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THE FORMATION OF A REALISTIC DISK GALAXY IN Λ-DOMINATED COSMOLOGIES

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ABSTRACT

We simulate the formation of a realistic disk galaxy within the hierarchical scenario of structure formation and study its internal properties to the present epoch. We use a set of smoothed particle hydrodynamic (SPH) simulations, with a high dynamical range and force resolution, that include cooling, star formation, supernovae (SNe) feedback and a redshift-dependent UV background. We compare results from a Λ cold dark matter (ΛCDM) simulation to a Λ warm dark matter (ΛWDM) (2 keV) simulation that forms significantly less small-scale structure. We show how high mass and force resolution in both the gas and dark-matter components play an important role in solving the angular momentum catastrophe claimed from previous simulations of galaxy formation within the hierarchical framework. Hence, a large disk forms without the need of strong energy injection, the $z = 0$ galaxies lie close to the *I* band Tully-Fisher relation, and the stellar material in the disk component has a final specific angular momentum equal to 40% and 90% of the dark halo in the ΛCDM and ΛWDM models, respectively. If rescaled to the Milky Way, the ΛCDM galaxy has an overabundance of satellites, with a total mass in the stellar halo 40% of that in the bulge+disk system. The ΛWDM galaxy has a drastically reduced satellite population and a negligible stellar spheroidal component. Encounters with satellites play only a minor role in disturbing the disk. Satellites possess a variety of star formation histories linked to mergers and pericentric passages along their orbit around the primary galaxy. In both cosmologies, the galactic halo retains most of the baryons accreted and builds up a hot gas phase with a substantial X-ray emission. Therefore, while we have been successful in creating a realistic stellar disk in a massive galaxy within the ΛCDM scenario, energy injection emerges as necessary ingredient to reduce the baryon fraction in galactic halos, independent of the cosmology adopted.

Subject headings: galaxies: formation — hydrodynamics — methods: *n*-body simulations

1. INTRODUCTION

Within the current paradigm of galaxy formation, realistic disks form only if gas retains most of its angular momentum gained by torques from nearby structures while it cools at the center of cold dark matter (CDM) halos (White & Rees 1978; Fall & Efstathiou 1980; Fall 1983; Mo et al. 1998). Some of the first simulations of galaxy formation that included star formation (Lake & Carlberg 1988; Katz 1992) provided strong evidence that hierarchical models do create rotationally supported stellar systems. However, simulations of galaxy formation in a full cosmological context have not yet been able to form realistic disk galaxies: dynamical friction suffered by dense gaseous lumps and subsequent catastrophic angular momentum loss caused typical disk scale lengths to come short of those observed (Navarro & White 1994). In addition, high-resolution simulations of dark matter (DM) halos in CDM models have far more substructure ("satellites") than observed;

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encounters with these satellites could destroy the stellar-disk component of spiral galaxies (Moore et al. 1999).

If these dark subhalos were the main problem, any mechanism capable of reducing the lumpiness of galaxy assembly would lead to realistic disks. However, resolution simulations ($N \sim 10^4$) also suffer from excessive artificial viscosity, which would overestimate the angular momentum transfer, as was early recognized in previous works (e.g., Sommer-Larsen et al. 1999). Poorly resolved disks will also suffer from two-body effects, which will lead to substantial disk angular momentum loss even after its eventual formation (Mayer et al. 2001).

Together, the failure to build galactic disks similar to those observed and the overabundance of substructure pose a formidable challenge to the ΛCDM paradigm, suggesting that a fundamental ingredient is missing from our understanding of the formation of galactic and subgalactic structures. As possible solutions, strong SN feedback (e.g., Thacker & Couchman 2000, 2001; hereafter TC00 and TC01, respectively), an external UV background produced by QSOs and massive stars (Quinn et al. 1996; Benson et al. 2000; Somerville 2002), and alternatives to ΛCDM (Spergel & Steinhardt 2000, among others) have been advocated. Among alternative DM models, warm dark matter (WDM; Pagels & Primack 1982) emerged as a good candidate as its lack of power at small scales could prove beneficial in reducing the number of subhalos and allowing a smoother accretion of gas, forming larger disks (Bode et al. 2001; Colín et al. 2000). Some of these solutions have been explored in recent studies (e.g., TC01; Sommer-Larsen & Dolgov 2001; Sommer-Larsen et al. 2003; Abadi et al. 2003).

