# Cosmological pseudobulge formation

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**Abstract.** Bulges can be classified into classical and pseudobulges; the former are considered to be end products of galactic mergers and the latter to form via secular evolution of galactic disks. Observationally, bulges of disk galaxies are mostly pseudobulges, including the Milky Way's. We here show, by using self-consistent cosmological simulations of galaxy formation, that the formation of pseudobulges of Milky Way-sized disk galaxies has mostly completed before disk formation; thus the main channel of pseudobulge formation is not secular evolution of disks. Our pseudobulges form by rapid gas supply at high-redshift and their progenitors would be observed as high-redshift disks.

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## INTRODUCTION

Bulges of disk galaxies can be classified into two types: classical bulges and pseudobulges. Pseudobulges show substantial rotational support and disky or boxy/peanut edge-on isophoto shapes. Pseudobulges are thus thought to have formed via secular evolution of discs [1]. The standard picture of galaxy formation predicts that galaxies from through hierarchical merging that naturally produces classical bulges. However, more than half of bulges of nearby large disk galaxies are pseudobulges [2, 3]. Therefore the high frequency of pseudobulges could be a challenge to the standard cosmology.

Investigating formation processes of simulated bulges of disk galaxies should provide important clues for understanding of bulge formation. Such simulations must resolve detailed structure of galaxies such as shape of bulges. Only recently cosmological simulations with high enough resolution have become possible [4, 5, 6].

In this paper, we analyze the bulges of two Milky Way-sized galaxies formed in ΛCDM simulations; the initial conditions are selected from the Aquarius project [7]: 'Aq-C' and 'Aq-D' in their labeling system. The simulation presented in this paper include a number of baryonic processes known to be relevant to galaxy formation. We make use of a model that has already had success in reproducing properties of the Local Group satellite galaxies [4, 5]. The details of the simulations please refer to Okamoto [8].

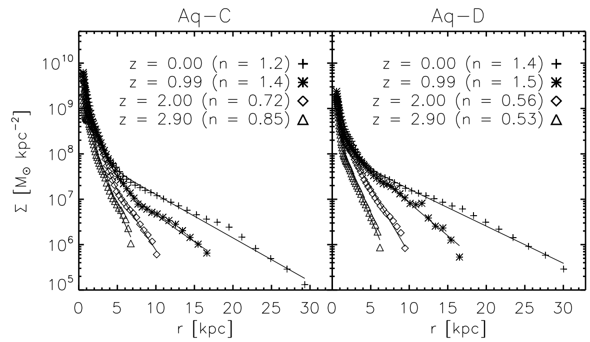


**FIGURE 1.** Evolution of the surface stellar density profiles. The surface stellar density profiles of Aq-C (left) and Aq-D (right) galaxies and their main progenitors are presented. The profiles around redshift 0, 1, 2, and 3 are indicated by the plus signs, asterisks, diamonds, and triangles, respectively. Each profile is fitted by a combination of a Sérsic bulge and an exponential disk, which is shown by a solid line. The Sérsic indices are shown in each panel.

## RESULTS

In order to classify bulges, the Sérsic profile fitting for a surface stellar density profile is frequently used:

$$\Sigma(r) = \Sigma_{\mathrm{e}} \exp\left[-b_n\left\{\left(\frac{r}{R_{\mathrm{e}}}\right)^{\frac{1}{n}} - 1.0\right\}\right], \tag{1}$$

where $R_{\mathrm{e}}$ is the effective radius and $\Sigma_{\mathrm{e}}$ is the surface density at this radius, respectively, and $n$ is the Sérsic index. The parameter $b_n$ is well approximated by $b_n = 2n - 0.324$. Bulges with $n < 2$ are usually classified as pseudobulges. We show the evolution of the surface stellar density profiles in Fig. 1. We fit each profile by a combination of the Sérsic and exponential profiles.

We obtain $n \simeq 1.2$ and 1.4 for Aq-C and -D's bulges, respectively; thus both bulges have pseudobulge-like profiles. We have confirmed that they not only show pseudobulge-like profiles, but they also have pseudobulge-like 'disky' bulge shape [see 8].

In Fig. 2, we show the formation histories of bulges stars, where we distinguish between stars born in the main progenitors (in situ) and those brought by accreted satellites (accreted). As shown in the top panels, most of bulge stars are born in starbursts between redshift 2 and 6 in Aq-C and between 2 and 4 in Aq-D. Thus, mergers do not contribute to the formation of the bulges. There is little star formation activity below redshift 1 in the bulge of Aq-C; Aq-D's bulge show slight activity at this epoch. About half of the star formation in the bulge of Aq-D below redshift 1 in the gas clumps. The contribution from the clumps is only about 10%.

## Conclusion

We have performed $N$-body/SPH cosmological simulations of galaxy formation, in which two Milky Way-sized galaxy have formed: Aq-C and Aq-D. Both galaxies have

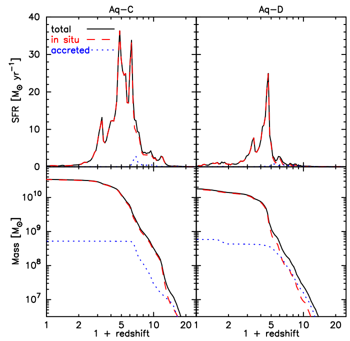


**FIGURE 2.** Distribution of formation times of bulge stars expressed in terms of redshift. Stars lie within 3 kpc from the galaxy center at redshift 0 are identified as the bulge stars. The solid lines indicate all the bulge stars, while the dashed and dotted lines respectively indicate those born in the main progenitors (in situ) and those brought by satellites (accreted). The upper and lower panels show the same data in differential and cumulative form, respectively.

well-defined disks with the bulge-to-disk mass ratio, $B/T \simeq 0.6$ and 0.3 at redshift 0. The Sśersic indices for Aq-C's and Aq-D's bulges are 1.2 and 1.4, respectively. These values suggest that both bulges are pseudobulges. The pseudobulges mainly form by high-redshift starbursts before redshift 2. The evolution of the surface stellar density profiles reveals that the pseudobulge components are already in place at redshift 2–3 as disky components with small scale length. The mass of these components at redshift 2 accounts for $\sim 70\%$ and $\sim 87\%$ of the final pseudobulge mass of Aq-C and Aq-D, respectively. These progenitors of the pseudobulges would be observed as high-redshift disks. The formation scenario of pseudobulges by high-redshift starbursts provides an explanation of pseudobulges in early-type disk galaxies such as S0 and Sa galaxies. Pseudobulges do exist in early-type disks and secular evolution may take too long to form such large pseudobulges.

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