on the galactic virial relation, the observed $M_{BH} - \sigma$ and $L_{bulge} - M_{bulge}$.

2. THE BULGE FORMATION MODEL

During the bulge formation, mass is falling into it and the gas in the bulge starts to form stars due to gravitational attraction. When stars in the bulge are ignited, the radiation pressure starts to suppress further accretion of mass into the bulge. The momentum imparted to the gas by radiation of luminosity L is given by $L(1 - e^{-\tau})/c$, where τ is the optical depth. During the bulge formation, τ is large due to the presence of dust and cold gas. Therefore, the momentum given by the radiation is simply L/c. Since the mean free path of a photon in the gas is $\lambda \sim \frac{mR_e^3}{M_{bulge}\sigma_T} \sim 0.1$ kpc $< R_e$, where m and σ_T are the mean mass of a gas particle and scattering cross section respectively, this momentum can be transferred throughout the galactic bulge by photons and collisions of gas particles. This gives the radial component of the equation of motion for gaseous matter:

$$\frac{d}{dt}\left[M_g(R)\dot{R}\right]+f\frac{GM_g(R)[M_{BH}+M_t(R)]}{R^2}=\frac{L(R)}{c} \tag{1}$$

where f is a parameter that depends on the density distribution, $L(R)$, $M_g(R)$ and $M_t(R)$ are the enclosed luminosity, gas mass and total mass profiles of the bulge respectively. Here, the total mass profile included stars, gas and dark matter in a galaxy. Also, the kinematics of the bulge may affect the density distribution, which have been account in the parameter$f$. Different values of f in different galaxies may give rise to the scatter in the empirical fittings. When the bulge luminosity is high enough, the falling of mass will be stopped when the radiation pressure is almost equal to the self-gravitational attraction ($\frac{d}{dt}M_g(R)\dot{R}=0$). Assuming $M_g \propto M_{bulge}$ and $M_{bulge} \gg M_{BH}$, and f are almost the same for all galaxies, the above equation becomes

$$\frac{GM_{bulge}^2}{R_e^2}\propto\frac{L_{bulge}}{c}, \tag{2}$$

where L_{bulge} is the bulge luminosity. Here, R_e is the effective radius from observations, which can be assumed to be directly proportional to the size of a galaxy. For some typical values of a galaxy, $L_{bulge}=10^{10}L_\odot$, $R_e=$ 1 kpc, $f=0.1$ and $M_g=0.1M_{bulge}$, we can get $M_{bulge}{\sim}10^{10}M_\odot$, which generally matches the typical value of bulge mass. Observational data shows that $L_{bulge}\propto M_{bulge}^{0.8}$ with a tight correlation (Fig. 1) [10,12,31,32]. Therefore, by Eq. (2), we have $R_e\propto M_{bulge}^{0.6}$. This result is closed to the empirical fitting $R_e\propto M_{bulge}^{0.67}$ by using the data from ref. [10] (Fig. 2).

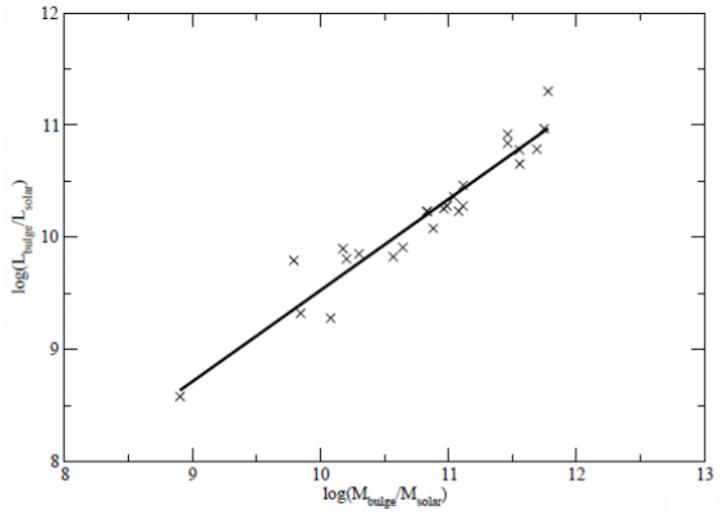

Fig. 1. The correlation between L$_{\text{bulge}}$ and M$_{\text{bulge}}$ of 25 early-type galaxies from ref. [12]. The best fit line is $\log\left(\frac{L_{bulge}}{L_\odot}\right)=(0.81\pm0.05)\log\left(\frac{M_{bulge}}{M_\odot}\right)+(1.4\pm0.5)$

