Formation of Galactic Bulges
Nickolay Y. Gnedin\(^1\), Michael L. Norman\(^2\), and Jeremiah P. Ostriker\(^3\)

**ABSTRACT**

We use cosmological hydrodynamic simulations to investigate formation of galactic bulges within the framework of hierarchical clustering in a representative CDM cosmological model. We show that largest objects forming at cosmological redshifts \(z \sim 4\) resemble observed bulges of spiral galaxies or moderate size ellipticals in their general properties like sizes, shapes, and density profiles. This is consistent with observational data indicating the existence of “old” bulges and ellipticals at more moderate redshifts. These bulges are gas dominated at redshift \(z = 3\), with high rates of star formation and would appear to be good candidates for small blue galaxies seen in the Hubble Deep Field.

*Subject headings:* cosmology: theory - cosmology: large-scale structure of universe - galaxies: formation - galaxies: intergalactic medium

1. Introduction

The fact that bulges of ordinary galaxies (and indistinguishable ellipticals of the same luminosity) are very dense is often used as an argument against the currently favored CDM-type cosmological models. Really, since the average density of the universe decreases with time, and the average density of a bound object is directly proportional to the density of the universe at the time when the object is formed, dense galactic bulges should have formed at very high redshift. Thus, it is reasonable to ask whether currently fashionable cosmological models normally have enough small scale power to account for the formation of massive \((10^9 - 10^{10}\) solar masses in baryons\) bulges at \(z \gtrsim 10\) (Peebles 1997).

This argument can be illustrated by the following simple estimate: the characteristic number density of baryons in the Galactic bulge within the sphere with the radius of 3 kpc is

\[
n_{GB} \sim 2 \text{ cm}^{-3}
\]  

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In comparison, the average density of the cosmological virialized object formed at redshift \( z \) is only

\[
 n_{TH} \sim 10^{-4}(1 + z)^{3} \text{cm}^{-3}
\]

for \( \Omega_b h^2 = 0.02 \), and we assume that the average density of the virialized object is about 200 times the average density of the universe at the moment of formation (Gunn & Gott 1972), according to the standard dissipationless collapse theory. Comparing equations (1) and (2) we can deduce that the bulge of our Galaxy formed at \( z_{GB} \sim 30 \). But, none of the currently acceptable CDM-type models can form \( 10^{10} \) solar mass baryonic objects at \( z = 30 \) in numbers even closely comparable to the observed number density of galactic bulges.

Does this argument imply that the CDM-type models are ruled out? We will try to show in this paper that the answer to this question is no. What this simple argument misses is the ability of baryons to cool and collapse to the densities exceeding that of the dark matter. We present a series of cosmological hydrodynamic simulations which include adequate physical modelling to properly account for formation of bulges of galaxies, and we show that typical bulges form in a realistic CDM-type model at \( z \sim 5 \) rather than at \( z \sim 30 \).

But before describing our detailed results, it is perhaps worth noting the conceptual flaw in the simple argument we first presented. The global ratio of baryons to dark matter in our simulation, and in typical current estimates is about 1:8. But in our own galactic bulge the baryonic – stellar – component exceeds the dark matter component and may exceed it by as much as a factor of a few. Thus, (taking the cube root of density enhancement) the baryonic stellar component has contracted relative to the dark matter component by a factor of two to four and, correspondingly, the bulge should have formed in the plausible redshift range of \( z \sim 5 - 10 \) rather than at \( z = 30 \). Furthermore, as we shall see, the observed (and computed) profiles are very different from those envisioned in the top-hat collapse picture.

An aside on a related but quite different problem may be useful here. There is currently a good deal of discussion on the subject of whether or not standard CDM models make bulges which are too dense (e.g. Spergel & Steinhardt 1999, Burkert & Silk 1999, Moore et al. 1999, Kravtsov et al. 1998). However, these papers address far lower mass systems and ones which are dark matter dominated, having circular velocities of only .... Here we address normal bulges with (equivalent) circular velocities of about 200 km/s or more, for which the advertised problem has been the opposite: why are they so dense?

