Effects of dark-matter density profiles on bulge formation in very late-type galaxies

Jie-Hao Huang
Department of Astronomy, Nanjing University, Nanjing 210093, China
jhh@nju.edu.cn

Zu-Gan Deng
Department of Physics, Graduate School, Chinese Academy of Sciences, Beijing 100039, China
dzg@vega.pku.bac.ac.cn

and

Yan-Ning Fu
Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China
National Observatories, Chinese Academy of Sciences, Beijing 100039, China
yanningfu@yahoo.com

Received ______________; accepted ______________
ABSTRACT

The dynamical evolution of super star clusters has been investigated in dark matter halos depicted with a cuspy- or soft-core density profile. The simulations show that (1) exponential bulges with central cusps form in both cases; (2) distinctive bulge formation rates are derived for cuspy- and soft-core profile; (3) masses of bulges and nuclear clusters are more heavier in case of cuspy-core profile; (4) massive, nuclear star clusters possibly form with no discernible bulges at different ages in cuspy- or soft-core cases.

Subject headings: galaxies: bulge – galaxies: kinematics and dynamics – star: super star clusters

1. Introduction

In our previous work (Fu, Huang & Deng 2003a, (FHD03)), we managed to construct a set of models for simulating the dynamical evolution of super star clusters (SSCs) embedded in dark matter (DM) halo with central cusp, motivated by observations in nuclear regions of galaxies. Among these observations we would mention the discovery of the presence of a black hole with intermediate mass (IMBH) in a young SSC located at some distance from the nucleus of M82 (Matsumoto et al. 2000). While another possible IMBH has been found in an evolved SSC located in the nucleus of M33 (Gebhardt et al 2001). These discoveries strongly imply the role of dynamical evolution of SSCs in the physical process causing the $M_{\text{BH}} - M_{\text{bulge}}$ relation (see, Fu, Huang & Deng 2003b), as well as in bulge formation in late-type galaxies.

The simulations in FHD03 have yielded bulges that are similar in many aspects to the observational ones. In particular, the derived surface density profiles can be well fitted
by an exponential structure with nuclear cusps, which is consistent with *Hubble Space Telescope (HST)* observations (Carollo 1999). The progress in observations (e.g. Marchesini et al. 2002; and the references therein) shows, however, that the cuspy-core DM profiles, such as the NFW profile, are not adequate for a large fraction of dwarf galaxies which are dominated by the DM halos, and suggested that the soft-core density profiles, the Burkert profile for example, is more suitable to these galaxies. It would then be very much instructive to perform simulations for the dynamical evolution of SSCs with both the cuspy- and the soft-core DM density profiles for the bulge formation, with the hope of constraining the bulge-formation model or the properties of the dark matter in late-type galaxies. That is what we would present in this paper.

2. Models

In view of what we described in introduction, we would then model the sinking and tidal stripping of SSCs in DM halos depicted with the NFW or the Burkert density profiles in this paper so as to derive something important as compared with observations. The part of the models in FHD03 are adjusted accordingly and are described in the following subsections. The readers are referred to FHD03 for detailed description about the other part of the models which remain unchanged in this work, including dynamical friction and tidal stripping.

2.1. SSC model

Recently, Parodi & Binggeli (2003) studied the spatial distribution of bright star-forming complexes in a volume-limited sample of 72 very late-type galaxies located within 10 Mpc. They derived the projected radial number distribution $R \exp(-R/R_l)$, with median
scale length \( R_l \approx 0.6 kpc \) and median number of bright star-forming lumps 17, respectively. Taking this spatial distribution with its median values as our SSCs’ radial distribution, rather than \( 1/R \) function inferred from 3 galaxies in FHD03, we generate a set of SSCs over the whole galaxy instead of setting both inner and outer boundary for its distribution. As in FHD03, these SSCs are assigned with local circular speed. Both the initial mass function of SSCs and the SSC itself remain unchanged as those in FHD03.