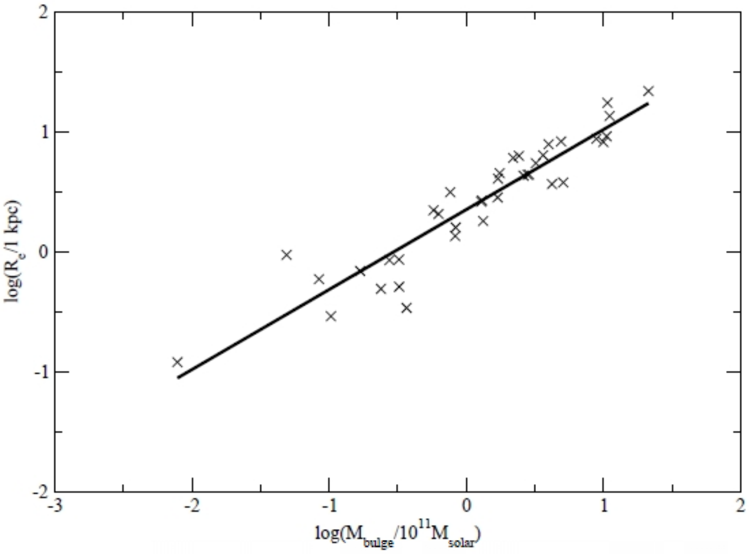

Fig. 2. The correlation between R_e and M_{bulge} of 38 early-type galaxies from ref. [10]. The best fit line is $\log\left(\frac{R_e}{1\,kpc}\right) = (0.67 \pm 0.04)\log\left(\frac{M_{bulge}}{10^{11}M_{\odot}}\right) + (0.35 \pm 0.03)$

3. THE SCALING RELATIONS OF GALACTIC BULGES

Magorrian et al. [11] first proposed the relation $M_{BH} \approx 0.006M_{bulge}$. Later the correlation becomes $M_{BH} \propto M_{bulge}^{\alpha}$, with α = 1.12 ± 0.06 [12], 0.9 ± 0.06 [9], 0.79 ± 0.09 [10] and 0.71−0.92 [33]. In general, the value of α is about 0.7 − 1.1.

By using the scaling relation obtained from the above section and the two well-known relations, the $M_{BH} - \sigma$ relation $M_{BH} \propto \sigma^{4.5}$ [6] and the virial relation $\sigma^2 = 5GM_{bulge}/R_e$ [10], we get

$$M_{BH} \propto \sigma^{4.5} \propto \left(\frac{M_{bulge}}{R_e}\right)^{\frac{4.5}{2}} \propto \left(\frac{M_{bulge}}{M_{bulge}^{0.6}}\right)^{\frac{4.5}{2}} \propto M_{bulge}^{0.9}. \tag{3}$$

Also, by using the virial relation and Eq. (2), we can get

$$L_{bulge} \propto \left(\frac{M_{bulge}}{R_e}\right)^2 \propto \sigma^4, \tag{4}$$

which is the well-known Faber-Jackson relation [13]. Besides, by substituting $L_{bulge} \propto M_{bulge}^{0.8}$ into Eq. (3), we can get another scaling relation:

$$M_{BH} \propto L_{bulge}^{\frac{0.9}{0.8}} \propto L_{bulge}^{1.1}, \tag{5}$$

The results in Eqs. (3)-(5) give excellent agreements with the observed fittings $M_{BH} \propto M_{bulge}^{0.9}$ [9], $M_{BH} \propto L_{bulge}^{1.1}$ [5] and the Faber-Jackson relation $L_{bulge} \propto \sigma^4$ [13].

Apart from the simple relations between the SMBH and the bulge properties, some fundamental plane relations have been reported relating M_{BH}, R_e, σ and I_e. The earliest robust fundamental plane relation is in the form $R_e \propto \sigma^a I_e^b$. Dressler et al. [34] obtain the kinematic and photometric data for 97 elliptical galaxies and get (a, b) = (1.325,−0.825). Later Jørgensen et al. [14] analyze a sample of 226 early-type galaxies and find (a, b) = (1.24,−0.82). The surface luminosity profile of a galaxy can be mostly described by the Sérsic's empirical formula [35]:

$$I(R) = I_e e^{-\gamma\left[\left(\frac{R}{R_e}\right)^{\frac{1}{n}}-1\right]}, \tag{6}$$

where n is called the Sérsic's index and ≈ 1.999n − 0.327. The total luminosity can be obtained by

$$L_{bulge} = \int_0^\infty 2\pi R I(R) dR = (2n)!\,\pi\gamma^{-2n} e^{\gamma} R_e^2 I_e \approx 3.75 n^{0.48} \pi R_e^2 I_e. \tag{7}$$

