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Relation between $M_{\rm BH}$ and $M_{\rm bulge}$: A Simulation Study

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Abstract

The dynamical evolution of super star clusters (SSCs) moving in the background of a dark matter halo has been investigated as a possible event responsible for the observed correlation between the mass of galactic bulge, $M_{\rm bulge}$, and the mass of its central black hole, $M_{\rm BH}$. The underlying physical processes include sinking of SSCs due to the dynamical friction, and stripping of SSCs on their way to the center. Model calculations show that only sinking of circumnuclear SSCs contributes to both the growth of the central dark object and the formation of the galactic bulge at the early stage. Based on the assumption of a universal density profile for the dark matter halo, and an isothermal model for the SSCs, our simulations have yielded the mass ratio of the central dark objects to the bulges to be about a few times 10^{-4}, consistent with the observed $M_{\rm BH}/M_{\rm bulge}$ for late-type spirals, such as M33.

1.1 Introduction

Recent observations with unprecedented high resolution have firmly established that many galaxies, whether active or not, host supermassive black holes (SMBHs) in their centers. These observations have revealed correlations of the mass of the SMBHs to their bulge luminosity (or mass), or to the luminosity-weighted line-of-sight velocity dispersion within the effective radius with much smaller scatter. The median black hole (BH) mass is 0.13% of the bulge mass (Kormendy & Gebhardt 2001) for early type galaxies, or much smaller for M33, a late-type spiral (Gebhardt et al. 2001).

The correlation between $M_{\rm BH}$ and $M_{\rm bulge}$ implies that the growth of the central BH and the bulge formation are probably caused by a same physical process. Recent discoveries may indicate the role of SSCs in this event. The one is the discovery of the presence of a BH with intermediate mass (IMBH) in a young SSC located at some distance from the nucleus of M82. The other is another IMBH found in an evolved SSC located in the nucleus of M33. These discoveries imply that the physical process causing the $M_{\rm BH}-M_{\rm bulge}$ relation might be related to the evolution of SSCs.

Motivated by these observations, we report our study on the dynamical evolution of circumnuclear SSCs moving in the dark matter halo as a possible process for the observed $M_{\rm BH}-M_{\rm bulge}$ relation of late-type galaxies.

Table 1.1. *Parameters of the chosen NFW halos*

$M_{200}(M_\odot)$	$r_{200}(kpc)$	c	$a_h(kpc)$	$M_{0h}(M_\odot)$
$10^{12}h^{-1}$	216.8	8.5	25.5	7.8×10^{10}
3×10^{11}	131.9	10	13.2	1.6×10^{10}

1.2 Models

1.2.1 SSC model

Based on the analogy with globular clusters (GCs), we assume that SSCs have a similar mass spectrum as the initial GC mass function but with larger mean value. According to Vesperini (2000,2001), we adopt the log-normal mass function as SSCs' mass function (SSCMF)

$$Log_{10}(\frac{M}{M_\odot}) \sim N(\exp(mean) = 2 \times 10^6 M_\odot, variance = 0.08) \tag{1.1}$$

Considering the mean GC's mass of about $1-2 \times 10^5 M_\odot$, we may infer the mean SSC's mass of about $2 \times 10^6 M_\odot$.

1.2.2 Background

Considering the bulge-formation process in very late-type galaxies (Sd type and later) we only take a dark matter (DM) halo as the initial background. For the dark halo, we assume the universal density profile (Navarro et al. 1997, hereafter NFW), which can be written as (e.g., Binney & Merrifield, 1998)

$$\rho_h(r) = \frac{M_{0h}}{r(a_h + r)^2} \tag{1.2}$$

where r is the distance from the halo center.

We consider two halos with quite different masses: a large one with mass $M_{200} = 10^{12}h^{-1}M_\odot$ and a smaller halo with mass $M_{200} = 3 \times 10^{11} M_\odot$. The NFW halos are determined via the scaling law (see Table 1), with the Hubble constant $H_0 = 75$ kms^{-1}Mpc^{-1}, $h = 0.75$.

In order to account for the background variation caused by the fallen SSCs together with their stripped mass, we add a spherical component, represented by shells of equal density, which varies according to the changing SSC mass contribution.