2.2. Background

Since very-late type galaxies are DM dominated at all radii (Marchesini et al. 2002; Persic, Salucci & Stel 1996), we only take, as in FHD03, a DM halo as the initial background for the bulge-formation process. In light of considering the effects of DM halo models on the bulge formation, we adopt the NFW (Navarro, Frenk & White 1997) and the Burkert (1995) profiles as the cuspy- and the soft-core density profiles, respectively. The mass of the dark matter halo is taken to be \( M_{200} = 10^{11} M_\odot \).

The NFW profile can be written as (Binney & Merrifield 1998)

\[
\rho_{NFW}(r) = \frac{M_{0h}}{r(a_h + r)^2},
\]

where \( r \) is the distance from the halo center, and, \( a_h \) and \( M_{0h} \) are two parameters. With a \( \Lambda \)CDM cosmological model (Jing 2000), the NFW halo is scaled to \( M_{200} = 10^{11} M_\odot \), which gives

\[
a_h = 9.1 kpc, \quad M_{0h} = 5.3 \times 10^{10} M_\odot.
\]

The Burkert profile writes

\[
\rho_{Burkert}(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)},
\]
3. Results and Discussions

3.1. Properties of formed bulges and formation rates

Fig 1 shows the evolution of surface density profiles of simulated individual galaxies obtained with the NFW and the Burkert density profiles, respectively. Obviously, the displayed profiles in Fig 1 fall into two categories, one with high-density central component and the other without. The latter ones basically correspond to the cases where no SSC contributes its mass to the bulge area, or to the cases of being at the pre-stage of bulge-forming. On the contrary, the former ones correspond to the cases where there is some mass contribution from SSCs down to less than 1 pc from the halo center, and the profiles clearly show that bulges are well-formed.

The mean surface density profiles of the formed bulges derived with the NFW or the Burkert density profiles at 3 Gyr are illustrated in Fig 2, together with the curves depicting the fitting to the model (Carollo & Stiavelli 1998; FHD03),

\[
\sigma(R) = \sigma_0 \exp(-1.678 \frac{R}{R_e}) + \sigma_1 (1 + \frac{R}{R_e})^\gamma \exp\left(-\frac{R}{R_s}\right).
\] (4)

As obtained in FHD03, the formed bulges, either with the NFW or the Burkert density profiles, do share the same characteristics with the HST observational results (Carollo 1999), i.e. the general presence of central cusps on top of the exponential bulges.

The half-mass radii, \(R_e\), of the formed exponential bulges for individual galaxies, derived from the fitting with equa (4), range over 100pc to 1000pc. Fig 3a,b show the
histograms of the scale radii $R_e$ of individual bulges formed at 3 Gyr. Either with the NFW or the Burkert density profile, the scale radii $R_e$ distributed over a few hundred parsecs are in accord with observed results by the $HST$ (Carollo 1999).

The above analyses indicate that neither the NFW nor the Burkert profile make a difference to the formed bulges in view of their structure. Nevertheless, the fraction of simulated galaxies with no bulges formed turn out to be quite different as Fig 1 illustrated. This situation is clearly manifested in Fig 4. The bulge formation rates are quite low in simulated galaxies derived with the Burkert density profile, about 30% and 70% at the age of 1 and 4 Gyr, respectively. On the contrary, the formation rates derived with the NFW profile are above 97% and about 100% at 1 and 4 Gyr, respectively.

Observations on searching for bulges in very late-type galaxies are at the very beginning indeed (see, e.g. Böker et al. 2003; Carollo 1999). These researches provide the bulge detection rates of about 50%, compatible with the bulge formation rates derived from the simulations with the Burkert profile. Though it would be natural to conclude that the DM density profiles suitable to very late-type dwarfs are soft-core ones, we should be cautious at the moment. For one thing, these surveys are based on samples of small number of sources, 19 galaxies at the most. On the other hand, Matthews & Gallagher (1997) found that bulges of extremely late-type spirals are often very weak.