### 2. Simulations

We use the SLH cosmological hydrodynamic code (Gnedin 1995, 1996; Gnedin & Bertschinger 1996). Physical modelling included in the code is fully described in Gnedin & Ostriker (1997). We
choose a CDM+Λ cosmological model with the following cosmological parameters:

\[ \Omega_0 = 0.37, \quad \Omega_L = 0.63, \quad h = 0.70, \quad \Omega_b = 0.049, \]

which is close to the “concordance” model of Ostriker & Steinhardt (1995) and to the models consistent with recent SNIa results (Riess et al. 1998, Perlmutter et al. 1999). We have performed one simulation with $128^3$ baryonic resolution elements, the same number of dark matter particles, and a number of stellar particles were formed during the simulation. The simulation box size was fixed to $3h^{-1}\text{Mpc}$, which resulted in the total mass resolution of $1.3 \times 10^6 h^{-1}\text{M}_\odot$. For reference, the Jeans mass at $z = 10$ and $T = 10^4 \text{K}$ is about $10^{10}h^{-1}\text{M}_\odot$. The spatial resolution was fixed at $1.5h^{-1}\text{comoving kiloparsecs}$. Because of the small box size, this simulation cannot be continued to $z = 0$. Instead, we stopped the simulation at $z \approx 3$. Even at this redshift our simulation is suffering from the lack of spatial of resolution, as can be illustrated by Figure 1. The

Fig. 1.— Evolution of the central dark matter density (solid lines), baryonic density (dashed lines), and stellar density (dotted lines) for the most massive object in our simulation. The thin solid line shows the central total density of the same object if it had the Navarro-Frenk-White (NFW) density profile. The central core appears because of finite spatial resolution in simulations.
Table 1: Four Most Massive Objects at $z = 4$

<table>
<thead>
<tr>
<th>Object</th>
<th>Total mass ($M_\odot$)</th>
<th>Baryonic mass ($M_\odot$)</th>
<th>Stellar mass ($M_\odot$)</th>
<th>$M_b/M_t$</th>
<th>$M_*/M_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$4.0 \times 10^{10}$</td>
<td>$8.2 \times 10^9$</td>
<td>$1.5 \times 10^9$</td>
<td>0.20</td>
<td>0.18</td>
</tr>
<tr>
<td>B</td>
<td>$2.9 \times 10^{10}$</td>
<td>$5.1 \times 10^9$</td>
<td>$1.2 \times 10^9$</td>
<td>0.18</td>
<td>0.23</td>
</tr>
<tr>
<td>C</td>
<td>$1.8 \times 10^{10}$</td>
<td>$3.3 \times 10^9$</td>
<td>$0.9 \times 10^9$</td>
<td>0.18</td>
<td>0.26</td>
</tr>
<tr>
<td>D</td>
<td>$1.4 \times 10^{10}$</td>
<td>$2.2 \times 10^9$</td>
<td>$0.6 \times 10^9$</td>
<td>0.16</td>
<td>0.29</td>
</tr>
</tbody>
</table>

decrease in central density of the most massive object is due to our spatial resolution (which is kept constant in comoving coordinates, and, thus becoming progressively worse with time in the physical coordinates) becoming comparable with the characteristic radius of an object by the end of the simulation.

Another simulation with eight times more resolution elements ($256^3$) and $6h^{-1}$ Mpc box was also performed. The large simulation thus had the same mass resolution as the small one, and the spatial resolution in the large simulation was fixed at $1.2h^{-1}$ comoving kiloparsecs. However, because the large simulation required a computational expense beyond what was available to us, it was terminated at $z = 9.5$. Thus, we used the large simulation to verify numerical convergence and estimate missing small scale power, but we will use the small ($128^3$) simulation as the source for scientific results.

By comparing the large and small simulation, we have found that the small simulation included most of the small scale power that was initially present in the baryonic component. Thus, our results are not significantly affected by the finite resolution in the initial conditions ($k$-space resolution), but they are, of course, subject to finite mass and spatial resolution.

