Size Evolution of Early-Type Galaxies and Massive Compact Objects as Dark Matter

Tomonori TOTANI
Department of Astronomy, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502
totani@kusastro.kyoto-u.ac.jp

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Abstract

The dramatic size evolution of early-type galaxies from \( z \sim 2 \) to 0 poses a new challenge in the theory of galaxy formation, which may not be explained by the standard picture. It is shown here that the size evolution can be explained if the non-baryonic cold dark matter is composed of compact objects having a mass scale of \( \sim 10^5 M_\odot \). This form of dark matter is consistent with, or only weakly constrained by the currently available observations. The kinetic energy of the dark compact objects is transferred to stars by dynamical friction, and stars around the effective radius are pushed out to larger radii, resulting in a pure size evolution. This scenario has several good properties to explain the observations, including the ubiquitous nature of size evolution and faster disappearance of higher density galaxies.

Key words: cosmology: dark matter — cosmology: theory — galaxies: evolution

1. Introduction

It has been well established that early-type galaxies were mostly built up before redshift \( z \sim 0.8 \) (e.g., Cirasuolo et al. 2007; Pozzetti et al. 2007). However, recent observations have revealed that passively evolving, early-type galaxies at higher redshifts (\( z \sim 1-2 \)) are surprisingly much more compact than the likely present-day descendants of the same stellar mass (e.g., Longhetti et al. 2007; Trujillo et al. 2007; Cimatti et al. 2008; Damjanov et al. 2009, hereafter D09). Such compact galaxies are not found in the local universe, and they must disappear (decrease in comoving number density by a factor > 5000, Taylor et al. 2009) by structural evolution, meaning that the evolution must occur ubiquitously, rather than stochastically, for all such galaxies. In the plane of \( M_\star - r_e \) (total stellar mass and the effective radius including half of the projected light), they must be “puffed up” with a typical size increase by a factor of 2–3 (a factor of more than 10 in stellar density) to move into the region populated by the present-day galaxies, without any significant increase in the stellar mass (figure 1). Furthermore, this evolutionary process seems to work in a broad context of galaxy formation spanning wide ranges of mass, radius, and redshifts (D09).

This size evolution problem thus presents a new major challenge for the theory of galaxy formation and evolution. Several scenarios have been proposed, but none of them has convincingly explained it. Here, a new scenario is proposed that may contribute to solve the problem. It is assumed that the dominant component of the non-baryonic cold dark matter in the universe is dark compact objects (DCOs), like primordial black holes (PBHs) or substructures in dark haloes, having a mass scale of \( M_\star \sim 10^5 M_\odot \). This possibility has not yet been excluded by currently available observations (see section 4).

In section 2, previously proposed scenarios for this problem and their potential difficulties are briefly reviewed. A new scenario concerning this work will be described in section 3, followed by some discussions in section 4 and section 5.

2. Proposed Scenarios for the Size Evolution

Dissipationless “dry” mergers of old stellar systems can increase galaxy sizes without new star formation activity, but the stellar mass should also be increased. Bezanson et al. (2009) argued that a mass increase with a scaling of \( M_\star \propto r_e \), which is expected in the case of major or equal-mass mergers, cannot solve the problem because it would violate the constraint from the stellar mass found in present-day early-type galaxies.

Minor dry mergers (\( r_e \propto M_\star^{2/3} \) in the limit of very large mass ratio) may be more helpful to solve this problem, as demonstrated by a simulation of Naab, Johansson, and Ostriker (2009). However, their simulation is only for one galaxy, and it must be further studied whether this scenario can explain the size evolution within the general context of galaxy formation (D09; Williams et al. 2009). All high-\( z \) compact galaxies must experience many minor mergers to gain a substantial mass and size increase, and they would all have to be dry to keep the old stellar population, which seems to be somewhat contrived. It should be noted that the largest mass (\( \sim 10^{12} M_\odot \)) of \( z \geq 1 \) galaxies in the D09 sample is already comparable with that of the local SDSS sample (see figure 1), and a further mass increase may contradict the data, even in the case of minor mergers. Theoretically, minor dry mergers should be effective for massive and high-redshift galaxies (Naab et al. 2009; Hopkins et al. 2009a), but the D09 data indicate that the required degree of size evolution is similar for galaxies in the mass range of \( M_\star \sim 10^{10.5-10.9} M_\odot \), and lower mass galaxies disappear faster at higher redshifts (figure 1). Nipoti, Treu, and Bolton (2009) have argued that constraints from gravitational lensing do not allow for any size evolution by more than a factor of \( \sim 1.8 \) by dry mergers, which seem too small to completely solve the size evolution problem.
A puffing up of galaxies by mass loss is another possibility, such as stellar mass loss (D09) or by quasar feedback (Fan et al. 2008). However, stellar mass loss is not satisfactory because of the small amount of mass loss and short time scales (D09). The physical process of quasar feedback is rather uncertain, and it seems to be difficult to puff up quiescent galaxies in a passive evolution phase after they have lost most of interstellar gas (Bezanson et al. 2009). It may require a significant fine-tuning to explain the ubiquitous size evolution by rather stochastic quasar feedback processes.