These most recent works have been successful in forming a rotationally supported stellar component, although in many cases a massive stellar spheroid is formed as well. In runs that use less than a few thousand particles to represent the virialized part of a galaxy DM halo (e.g., Eke et al. 2001), the rotating stellar component does not allow one to distinguish a disk. In TC01, in which $\sim 1.5 \times 10^4$ DM particles with the halo virial radius were used, the "bulge" component is still almost twice as massive as the thin disk. The bulge component decreases to only 50% of the stellar disk in the simulation presented by Abadi et al. (2003), which had 3.6×10^4 DM particles within the virial radius of their simulated galaxy. While these results are encouraging, previous simulations do not clarify whether stronger feedback was necessary or just sufficient to avoid systematic loss of angular momentum during the formation of galactic disks. Runs with larger particle numbers also had larger disks, suggesting that resolution effects still play a major role. Important differences in the results might also arise from the different merging histories of each individual halo simulated, the spin of their halos (e.g., TC01 simulated a halo with a larger than average spin, which in turn makes it easier to form larger disks), and the different SN feedback recipes used in various works.

We have performed a new set of smoothed particle hydrodynamic (SPH) simulations that use a high number of particles and high force resolution to follow the formation and internal structure of the stellar component of galaxies. These simulations implement cooling, star formation, SN feedback, and a UV background. In this paper, we describe the formation and evolution of realistic disk-dominated galaxies in a cosmological numerical simulation and compare these to a high-resolution spiral galaxy formed in two different (ΛCDM and ΛWDM) flat cosmologies. Rather than simulate a large sample of galaxies, our strategy is to achieve the highest possible resolution with the available computing resources to avoid unwanted numerical systematics. Our aim is to find a good, clear-cut case in which a realistic disk forms in a fully cosmological environment, rather than exploring the full range of galactic morphologies. We also evaluate the various numerical and physical processes responsible for the angular momentum loss of the gaseous and stellar components. We describe the initial conditions in § 2, and we present our results and discuss their implications in §§ 3 and 4, respectively.

2. SIMULATION PARAMETERS AND INITIAL CONDITIONS

We adopted a flat Λ-dominated cosmology: $\Omega_0 = 0.3$, $\Lambda = 0.7$, $h = 0.7$, $\sigma_8 = 1$, shape parameter $\Gamma = 0.21$, and $\Omega_b = 0.039$ (Perlmutter et al. 1997; Efstathiou et al. 2002). Power spectra were calculated using the CMBFAST code to generate transfer functions (Zaldarriaga & Seljak 2000). The ΛWDM model can be characterized in terms of the reduction in fluctuations on dwarf-galaxy scales. For our choice of 2 keV neutrinos, the fluctuations on scales smaller than $\sim 10^{9.5}\ M_\odot$ are vastly reduced. We retained the phases of the waves that describe the initial density field. These allowed us to discriminate between the different effects of the two power spectra used.

From a 100 Mpc box, low-resolution simulation, we selected and resimulated (Katz & White 1993) at higher resolution a "typical" spiral-galaxy candidate halo with mass $3 \times 10^{12}\ M_\odot$ and a quiet merger history after $z \sim 2.5$. The halo is relatively isolated, and its formation time (defined as the main progenitor achieving 50% of its final mass) is $z = 0.75$. Its spin parameter, λ, is 0.035 (0.03 for ΛWDM), which is close to the average value for cosmic halos (Gardner 2001). Note that because of the finite size of the box, the actual σ_8 in the simulation volume is actually ~0.9 at the present time. The above constraints are consistent with the Milky Way forming several Gyr ago (Wyse 2002) and predictions from semianalytical models (Baugh et al. 1996). A large starting box is important, as lack of large scale power would significantly reduce the amount of torques on collapsing halos. To run the simulations, we used a parallel tree code + SPH with multiple time steps, GASOLINE, which is described in detail in Wadsley et al. (2004) and Stadel et al. (2002). The code treats artificial viscosity as suggested in Balsara (1995). The energy equation is computed asymmetrically (Springel & Hernquist 2002; Evrard 1988; Monaghan 1992). This approach avoids the energy conservation and negative energy problems of the arithmetic and geometric forms and converges to the high-resolution answer faster than other proposed methods (Benz 1990; Springel & Hernquist 2002).