3. Results

Since we are concerned with the process of formation of galactic bulges and small ellipticals, we will focus in this paper on properties of individual objects formed in our simulations. Specifically, we will focus on four most massive objects. Each of those objects contains more than ten thousand particles of each kind (i.e. the dark matter, gas, and stars), and thus they are fully resolved numerically.

Tables 1 and 2 present the general properties of the four objects: their total, baryonic, and stellar masses, as well as the ratio of the baryonic to the total mass, and the stellar to the baryonic mass at $z \approx 4$ and $z \approx 3$ respectively.

A few observations can easily be made from the table. First, the objects contain more baryons than the cosmic average of $\Omega_b/\Omega_0 = 0.13$. Second, they are still dominated by gas, as only about
Table 2: Four Most Massive Objects at \( z = 3 \)

<table>
<thead>
<tr>
<th>Object</th>
<th>Total mass ((M_\odot))</th>
<th>Baryonic mass ((M_\odot))</th>
<th>Stellar mass ((M_\odot))</th>
<th>( M_\bullet/M_t )</th>
<th>( M_*/M_\bullet )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( 7.1 \times 10^{10} )</td>
<td>( 1.1 \times 10^{10} )</td>
<td>( 2.4 \times 10^9 )</td>
<td>0.15</td>
<td>0.23</td>
</tr>
<tr>
<td>B</td>
<td>( 2.9 \times 10^{10} )</td>
<td>( 4.5 \times 10^9 )</td>
<td>( 1.2 \times 10^9 )</td>
<td>0.16</td>
<td>0.27</td>
</tr>
<tr>
<td>C</td>
<td>( 1.8 \times 10^{10} )</td>
<td>( 3.0 \times 10^9 )</td>
<td>( 0.9 \times 10^9 )</td>
<td>0.17</td>
<td>0.22</td>
</tr>
<tr>
<td>D</td>
<td>( 1.6 \times 10^{10} )</td>
<td>( 2.5 \times 10^9 )</td>
<td>( 0.9 \times 10^9 )</td>
<td>0.16</td>
<td>0.34</td>
</tr>
</tbody>
</table>

20–30\% of their baryonic mass is turned into stars when we terminated the computation at \( z \approx 3 \). These objects have a moderately high rate of star formation (several solar masses per year), and would appear to correspond well to the numerous small blue objects seen in the Hubble Deep Field (Contardo, Steinmetz, & Alvensleben 1998).

But, it must be noted here that the amount of gas turned into stars really depends on the specifics of the star formation algorithm adopted in the simulation. We make no pretense that we can fully account for the star formation in our simulations, it is clear that modeling of star formation needs to be much advanced before simulations could claim to predict the star formation rate in (proto-)galaxies with sufficient detail. Thus, for the purpose of this paper we will pay little attention to the stellar component of our simulated bulges, and will focus primarily on the total baryonic component instead. We assume that with proper star formation algorithm, our simulated bulges will form stars at an appropriate rate as long as the total baryonic distribution is compatible with observations.

Since at \( z < 3.8 \) our results become substantially contaminated by the lack of spatial resolution, we will restrict most of our analysis to the redshift \( z = 3.8 \), the lowest redshift at which characteristic radii of bound objects are still well resolved. Density profiles of the four most massive objects are shown in Figure 2. The most massive object, object A, is less dense at the center than other three objects because it experienced a major merger shortly before \( z = 4 \) and has not fully relaxed yet. Object D has also experienced a major merger at \( z \approx 6 \), whereas objects B and C have been accreting matter quietly since \( z \sim 10 \). We point out here that in all four objects baryonic density at the center is greater than or similar to the dark matter density, i.e. baryons in all four objects are self-gravitating. As an aside we note that should the gaseous component dominate at the center at any time, a rapid collapse would occur which presumably would be accompanied by rapid star formation or, should a black hole of sufficient mass be presents, the concomitant flare up of an AGN. Clearly, we have not sufficient resolution to follow this phase (but see Abel, Bryan, & Norman 1998).