3.2. The mass relation of bulges to their nuclear cusps

Though Carollo et al. (2002) discovered that each exponential bulge in their sample hosts a stellar nucleus in its center, they claimed no necessarily causal connection between these two components. In our simulations (FHD03, and this work), however, every formed bulge is always paired with its central, stellar cusp. The stripped stars from SSCs contribute
to the bulge formation, while the remaining, undissociated SSCs form the nuclear cusps.

Needless to say, to confirm the causal connection between nuclear cusps and the exponential bulges would shed much light on the evolution of galaxies.

Recent work by Balcells et al. (2003) seems to confirm the existence of the causal connection between the paired bulges and nuclear cusps, where a tight luminosity correlation in H-band has been reported. In order to see if there is a corresponding correlation between the masses of our simulated bulges and their paired cusps, we have measured the scale sizes of nuclear cusps quantified by their FWHMs, following Carollo et al. (2002). Considering the minimum angular size of 0.\"03 that WFPC2 on board HST can resolve and the distance ranges of 12 and 37 Mpc for observed galaxies, we have averaged the simulated nuclear cusps over central radius of 2 or 5 pc so that the measured FWHMs of simulated nuclear cusps are comparable to the observed ones. Fig 3c,d show the FWHMs thus obtained of the simulated nuclear cusps, which conforms with observed results (Carollo et al. 2002), ranging from a few pc up to 20 pc.

The derived mass relation between simulated bulges and their paired nuclear cusps is illustrated in Fig 5, where the correlations are obviously reached either for the NFW or the Burkert profile at 3 Gyr. The consistency between the observed and simulated mass correlation provides further evidence favorable to the proposed scenario (FHD03 and this work) for bulge formation in very late-type galaxies.

Besides, it would be worth noticing what Fig 5 reveals that the formed bulges and nuclear cusps are more heavier in case of the NFW density profile, with median values of about $2 \times 10^7 M_\odot$ and $1.5 \times 10^6 M_\odot$ respectively at 3 Gyr. On the other hand, the relevant values derived in the Burkert profile are about $8 \times 10^6 M_\odot$ and $6 \times 10^5 M_\odot$ respectively. This difference is mainly made by the different local densities and density variation of DM within the circumnuclear region in the cuspy- and soft-core profiles. Further observations
are surely needed to confirm this kind of disparity.

### 3.3. Formation of nuclear star clusters without bulges

Now it is believed that the occurrence of compact star clusters at nuclei of very late-type spirals is a common phenomenon (e.g. Böker et al. 2002). A fraction of these clusters are located in bulge-less galaxies, with ages roughly ranging from $10^7$ to $10^9$ yr (e.g. Walcher et al. 2003).

As we have shown (FHD03 and this work), our proposed scenario provides a promising mechanism for the formation of massive, nuclear star clusters in galaxies having detected bulges, with masses compatible with observed values ranging very crudely from a few times $10^5$ to $10^7 M_\odot$ (e.g. Matthews & Gallagher 2002).

The existence of nuclear star cluster in bulgeless galaxies, however, remains a mystery. This phenomenon is closely related to several hot topics, especially the properties of DM halos in galaxies. We have then made records of simulations for spatial distances of sinking SSCs during 1Myr and 3 Gyr, either in case of the NFW or Burkert profile, to see if some massive SSCs could survive tidal stripping so as to sink into center of simulated galaxies before bulge formed.

The snapshots of this kind are illustrated in Fig 6 for DM of NFW and Burkert profile, respectively. It is very intriguing to find from Fig 6 that massive, nuclear star clusters do form in NFW profile at 10Myr and in Burkert profile around 100Myr with no discernible bulges. Indeed, this situation has already been manifested in Fig 1 at corresponding ages. After 10Myr, the probability to have nuclear star cluster with no bulge formed becomes low for DM depicted with NFW density profile, while it is low before around 10Myr in case of Burkert profile. After 1 Gyr, this probabilities are quite low in both cases, especially in
case of NFW profile due to very high bulge formation rate, above 97%.