3. Size Evolution by DCOs

Various observations of nearby early-type galaxies based on stellar kinetics (e.g., Cappellari et al. 2006), X-ray emitting interstellar gas (e.g., Fukazawa et al. 2006), and strong/weak gravitational lensing (e.g., Gavazzi et al. 2007) have shown that stellar mass is dominant at inner radii, while dark matter dominates at outer radii, and the transition occurs at around the effective radius. Therefore, if there is a significant transfer of kinetic energy from dark matter to stars, it would puff up stars at $r \gtrsim r_e$, resulting in a pure-size evolution of the stellar component.

This energy transfer occurs by dynamical friction. When stars have a stellar mass density of $\rho_{\text{se}}$ and the Maxwellian velocity distribution with one-dimensional dispersion, $\sigma_{\text{se}}$, the dynamical friction timescale for a DCO having a velocity $V$ is given as follows (Binney & Tremaine 1987):

$$t_{\text{df}} \equiv \frac{V}{V} = \frac{V^3}{4\pi G^2 \ln \rho_{\text{se}} M_e B(X)} ,$$

where the function $B(X) \equiv \text{erf}(X) - 2 X e^{-X^2} / \sqrt{\pi}$ and $X \equiv V / \sqrt{2 \sigma_{\text{se}}}$. The Coulomb logarithm, $\ln \Lambda = \ln \left[ b_{\text{max}} V^2 / (G M_e) \right]$, becomes 13.74 and 7.60 if we take the maximum impact parameter $b_{\text{max}}$ to be 10 kpc (the galaxy scale) and $(\rho_{\text{se}}/M_e)^{-1/2}$ (the mean separation of DCOs), respectively, for typical values of $M_e = 10^5 M_\odot$, $V = 200$ km s$^{-1}$, and $\rho_{\text{se}} = 10^{10} M_\odot$ kpc$^{-3}$. In the following $\ln \Lambda = 10$ is adopted.

Since $t_{\text{df}}$ is strongly dependent on $V$, we should carefully take the effective mean about $V$. The total kinetic energy, $E \propto \int (M_e V^2/2) f(V) d^3V$, of DCOs will decrease by a factor of 1/2 in a time of $t_{1/2} \equiv E/(2 E)$, where $f(V)$ is the phase-space distribution function of DCOs. Assuming that the initial velocity distribution of DCOs is the same as that of stars, $t_{1/2}$ is found to be:

$$t_{1/2} = \frac{B(\sqrt{3}/2) \Gamma(5/2)}{3 \sqrt{6} \int_0^\infty B(\sqrt{x}) e^{-x} dx} t_{\text{av}} \sim 0.31 t_{\text{av}} ,$$

where $t_{\text{av}}$ is $t_{\text{df}}$ when $V$ is the mean value, $(V^2)^{1/2} = \sqrt{3} \sigma_{\text{se}}$.

To compare with observed data figure 1, we convert $\sigma_{\text{se}}$ into stellar mass using the direct correlation between the two (i.e., equivalent to the Faber–Jackson relation for a constant stellar mass-to-light ratio). The virial relation, $\sigma_{\text{se}}^2 \sim G M_e / r_e$, is another option of this conversion, but we take the former because the $M_e - \sigma_{\text{se}}$ correlation is tight and the latter could be affected by the size evolution (as discussed here) and the contribution from dark matter. We expect a rather mild evolution of $\sigma_{\text{se}}$ against the size evolution, considering the roughly flat velocity profiles of elliptical galaxies including dark matter (e.g., Mamon & Łokas 2005). Using observed velocity dispersions, $\sigma_{\text{obs}}$ of the SDSS early-type galaxies (Bernardi et al. 2003) and the stellar-mass estimates of D09, $M_e = 4.7 \times 10^{11} \left( \sigma_{\text{se}}/200 \text{ km s}^{-1} \right)^{3.98} M_\odot$ is found, and hence