Evolution of average properties of these objects is shown in Figure 3. One can immediately see that all four objects are experiencing heavy merging at \( z \sim 4 – 6 \), increasing their mass by about an order of magnitude. The stellar fraction of object A decreased significantly at \( z = 4 – 5 \).
because of accretion of a large quantity of fresh gas. Also noticeable is the increase in the total baryonic fraction in object A at $z \sim 4$. Since baryons are almost self-gravitating at the center of object A, their efficiently cool and collapse toward the center, leading to the increase in the baryonic fraction of the object.

Figure 1 shows the evolution of the central density for the dark matter, baryonic and stellar components of object A. The central density is defined as the average density within the sphere of two resolution lengths of our simulations ($\sim 900$ pc at $z = 3.8$). One can see that the dark matter density does not change systematically with time (albeit fluctuating significantly) until the lack of resolution contaminates results, because the object is close to the virial equilibrium. On the contrary, the baryonic density increases with time because of efficient cooling at the center of the object. The recent merger at $z \sim 5$ triggered a considerable increase in the central density of gas, but this increase has not yet resulted in the burst of star formation. We expect, that
if we continued the simulation to lower redshift with higher spatial resolution, object A would experience a burst of star formation at the center, which would transform most of the gas into stars on a rather short time-scale.

We are now ready to address the major question of this paper: are those objects formed in the simulation resemble real galactic bulges? In order to answer this question, we show in Fig. 4 the surface density profiles for our four objects. Also, for the total baryonic profile we compute the exponential fits in the form:

\[ \Sigma(R) = \Sigma_0 e^{1-R/R_C} \]  \hspace{1cm} (3)

and \( r^{1/4} \) law fits,

\[ \Sigma(R) = \Sigma_0 10^{-3.3307(R/R_e)^{1/4}-1}. \]  \hspace{1cm} (4)

Both, Kent, Dame & Fazio (1991) and Freudenreich (1998) models for the galactic bulge are well fitted by the exponential profile for the range 0.1 kpc < r < 3 kpc (with respective rms errors of 3 and 8 percent respectively).
Fig. 4.— Surface mass density profiles for the dark matter ([solid lines]) and total baryons ([dashed lines]) of four most massive objects at $z = 3.8$ as a function of radius in physical (not comoving) units. The profiles are terminated at the resolution limit of the simulation (450 pc). Tilted long-dashed lines show $r^{1/4}$ law for the baryonic profiles, and dotted lines show exponential profiles. Bold arrows show characteristic radii $R_e$ for $r^{1/4}$ profiles. The horizontal long-dashed line show the central surface density of a homogeneous top-hat sphere.

![Graph showing mass density profiles](image)

We put together the parameters of the fits in Table 3. In addition, we list the parameters that describe the Galactic bulge from Kent, Dame, & Fazio (1991) and Freudenreich (1998) for comparison. As one can see, objects that we observe in the simulation are very similar to (or perhaps even a little bit larger than) the bulge of Milky Way, provided, they convert most of their gas into stars.

Why did we then erroneously conclude in the Introduction that the CDM-type models predict too low density bulges? The answer to this puzzle is again illustrated in Fig. 4. The horizontal long-dashed line in that figure shows the central surface density for a homogeneous top-hat sphere, i.e. for a spherical object with the constant density of 200 times the average density of the universe and with a radius equal to the virial radius of object A (all four objects have quite similar virial radii). One can immediately see that the top-hat model underestimates the central density of an
Table 3: Fit Parameters for Four Most Massive Objects at $z = 3.8$

<table>
<thead>
<tr>
<th>Object</th>
<th>$R_C$ (kpc)</th>
<th>$\Sigma_C$ ($M_\odot$/pc$^2$)</th>
<th>$R_e$ (kpc)</th>
<th>$\Sigma_e$ ($M_\odot$/pc$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.70</td>
<td>1200</td>
<td>1.47</td>
<td>310</td>
</tr>
<tr>
<td>B</td>
<td>0.54</td>
<td>1270</td>
<td>1.11</td>
<td>310</td>
</tr>
<tr>
<td>C</td>
<td>0.58</td>
<td>664</td>
<td>1.27</td>
<td>140</td>
</tr>
<tr>
<td>D</td>
<td>0.46</td>
<td>790</td>
<td>0.91</td>
<td>200</td>
</tr>
<tr>
<td>Galactic bulge$^a$</td>
<td>0.58</td>
<td>650$^c$</td>
<td>0.97</td>
<td>250$^c$</td>
</tr>
<tr>
<td>Galactic bulge$^b$</td>
<td>0.47</td>
<td>560$^c$</td>
<td>0.76</td>
<td>260$^c$</td>
</tr>
</tbody>
</table>