The high-resolution region has DM and gas particles of mass 2.32×10^7 and $3.44 \times 10^6\ M_\odot$, respectively. The rest of the simulation box was resampled at increasing particle masses, for a total of nearly 1.1×10^6 DM particles and 2.2×10^5 gas particles. For all particle species in the high-resolution region, the gravitational spline softening $\epsilon(z)$ evolved comovingly, starting at $z = 100$ until $z = 9$, and remained fixed at 1 kpc from $z = 9$ to the present. This choice of $\epsilon(z)$ reduces two-body relaxation at high z in small halos. The value chosen is a good compromise between reducing two-body relaxation and ensuring that disk scale lengths and the central part of DM halos will be spatially resolved (see Diemand et al. 2004 for a number of relevant tests). Moreover, a constant softening in physical coordinates is more appropriate at low redshift when stellar structures have detached from the Hubble flow. Integration parameter values were chosen as suggested in Moore et al. (1998) and then confirmed in Power et al. (2003). Most of the stars formed in the simulation required 32,768 integration steps to $z = 0$, with a significant fraction of them requiring 4 times as many steps. At comparable or better force resolution, particle numbers within the virial radius are 3 times that of Navarro & Steinmetz (2000), 8 times that of TC01, 3 times that of Abadi et al. (2003), and comparable to the highest resolution run reported in Sommer-Larsen et al. (2003).

Two main SPH simulations were run, one for each cosmology. Both runs included Compton and radiative cooling, assuming a gas of primordial composition; and star formation and SN (Types I and II) feedback, treated following the prescription described by Katz (1992), in which stars spawn from cold, Jeans unstable gas particles in regions of converging flows. The star formation efficiency parameter ϵ was set to 0.15, but with the adopted scheme, the exact value has only a minor effect on the star formation rate (Katz 1992). SNe enrich the surrounding gas according to the respective metal yields. Star particles inherit the metal abundance of the parent gas particles. However, we did not allow for diffusion of metals between gas particles.

After a gas particle is less than 10% of its initial mass because of multiple star formation events, it is removed and its mass is reallocated among its gas neighbors. Up to six star particles are then spawned for each gas particle in the disk. The adopted "minimal" feedback recipe dumps energy from SNe into thermal energy of the nearest 32 gas neighbors. As energy is quickly radiated away in dense gaseous regions, this feedback recipe has a weak effect on star formation (TC00). We explicitly choose a fairly massive galaxy with weak feedback, in order to explore a regime in which feedback is likely to play a minor role.

The evolution and strength of the uniform UV background from QSOs followed Haardt & Madau (1996) and F. Haardt (2002, private communication). To complement our study, we performed DM-only simulations of this same halo at similar and 8 times higher resolution and 50% better spatial resolution. These simulations showed that the main properties of the galaxy's DM halo (inner profile, spin) are not changed substantially by the introduction of WDM, as the galaxy mass is much greater than the free-streaming mass at $10^{9.5}\ M_{\odot}$.

3. RESULTS

Within the ΛCDM galaxy virial radius (defined by $\delta\rho/\rho_{\rm crit} = 97.1$ at $z = 0$), there are $\sim 1.2\times10^5$ DM, 5×10^4 gas, and 6×10^5 star particles. The main parameters of the galaxies at $z = 0$ are described in Table 1. Star formation (Fig. 1) begins at $z = 10$, before the external UV background kicks in at $z \sim 7$. The star formation rate (SFR) peaks around $z = 5$ at 80 $M_{\odot}$ yr^{-1}, while for the ΛWDM run, the peak is delayed and is only 45 $M_{\odot}$ yr^{-1} at $z = 4$ because of the effect of removal of power at small scales.

In both cosmologies, the bulge of the galaxy forms through a series of rapid major merger events that end by $z = 2.7$, turning mostly low angular momentum gas into stars. At $z = 2.5$, the hot gas ($T > 10^5$ K) left within 50 kpc has a higher specific angular momentum than the DM (van den Bosch et al. 2002). Soon after the last major mergers, the disk starts forming from the infall of this high angular momentum gas. At this stage, the disk of the ΛWDM galaxy is thinner than that formed in the ΛCDM one. In both simulations, the final 3–4 Gyr of evolution are marked by a bar instability, seen also in our own Milky Way (Cole & Weinberg 2002), and by repeated encounters of the galaxy with a few relatively massive infalling satellites.