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1 The Bernardi et al.’s $\sigma_{\text{obs}}$ has been corrected to an aperture radius of $r_e/8$, and the central velocity dispersion is typically $\sim 1.4$ times higher than that around $r_e$ (e.g., Cappellari et al. 2006). Therefore, $\sigma_{\text{obs}} = 1.4 \sigma_{\text{se}}$ has been adopted here.
the energy transfer time scale becomes

$$\frac{t_{1/2}}{\text{Gyr}} = 2.8 \left( \frac{M_\star}{10^{11} M_\odot} \right)^{-0.247} \left( \frac{r_e}{1 \text{ kpc}} \right)^3 \left( \frac{M_*}{10^5 M_\odot} \right)^{-1}. \quad (3)$$

Here, the stellar mass fraction of 0.42 within $r_e$ (corresponding to the Sérsic index $n = 4$, e.g., Mamon & Lokas 2005) has been used to convert $\rho_{sc}$ (the mean density within $r_e$) into $M_\star$ and $r_e$.

This time scale is compared with the observed data of early-type galaxies in the plane of $M_\star$ vs. $r_e$, as well as $\rho_{sc}$ vs. $r_e$, (figure 1). The high-density galaxies ($\rho_{sc} \gtrsim 10^{10} M_\odot$ kpc$^{-3}$) of the D09 sample is found only in the higher redshift bin of $z > 1.46$ (red symbols in figure 1), indicating that these galaxies should disappear on a shorter time scale of a few Gyr, while galaxies of lower densities ($\rho_{sc} \lesssim 10^{10} M_\odot$ kpc$^{-3}$, blue symbols) seem to disappear more slowly on a time scale of $\sim 10$ Gyr. Figure 10 of D09 shows this trend even more clearly in a $\rho_{sc}$ vs $r_e$ plot, where galaxies having a higher stellar density disappear at higher redshifts. This trend is expected in the proposed scenario, because galaxies having higher stellar density are located in the region of shorter $t_{1/2}$, as indicated in figure 1.

The $t_{1/2}$ value of high-$z$ early-type galaxies with the largest mass is larger than the age of the universe. We may need a larger DCO mass than the assumed $10^5 M_\odot$, or some other mechanisms, for these galaxies to evolve into the location of the local galaxies. On the other hand, Mancini et al. (2010) have recently reported that the sizes of the most massive early-type galaxies at $z \sim 1.5$ are similar to those of local galaxies, indicating a possibility that the size shift in the $M_\star$ vs. $r_e$ plane is smaller for more massive galaxies. In this case DCOs with $M_\star \sim 10^5 M_\odot$ could be sufficient to solve the problem.

It should be noted that stellar density is larger than that of dark matter at $r \ll r_e$ (e.g., Mamon & Lokas 2005), and we do not expect a strong structural evolution of stars at $r \ll r_e$. This is in contrast to the change of the stellar distribution by stellar remnant black holes that have the same initial density profile as that of stars (e.g., Merritt et al. 2004). The small effect at $r \lesssim r_e$ is consistent with the observations indicating that the core densities of high-$z$ elliptical galaxies are not much different from those of local galaxies (Bezanson et al. 2009; Hopkins et al. 2009b). The expected mild evolution of the velocity dispersion is also consistent with the observational result of Cenarro and Trujillo (2009). \cite{Cenarro2009}

To conclude, the proposed scenario has several features that are good to explain the observed trends: (1) the evolution should be pure-size evolution, (2) it works ubiquitously for all galaxies in a non-stochastic manner on cosmological time scales, (3) higher density galaxies should disappear on shorter time scales, (4) the stellar density at $r \ll r_e$ is not much affected, and (5) the evolution of the velocity dispersion should be mild.

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4. Observational Constraints on DCOs

There are no strong observational constraints to exclude the possibility of $10^5 M_\odot$ DCOs as the dominant form of dark matter (for reviews see Mack et al. 2007; Ricotti et al. 2008, hereafter M07 and R08). DCOs of $\lesssim 10^5 M_\odot$ are marginally allowed by constraints from strong lensing of compact radio galaxies (Wilkinson et al. 2001) and the millelensing of gamma-ray bursts (Nemiroff et al. 2001). On the other hand, the anomalous flux ratios in gravitational lenses may be explained by DCOs of $10^4 - 10^5 M_\odot$, rather than dark matter of particle-mass scale (Mao et al. 2004).

Yoo, Chanamé, and Gould (2004) declared “the end of MACHO era” by closing the window of $M_\star \sim 30 - 10^6 M_\odot$ based on the existence of wide binary stars in our Galaxy halo, but the robustness of their conclusion has been questioned by Quinn et al. (2009) using new data.