1.2.3 Dynamical friction

We define M and $\vec{V}_M$ (with $V_M = |\vec{V}_M|$) equal to, respectively, the mass and velocity of cluster experiencing the dynamical friction. Assuming the background matter has a Maxwellian velocity distribution with dispersion σ_{bkgd}, and is composed of particles with mass much smaller than M, the dynamical friction formula may be written as (e.g., Binney & Tremaine, 1987)

$$\frac{d\vec{V}_M}{dt} = -\frac{2\pi \log(1+\Lambda^2) G^2 M \rho}{V_M^3}[\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}}\exp(-X^2)]\vec{V}_M \tag{1.3}$$

where erf is the error function. The readers are advised on referring to Binney & Tremaine (1987) about Λ *and* X.

1.2.4 Stripping

We assume that the stellar mass outside a sphere of radius R_t, which corresponds to the instantaneous Hill stability region around the SSC center, will be stripped. As a first-order approximation, the mass of the stripped stars is considered to be, at some later epoch, uniformly distributed in the shell bounded by $r+R_t(r)$ and $r-dr-R_t(r-dr)$. By summing up all of the stellar mass stripped at various rs, the stripped stellar mass distribution can be derived.

If a single massive object is embedded in the center of an SSC, stripping cannot proceeded further when only this object is left. Therefore, in our simulations, we consider two extreme cases: stripping is not allowed when the mass of the stripped SSC is less than $1M_\odot$ and $1000M_\odot$, respectively. The realistic situation should be somewhere in between these two cases. The SSCs' mass contributed to the galactic center, taken as a globe with radius 0.5 pc following the reverberation measurements in AGN, is supposed to be the upper mass limit of the central massive dark object (MDO).

1.3 Results

Figure 1.1 illustrates the predicted $M_{\rm MDO} - M_{\rm bulge}$ relation derived from our simulations with NFW density profiles. The solid lines denote the observed $M_{\rm BH} - M_{\rm bulge}$ relation for early-type galaxies, and the star symbols $M_{\rm MDO} - M_{\rm bulge}$ relation for late-type ones (Salucci et al. 2000). The model prediction of the median MDO mass is about a few times 10^{-4} of the bulge mass, consistent with the observed $M_{\rm BH} - M_{\rm bulge}$ mass ratio for M33 (Gebhardt et al 2001).

. Figure 1.2 shows the mean surface density profiles of simulated galaxies with high-density central components formed at 1 Gyr (with a proportion of about 65% and 90% for the larger and smaller halos, respectively).

The predicted mean surface density profiles are fit with a model, following Carollo & Stiavelli (1998), which is given by

$$\sigma(R) = \sigma_0 \exp(-1.678\frac{R}{R_e}) + \sigma_1 (1+\frac{R_c}{R})^\gamma \exp(-\frac{R}{R_s}) \tag{1.4}$$

Except at radii less than about 2 pc, the fittings shown in Fig. 1.2 are quite satisfactory. The half mass radii of the formed bulges are about 300pc, and the scale-sizes of the nuclear cusps are about 10pc , which are consistent with *HST* observations (Carollo 1999).

In order to see what could happen to the galaxies where no high-density central component is formed at 1 Gyr, we extend the simulations to 1.5 Gyr. The bulge formation rates are then increased to about 90% and 99% for the larger and smaller halos, respectively. The predicted $M_{\rm MDO} - M_{\rm bulge}$ relation, however, has not been changed much. This result implies that the proposed mechanism may be a viable mode responsible for the $M_{\rm BH} - M_{\rm bulge}$ relation, as well as for the bulge formation in very late-type spirals.

1.4 Discussion

Now more and more evidence seems to show (e.g. Marchesini et al. 2002 and the references therein) that the NFW profiles are not adequate for a fraction of dwarf galaxies