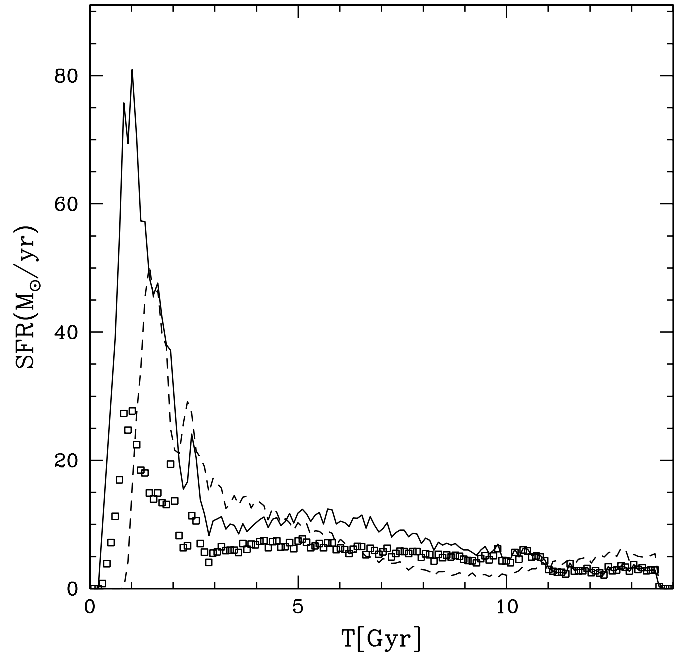

Fig. 1.—SFR of the ΛCDM (*solid line*) and ΛWDM (*dashed line*) galaxies. The small squares show the SFR of the ΛCDM disk.

3.1. *The Galaxy Bulge and Disk Components*

The resulting galaxies show that we successfully formed extended and fairly old stellar disks in Λ-dominated hierarchical models. In Figure 2, the stellar spheroid (including bulge and halo stars) is defined as the sum of all stars born before or at the time of the last major merger; this selects low angular momentum stars for which $v_{\rm rot}/\sigma < 0.5$ (where $v_{\rm rot}$ is the tangential velocity and σ is the radial velocity dispersion), with the stars in the central few kpc having a $v_{\rm rot}/\sigma$ as low as 0.1–0.2, similar to what is inferred for the stars belonging to the spheroid of the Milky Way (Minniti 1996). We were not able to use a kinematic criterion to separate the central bulge from the diffuse extended spheroid—this resembles what is found for our own Milky Way, where only a combination of metallicities and kinematics allows a distinction (Minniti 1996). We fit a de Vaucouleurs profile, characterized by a scale length R_b, to

TABLE 1

Masses of Galaxy Components, Bulge-to-Disk Ratios and Disk Scale Lengths for the Simulations at $z = 0$

Run	$M_{\rm total}$ ($M_{\odot}$)	$M_{\rm cold\ gas}$ ($M_{\odot}$)	$M_{\rm disk+bulge}$ ($M_{\odot}$)	$M_{\rm stars}$ ($M_{\odot}$)	$M_{\rm bulge}:M_{\rm disk}$	$R_{\rm disk}$ (kpc)
ΛCDM............	3.34×10^{12}	2.0×10^9	1.4×10^{11}	2.75×10^{11}	1:2.8	3
ΛWDM...........	2.7×10^{12}	5.9×10^9	1.1×10^{11}	1.52×10^{11}	1:4	3.6