DCOs of $M_\star \gtrsim 10^5 M_\odot$ do not affect the stellar distribution of dwarf spheroidal galaxies (dSphs), like Draco in the Milky Way halo (Jin et al. 2005), and $10^5 - 10^3 M_\odot$ DCOs may even be helpful to solve some problems in galaxy formation, such as disk heating (Lacey & Ostriker 1985) and the core/cusp problem (Jin et al. 2005). Sánchez-Salcedo and Lora (2007) have claimed that $10^5 M_\odot$ DCOs are excluded as dark matter from the survival of a kinetically cold stellar clump found in the Ursa Minor (Kleyena et al. 2003, hereafter K03). However, a quantitative constraint on the velocity dispersion of the cold clump was not derived by K03, making a quantitative analysis difficult. The origin and history of the clump is also still uncertain (see, e.g., Muñoz et al. 2008; Peñarrubia et al. 2009). It should be noted that Ursa Minor shows substantial morphological distortions, unlike most other dSphs (K03).

Afshordi, McDonald, and Spergel (2003) excluded DCOs heavier than a few-times $10^4 M_\odot$ as dark matter, using the small-scale density fluctuations inferred by Ly$\alpha$ forests. However, this analysis depends on the modeling of complicated baryonic physics about Ly$\alpha$ forests, which may include significant systematic uncertainties.

Mii and Totani (2005) and Mapelli, Ferrara, and Rea (2006) discussed the expected number of X-ray sources in nearby galaxies while considering radiatively inefficient accretion flow onto halo black holes of $M_\star \gtrsim 10^2 M_\odot$. R08 set strong constraints on PBHs as dark matter by requiring that the accretion activity onto PBHs does not affect the anisotropy of the cosmic microwave background. However, these calculations include many assumptions and large uncertainties, especially concerning accretion physics and feedback effects. R08 discussed the angular momentum, estimating it from the normal cosmic density fluctuation. However, the proper mean separation of $10^3 M_\odot$ dark matter DCOs at $z \sim 1000$ is about 10 pc, which is comparable to the Bondi radius at that epoch estimated by R08. Then, interaction with nearby DCOs would result in significant angular momentum, which should prevent efficient accretion.

5. Discussion

Although DCOs are less popular than elementary particles as candidates of dark matter, several formation scenarios have

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2 The accumulation of DCOs in a galactic center may affect the innermost stellar distribution, such as stellar core formation, but it would also be complicated by the existence of super-massive black holes. This is an interesting issue to be investigated, but beyond the scope of this letter.

3 But see also van Dokkum, Krick, and Franx (2009) who have reported a large velocity dispersion for one galaxy at $z = 2.186$. Velocity dispersion measurements of early-type galaxies at $z \gtrsim 1$ are still a difficult task, and more observational studies are highly desired.
been proposed (see M07 and R08 for reviews). PBHs can be formed by a density fluctuation of a modest amplitude, or a softening of the equation of state, when the fluctuation scale enters the event horizon of the universe. A mass scale of $10^5M_\odot$ corresponds to the horizon mass ($M_{\text{hor}} = \frac{c^3}{G}$) at a temperature of $\sim$ MeV, i.e., close to the $e^\pm$ annihilation era. Note that only a small portion ($\sim 10^{-6}$) of the universe should be converted into PBHs to explain the dark-matter density, and hence it may not necessarily affect the primordial nucleosynthesis.

DCOs need not be very compact, like PBHs, but substructures in dark haloes generally found in simulations of structure formation should also contribute to the dynamical heating of stars. However, the mass fraction of the substructure must be on the order of unity to explain the size evolution, which seems to be rather unlikely within the standard picture because less than $\sim$10% of the dark mass within the virial radius (and even smaller fraction at inner radii) has been found in substructures in recent simulations (Springel et al. 2008).

The black-hole masses found in active galactic nuclei are always $\gtrsim 10^6M_\odot$. Black holes heavier than $10^6M_\odot$ have been discovered in quasars beyond $z > 6$ (e.g., Willott et al. 2003), and their existence at such high redshifts is not easy to explain by evolution starting from stellar-mass black holes (e.g., Tanaka & Haiman 2009). It is obvious that the explanation would become easier if the dark matter is composed of $10^5M_\odot$ DCOs.

More realistic numerical studies of galaxy size evolution would be required to confirm this hypothesis. Observational searches for DCOs by various approaches (as discussed in section 4) may detect DCOs in the future.

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