Since L_{bulge} is a slow function of n and most n fall in the range 2 − 6 [36], we can write $L_{bulge} \propto R_e^2 I_e$. Since $L_{bulge} \propto M_{bulge}^{0.8}$, we get

$$I_e \propto L_{bulge} R_e^{-2} \propto M_{bulge}^{0.8} R_e^{-2} \propto (\sigma^2 R_e)^{0.8} R_e^{-2} \propto \sigma^{1.6} R_e^{-1.2}. \tag{8}$$

Rearranging the above equation, the derived fundamental plane relation is given by

$$R_e \propto \sigma^{1.3} I_e^{-0.83}. \tag{9}$$

The above result agrees with the empirical fitting (a, b) = (1.24 ± 0.07,−0.82 ± 0.02) [14].

Another tight fundamental plane relation is given by $M_{BH} \propto \sigma^u R_e^v$. Hopkins et al. (2007) get (u, v) = (3.0 ± 0.3, 0.43 ± 0.19). By starting from the product $\sigma^3 R_e^{0.5}$ and using the results $R_e \propto M_{bulge}^{0.6}$ and $M_{BH} \propto M_{bulge}^{0.9}$ in the previous section, we have:

$$\sigma^3 R_e^{0.5} \propto \sigma^3 M_{bulge}^{0.3} \propto \sigma^3 M_{BH}^{\frac{0.3}{0.9}} \propto M_{BH}^{\frac{3}{4.5}} M_{BH}^{\frac{0.3}{0.9}} \propto M_{BH}. \tag{10}$$

Therefore, the derived fundamental plane relation is $M_{BH} \propto \sigma^3 R_e^{0.5}$, which again agrees with the empirical fitting [15]. Moreover, since $M_{BH} \propto \sigma^{4.5}$, we can get a relation $M_{BH} \propto R_e^{1.5}$, which also agrees with the observation $M_{BH} \propto R_e^{1.33\pm0.25}$ [15].

4. RESULTS AND DISCUSSION

In this article, I present the derivation of some important scaling relations of galactic bulges by using a simple model of bulge formation. This model assumes that the radiation from the ignited stars suppresses the mass from falling into the bulge. Together with the $M_{BH} - \sigma$ relation, the $L_{bulge} - M_{bulge}$ relation and the virial relation in the bulge, all the results $M_{BH} \propto M_{bulge}^{0.9}$, $M_{BH} \propto L_{bulge}^{1.1}$, $L_{bulge} \propto \sigma^4$, $R_e \propto \sigma^{1.3} I_e^{-0.83}$ and $M_{BH} \propto \sigma^3 R_e^{0.5}$ are consistent with each other and can be obtained naturally. All the above scaling relations agree with the empirical fittings from observational data. Therefore, the unification and consistency of these relations indicate the stars in each galaxy play a crucial role in the bulge formation. This universal theoretical framework brings all the scaling relations together to make a consistent picture. Furthermore, this result favours the dissipative collapse model in galaxy formation. The free-fall time scale will be much longer because of the bulge luminosity so that the gas may have longer time to radiate its energy away. As a result, the time for galaxy formation would be much longer than that expected before. Also, the radiation pressure should be considered in galaxy evolution numerical simulations. On the other hand, if galaxies were formed by merging process, the gas mass would be continuously supplied to the galaxies so that equilibrium can no longer be reached. All the scaling relations derived here would be incorrect. Therefore, our results do not support the merger to be the major mechanism in galaxy formation.

MacMillan and Henriksen [18] suggest a simple model to explain the $M_{BH} - \sigma$ relation. They assumed that the density and velocity distributions of matter are self-similar. The galaxy is formed by the extended collapse of a halo composed of collisionless matter. In this model, β depends strongly on the index of the primordial matter power spectrum n′. When n′ = −5/3, β = 4.5. If it is true, then we have a general picture of the bulge formation. When a seed black hole is formed at the galactic center, it grows and accretion of mass occurred. When the growth rate is large enough, the SMBH may enter a super-Eddington accretion stage [37]. The mechanism suggested by MacMillan and Henriksen [18] relates MBH with the kinetic properties of the bulge. After that, when most of the stars in the bulge are ignited, the strong outward radiation stops the mass from falling into the bulge. Finally, the bulge is formed and its radius is defined. Since the kinetic properties of the bulge depend on its radius and mass, all the physical properties of the bulge are thus correlated to MBH. As a result, the size, mass, surface brightness, and luminosity of a galactic bulge can uniquely determine the black hole's mass.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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