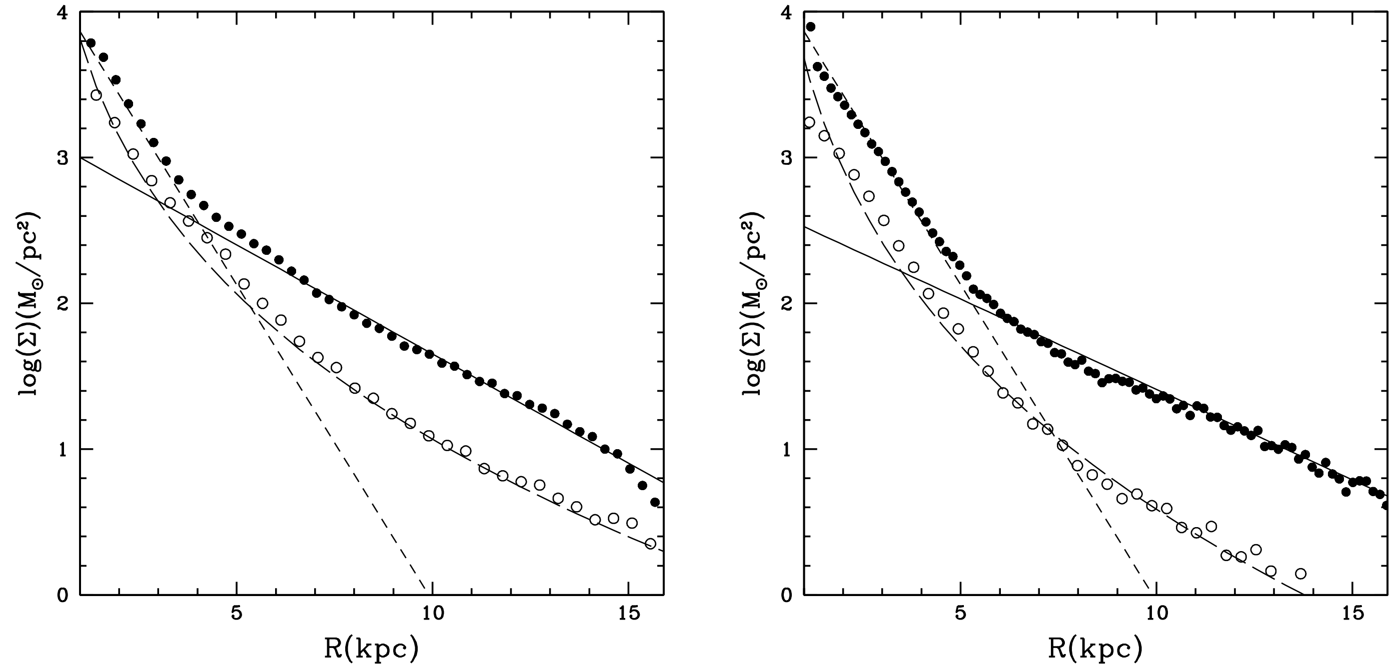

FIG. 2.—Stellar surface density profiles for the different stellar components at $z = 0$, for (*left*) the ΛCDM and (*right*) the ΛWDM galaxies. Filled circles are for the total stellar surface density profile, open circles are for the spheroid only (stars older than 10 Gyr). The solid lines are exponential fits to the disk component, with scale lengths 3 and 3.6 kpc for the ΛCDM and the ΛWDM galaxy, respectively. The short-dashed lines are exponential fits to the central stellar mass distribution, with scale lengths of 1 kpc for both galaxies (the bar and the bulge are both contributing); the long-dashed lines are a de Vaucouleurs fit to the spheroid, with scale lengths of 800 pc (ΛCDM galaxy) and 500 pc (ΛWDM galaxy).

the old stellar distribution and then define the mass of the bulge as twice the mass contained within R_b (R_b by definition corresponds to the half-mass radius of the system if we rely on the fit). This yields the total bulge masses indicated in Table 1 (more precisely, the ratio between the mass of the bulge and the mass of the disk, $M_{\rm bulge}/M_{\rm disk}$ is indicated there), and the bulge scale length is about 800 and 500 pc in the ΛCDM and the ΛWDM runs, respectively.

At $z = 0$, a flat, rotationally supported stellar component with $v_{\rm rot}/\sigma > 1$ extends out to almost 20 kpc (Fig. 3). This disk component is thinner and dynamically colder (lower $v_{\rm rot}/\sigma$) in the ΛWDM model. The decomposition of the stellar distribution into a dynamically separate disk and a bulge is complicated by the presence of a third component, namely, a prominent barlike structure. The latter is significantly more elongated and easier to distinguish in the ΛWDM galaxy. In