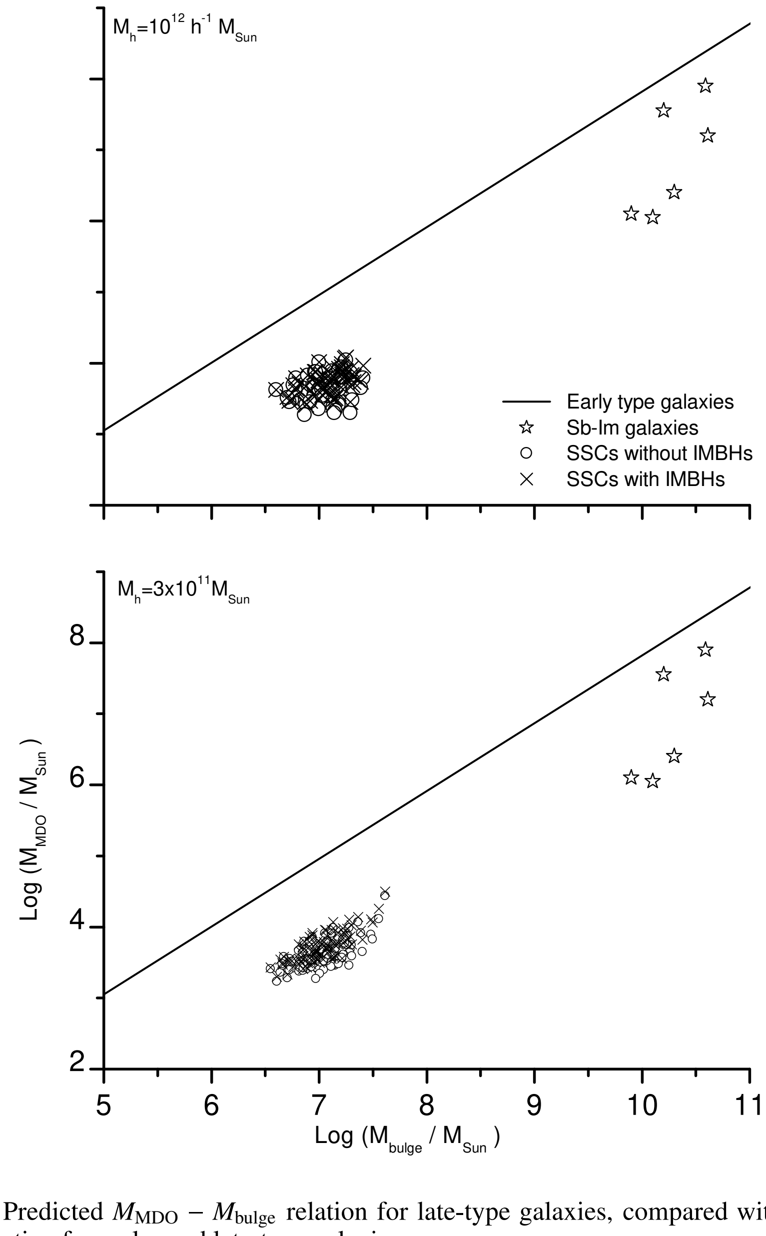

Fig. 1.1. Predicted $M_{\mathrm{MDO}} - M_{\mathrm{bulge}}$ relation for late-type galaxies, compared with the observed relation for early- and late-type galaxies.

which are dominated by the dark matter halos, and suggested that the Burkert profile is more

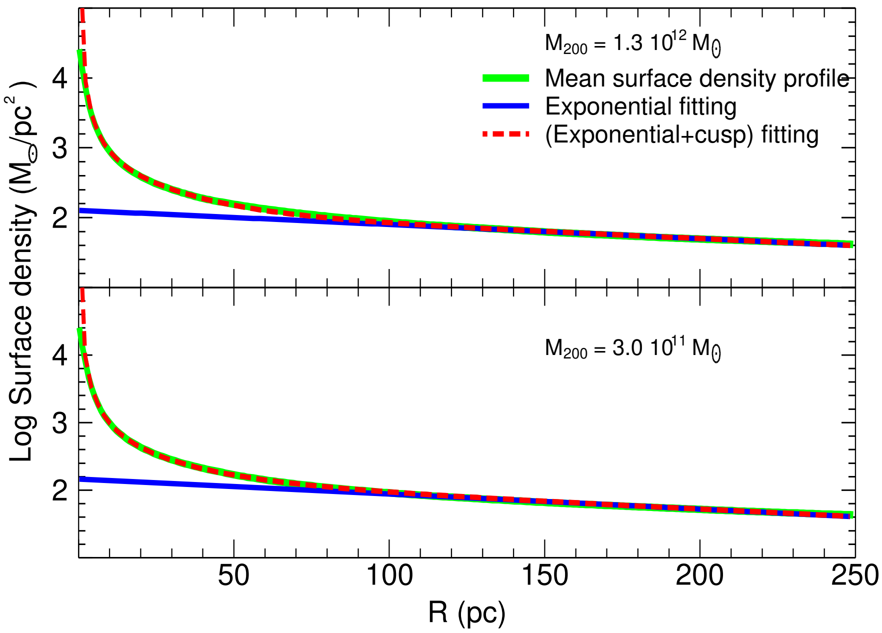

Fig. 1.2. Mean surface densities derived by SSCs without IMBHs for two DM density profiles adopted. The model fittings are illustrated with blue solid and red dashed lines

suitable to these galaxies. We would then take the Burkert density profile given below for our simulations.