It seems then the scenario we proposed could be a promising mechanism to form nuclear star clusters in bulge-less galaxies. Before drawing a conclusion about the suitability of cuspy-core density profiles for very late-type dwarfs, however, the models presented in FHD03 do need inclusion of more physical processes, e.g. the reaction of DM halo to the sinking of SSCs. This process might have strong effect on changing the DM density profiles (El-Zant et al. 2001).

This work is supported by NKBRSF G19990754, and NSFC.
REFERENCES

Balcells M., Graham A.W. & Dominguez-Palmero L. 2003, ApJ, 582, L79

Binney J., Merrifield M. 1998, Galactic Astronomy, Princeton University Press, Princeton, New Jersey

Binney J., Tremaine S.D. 1987, Galactic Dynamics, Princeton University Press, Princeton, New Jersey

Böker T., Laine S., van der Marel R.P., Sarzi M., Rix H-W., Ho L.C. & Shields J.C. 2002, AJ, 123, 1389

Böker T., Stanek R., van der Marel R.P. 2003 AJ, in press (astro-ph/0212078)

Burkert A. 1995, ApJ, 447, L25

Carollo C.M. & Stiavelli M. 1998, AJ, 115, 2306

Carollo C.M. 1999, ApJ, 523, 566

Carollo C.M.Stiavelli M.Seigar M., de Zeeuw P.T. & Dejonghe H. 2002, AJ, 123, 159

El-Zant A., Shlosman I., & Hoffman Y. 2001, ApJ, 560, 636

Fu, Y. N., Huang, J. H., Deng, Z. G. 2003a, MNRAS, 339, 442 (FHD03)

Fu, Y. N., Huang, J. H., Deng, Z. G. 2003b, Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Pasadena: Carnegie Observatories, http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html)

Gebhardt K., Lauer T.R., Kormendy J., et al. 2001, AJ, 122, 469

Jing, Y.P. 2000, ApJ, 535, 30
Marchesini D., D’Onghia, E., Chincarini, G., et al. 2002, ApJ, 575, 801

Matsumoto H., Tsuru T.G., Koyama, K. et al. 2001, ApJ, 547, L25

Matthews, L. D., & Gallagher, J. S. 1997, AJ, 114, 1899

Matthews, L. D., & Gallagher, J. S. 2002, ApJS, 141, 429

Navarro J.F., Frenk C.S. & White S.D.M. 1997, ApJ, 490, 493

Persic M., Salucci P. & Stel F. 1996, MNRAS, 281, 27

Walcher C.J., Haring N., Böker H.-W., van der Marel R. & Gerssen J. 2003, Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Pasadena: Carnegie Observatories, http://www ociw edu/ociw/symposia/series/symposium1/proceedings html)
Fig. 1.— Evolution of surface density profiles of simulated galaxies in the NFW and Burkert profile.
Fig. 2.— Mean surface density profiles of the formed bulges, along with the curves depicting the model fitting. Legends: Stars – simulated mean profiles, dashed lines – fitted exponential components, solid lines – fitting to model (4).
Fig. 3.— (a) and (b) Distribution of half-mass radii of individual bulges, $R_e$. (c) and (d) FWHMs of simulated nuclear cusps. Legends: Columns shaded with backward and forward slashes are results obtained by setting the central peak values of surface density as those averaged over central 2 and 5 pc globes, respectively. See the text for details.
Fig. 4.— Bulge formation rates in the NFW and the Burkert profiles, respectively.
Fig. 5.— Mass relation of the formed bulges to their central cusps. Legends: The filled squares and stars denote masses of central cusps obtained by spatial resolution of 2 and 5 pc as Fig 4, respectively.
Fig. 6.— Mass of remaining SSCs of simulated galaxies plotted against the SSCs’ distance from the halo center in the NFW and Burkert halos.