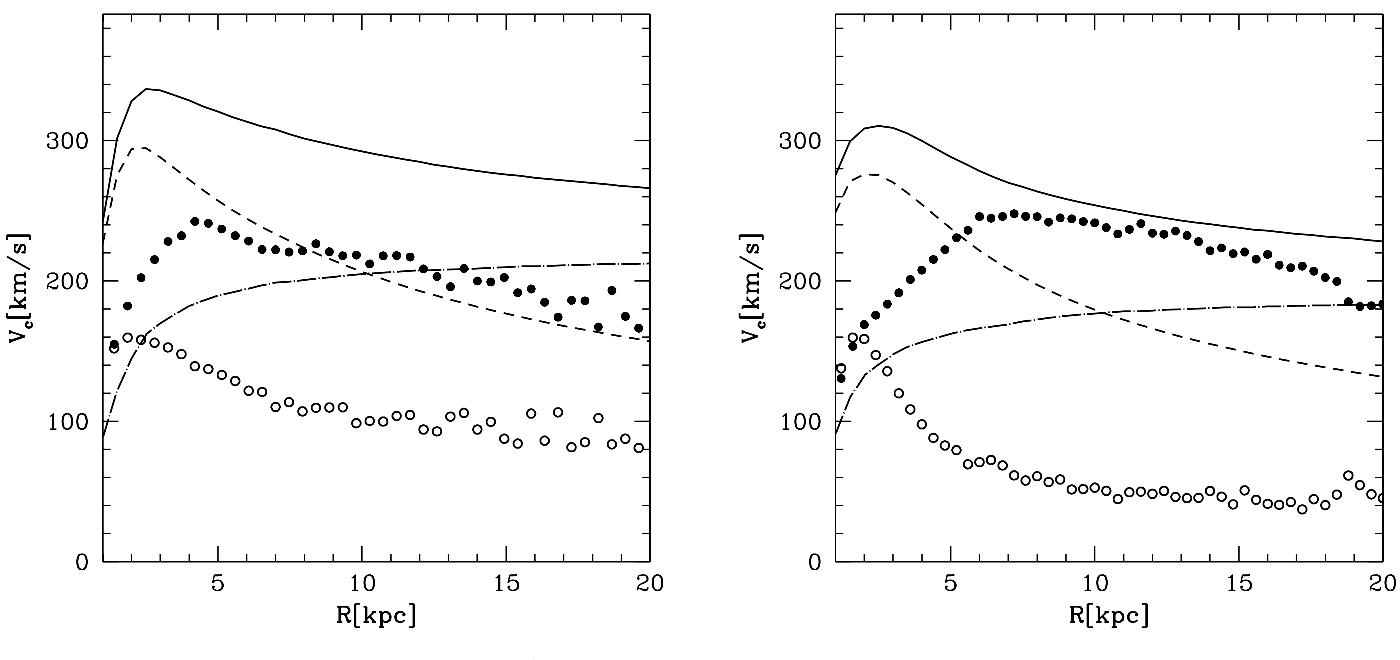

FIG. 3.—Rotation curve (defined as $V_c = \{M[(r < R)/R]\}^{1/2}$) for all components (*solid line*), stars (*dashed line*) and DM (*dot-dashed line*) for the ΛCDM galaxy (*left*) and for the ΛWDM galaxy (*right*) at $z = 0$. The stellar kinematics are also shown: the rotational velocity is indicated by the filled circles, while the (azimuthally averaged) radial velocity dispersion in cylindrical coordinates (the z-axis being chosen along the angular momentum vector of the disk) is shown with open circles.

the ΛCDM galaxy a "fat" bar or oval distortion typical of early-type galaxies (Athanassoula 2003) is first seen at $z = 0.6$ and then is progressively thickened by tidal heating from infalling satellites as well as by numerical heating, becoming progressively harder to distinguish. However, its signature is clearly evident in the kinematics: if we select all stars younger than 10 Gyr, i.e., born after the last major merger, the kinematics are disklike from 20 kpc going toward the center ($v_{\rm rot}/\sigma > 1.5$), but become hotter ($v_{\rm rot}/\sigma \simeq 1$) at 3–4 kpc from the center, the transition being sharper in the case of the ΛWDM galaxy (Fig. 3).

As mentioned above, the stellar density profiles of both galaxies at $z = 0$ is thus the sum of the old spheroid formed by the last major merger and the much younger stellar bar in the inner few kpc, whereas the cold disk dominates in the outer part. The stellar surface density is shown in Figure 2. A double exponential provides a very good fit to the data. However, from Figure 2 it is worth noting that a straightforward $M_{\rm bulge}/M_{\rm disk}$ decomposition based on the inner and outer component resulting from such a fit would give erroneously large bulge masses and sizes, because it counts the thin, rotating, and relatively young stars in the bar as part of the bulge. The overestimate of the bulge mass would be particularly severe in the ΛWDM galaxy.