$$\rho_{DM}(r) = \frac{\rho_o\, r_o^3}{(r+r_o)(r^2+r_o^2)} \tag{1.5}$$

The work of this kind has not been finished yet. One of our preliminary results is illustrated in Fig. 1.3, obtained with a central density of $0.10\ M_\odot\ pc^{-3}$. It is very instructive to notice that the exponential bulges with nuclear cusps formed in about 40% simulated galaxies, and a large fraction of dwarf spirals have no bulges and no nuclear cusps formed. In

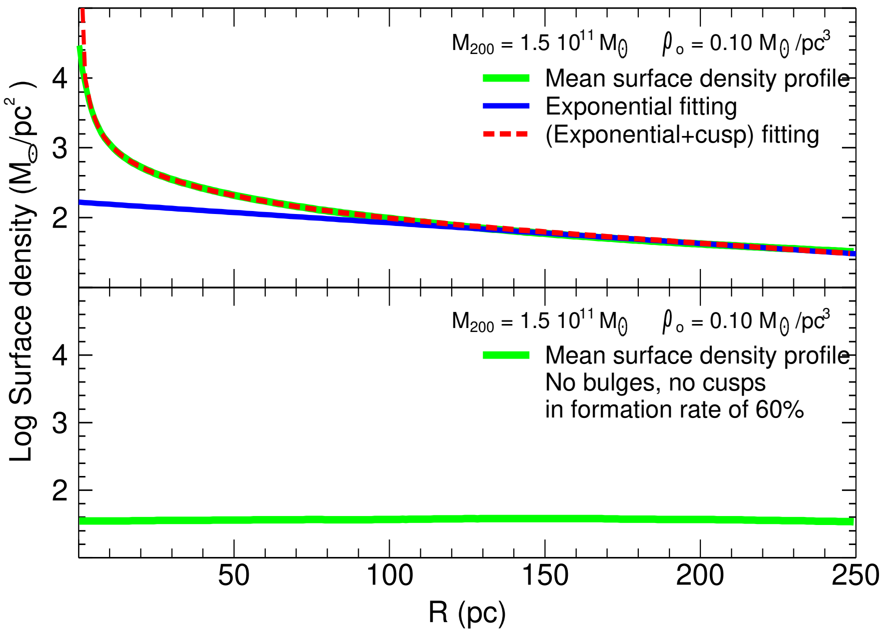

Fig. 1.3. Model fitting to the simulations with the Burkert density profiles

the former case, the predicted $M_{\rm MDO} - M_{\rm bulge}$ relation is about the same as that shown in the lower panel of Fig. 1.1, which will not be shown here due to the limited space.

In contrast to the case of NFW density profiles, shown in Fig. 1.2, the bulge formation rates yielded with the Burkert ones are obviously lower, which are basically in accordance with observations of vary late-type spirals (see, e.g. Carollo 1999; Matthews et al. 2002)

Nevertheless, we have to be cautious of the above claim. For one thing, the observed properties for galaxies with Hubble type of Sd or later are taken from a small sample of about 20 sources only. And more important is that the results obtained for the Burkert profiles are very preliminary. A detailed investigation on this topic is underway.

References

Binney, J., & Merrifield, M. 1998, Galactic Astronomy (Princeton: Princeton Univ. Press)
Binney, J., & Tremaine, S. D. 1987, Galactic Dynamics, (Princeton: Princeton Univ. Press)
Carollo, C. M., & Stiavelli, M. 1998, AJ, 115, 2306
Carollo, C. M. 1999, ApJ, 523, 566
Gebhardt, K., et al. 2001, AJ, 122, 2469
Marchesini, D., D'Onghia, E., Chincarini, G., Firmani, C., Conconi, P., Molinari, E., & Zacchei, A. 2002, ApJ, 575, 801
Matthews, L. D., & Gallagher, J. S., III 2002 ApJS, 141, 429
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Salucci, P., Ratnam, C., Monaco, P., & Danese, L. 2000, MNRAS, 317, 488
Vesperini, E. 2000, MNRAS, 318, 841
Vesperini, E. 2001, MNRAS, 322, 247