$^a$Kent, Dame, & Fazio 1991  
$^b$Freudenreich 1998  
$^c$A mass to light ratio of 3 is assumed in converting luminosity to mass.

object by about two orders of magnitude! Even the density at the characteristic radii ($R_C$, $R_e$) is 30–100 times greater than the fiducial top-hat virial density.

Evolution of the two fit parameters, the characteristic radius and density, is shown in Fig. 5 for the four most massive objects in the simulation. The densities increase steadily as the gas continues to accrete and cool inside the dark matter halos, whereas characteristic radii stay approximately constant for all objects.

Finally, if we want to demonstrate that we can form galactic bulges in a realistic cosmological simulation, we should address the question of the bulge shape. The bulge of our Galaxy is quasi-spherical, or, at the very least, slightly ellipsoidal. Is this shape also reproduced in the simulation? Figure 6 addresses this question. In it we show the axis ratios for the dark matter, gas, and stars for our four objects as a function of radius. One can see that in the central parts the gas and the stellar distributions are quite close to spherical. Shapes at larger radii, $r > 3$ kpc, shown shaded in Fig. 6, vary significantly among all objects, but at those large distances the gas is far from equilibrium, and the minute shape of its distribution has little relation to its final state. The fact that the objects we observe in the simulation are more-or-less spherical, rather than disk-shaped, is due to the fact that at high redshift the slope of the linear power spectrum of the density fluctuations is close to $-3$. This results in a range of scales becoming nonlinear almost at the same time, which, in turn, leads to heavy merging among objects observed in the simulation. Thus, gaseous disks do not have enough time to form, and the shape of the objects remains quasi-spherical. Only at later times, when the rate of merging falls down, can a gaseous disk form inside an object.
Fig. 5.— Evolution of the characteristic radii (lower panel) and densities (upper panel) for the four objects: A (solid lines), B (long-dashed lines), C (short-dashed lines), and D (dotted lines). The horizontal shaded areas mark the range of values for the Galactic bulge, and the vertical line marks the boundary $z = 3.8$ beyond which our simulation fails to resolve cores of the galactic bulges.

4. Conclusions

We have showed that objects that form in a realistic cosmological simulation of a CDM-type cosmological model do look similar to bulges of normal galaxies. Our objects are still 75% gaseous at $z \approx 4$, but they form stars at a high rate, and when most of the gas in those objects will be converted into stars by redshift $z = 2$. In this time frame they resemble the numerous small blue galaxies seen in the HDF. Later they will look like slightly ellipsoidal stellar objects with the density profiles well fit by the exponential profile and with the parameters of the fit similar to the parameters of the Milky Way bulge and small elliptical galaxies.

We thus conclude that currently favorable CDM-type cosmological models have no difficulty in reproducing observed properties of galactic bulges. On the contrary, models that have galaxy
Fig. 6.— Axis ratios for the dark matter (solid lines), total baryons (gas and stars, dashed lines), and stars (dotted lines) of four most massive objects at $z = 3.8$ as a function of radius in physical (not comoving) units.

formation at $z \sim 30$ (Peebles 1997) would form bulges that are two to three orders of magnitude more dense than the observed ones. This conclusion is further boosted by the consideration that, due to the limited mass and spatial resolution of our simulation, we can only underpredict the densities and masses of cosmological objects. With several bulges observed in approximately correct mass range (note the local group with M31, M33, and the Galaxy), and a total luminosity of about $L_*$ in the volume of $27h^{-3}$ Mpc$^3$, we conclude that the model produces approximately the correct density of bulges.

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