Given the initial halo spin ($\lambda = 0.030$–0.035), the disks have scale lengths comparable to those predicted by theoretical models in which baryons conserve their specific angular momentum during infall (see Mo et al. 1998, who take into account the adiabatic contraction of the DM halo due to the baryonic build up). The average age at the solar radius is 9–10 Gyr for the ΛCDM run (8 Gyr for the ΛWDM run), in agreement with current observational estimates (e.g., van den Bergh 1996). In Figure 2 we also plot the surface-density profile of the old spheroid component—clearly this accounts only in part for the inner steepening. The bar contributes the remaining part: the connection between the presence of a bar and a steep inner stellar profile has been widely shown by a number of numerical simulations on bar formation and evolution (Sparke & Sellwood 1987; Pfenniger & Friedli 1991; Mayer & Wadsley 2003). Interestingly even in the case of the Milky Way, the debate is still ongoing as to whether the central, kinematically hot component usually identified as the bulge is actually in part or even entirely a stellar bar (Zhao et al. 1996).

Our final spiral galaxies are more massive than M31 and the Milky Way. In both cosmologies, the circular velocity (defined as $v_c = [M(r < R)/R]^{1/2}$) at the virial radius is ∼185 km s^{-1}, while recent estimates (Klypin et al. 2002) yield a v_c at the virial radius around 150–160 km s^{-1} for our Galaxy. At 2.2 disk scale lengths (a distance typically used for observational samples), $v_{2.2} = 320$ km s^{-1} (280 km s^{-1} for ΛWDM; see Fig. 3). As in other works, some of them including strong SN feedback (e.g., Abadi et al. 2003), the rotation velocity peaks even higher and in regions very close to the galaxy center that are only poorly resolved. These unrealistic high central velocities, linked to a very concentrated spheroidal component, are present in runs with and without SN feedback. They are a problem for most current galaxy formation numerical simulations.

At the end of the simulation, star formation has turned about 64% (55% for ΛWDM) of the gas inside the virial radius into stars, with the ΛCDM having a slightly larger bulge component. Only a small amount of gas within the virial radius remains in the cold phase (1.5%, compared to 2% at $z = 0.25$ and 9% at $z = 1$ in the ΛCDM). Most of it is in the central disk. The ΛWDM has 3 times as much cold gas in the disk. The exponential fits to the stellar disk mass distribution yield scale lengths of ∼3 kpc for the ΛCDM and ∼3.6 kpc for the ΛWDM. Bulge scale lengths are considerably smaller (Fig. 2, *left*).

The latter fits to the stellar distribution were obtained excluding the inner, bar-dominated region from the disk. Strictly speaking, the bar is part of the disk, since it was formed from disk material that underwent nonaxisymmetric instabilities. Therefore, we also tried fitting a single exponential over the whole stellar component with age less than 10 Gyr; given the remarkable change of shape of the stellar density profile at a few kpc from the center, a single exponential provides a poor description. Nevertheless, it is worth noticing that by doing this, the scale lengths drop to 2 kpc and 1.5 kpc for the ΛCDM and the ΛWDM galaxy, respectively (as expected, the change is more marked for the ΛWDM galaxy, which exhibits a stronger and longer bar). In the existing literature (see Carollo et al. 2001; Debattista et al. 2004), the flatter component of the stellar profile is always included in the definition of the disk, while bars are often identified with a central bulge. These results support our double fits and the resulting scale lengths.

By measuring the ratio of the specific angular momentum inside the virial radius of the halo in a DM-only version of the simulations to that of the stellar disk at $z = 0$, we found that ∼60% of the specific angular momentum has been lost in the ΛCDM galaxy and only 10% in the ΛWDM galaxy. The expected disk scale length R_d, based on the models by Mo et al. (1998; see also Fall 1983 and Navarro & Steinmetz 2000), is 3.4 kpc (ΛCDM), assuming a 50% loss of the specific angular momentum, and is thus very close to what we find, once the halo's spin and the adiabatic contraction of the dark halo due to the formation of both the bulge and the disk are taken into account. By neglecting the latter, a much larger disk scale length of ∼5 kpc would be predicted by the analytical approach. A comparison between analytical predictions by Mo et al. (1998) and observed disk galaxies (Courteau 1997) shows that the scatter in disk scale length measured by Courteau (1997) is more than a factor of 3 across the entire circular velocity range. A galaxy with a scale length of about 3 kpc and $v_{2.2} = 320$ km s^{-1} stays lower than the mean of the relation predicted by the analytical model of Mo et al. (1998), but still quite consistent with data samples that consist mostly of Sb and Sc galaxies. However, to match the average properties of disk galaxies of type Sb and later, a smaller angular momentum loss or a higher initial halo angular momentum will be required. Indeed, the ΛCDM galaxy would most likely be classified as Sa or Sab because of its prominent bulge.

Using age and metallicity information from every star particle created and single stellar population models (Tantalo et al. 1998), we find that at $z = 0$, the ΛCDM galaxy has $M_I = -24.3$ (including disk and bulge) and lies close to the Tully-Fisher relation (Giovanelli et al. 1997). Its disk *B-R* color is 1.05, while the average *B-R* in the Courteau (1997) sample is 0.8.

Internal instabilities of the stellar disk and perturbations by satellites cause structural and kinematical changes in the disk, heating it substantially after most of its mass has been assembled by $z > 0.5$–0.7. As mentioned above, the inner, colder regions where Q (Toomre's instability parameter) is initially less than 2 become unstable to a barlike mode at $z \sim 0.6$; part of the gas loses angular momentum to the stellar bar, flows to the center, and becomes the site of a final episode

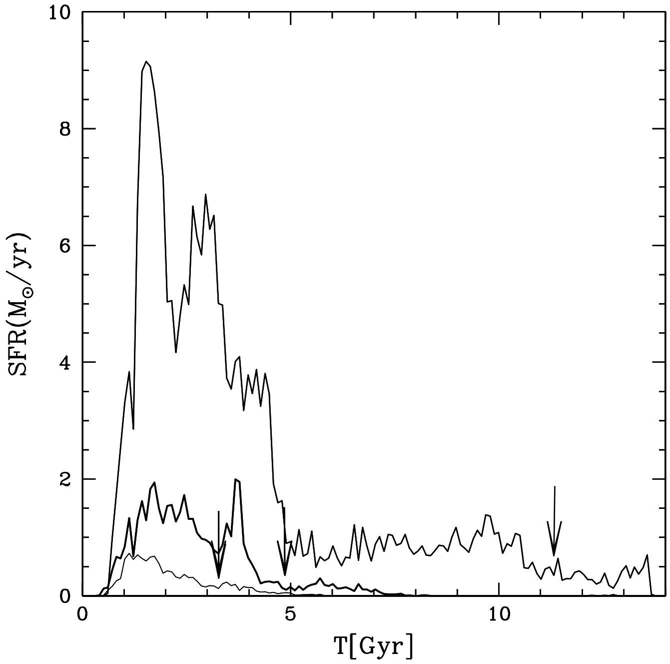

FIG. 4.—Star formation histories for three satellites of the ΛCDM galaxy at $z = 0$. Arrows mark the time they entered within $R_{\rm vir}$. The satellites' SFR peaks correspond to merger events and pericentric passages.

of star formation. The disk of the ΛWDM galaxy stays thinner, because tidal heating by satellites is largely suppressed. We test (§ 4) whether the ΛCDM galaxy becomes bar-unstable mostly because of its fairly massive disk (Efstathiou et al. 1982; Athanassoula & Sellwood 1986).

3.2. *The Galaxy Halo*

As expected in ΛCDM models, a rich amount of substructure develops and forms a substantial stellar component because of a combination of weak feedback and early star formation. In excess of what is observed for Andromeda or the Milky Way (Mateo 1998), the ΛCDM model has at least 30 satellites with stellar masses larger than 1.35×10^9 $M_\odot$. Consistent with its lack of small-scale power, the ΛWDM galaxy only has seven. A total of 20% of the stars formed within the virial radius of the ΛCDM galaxy are in the satellites, and another 15% are in the halo within $r > 20$ kpc. In comparison, because of its lack of power at small scales, only 15% of stars are in the ΛWDM satellite system (three of them are within 35 kpc of its center), and only 0.2% of the stars are in the outer part of the halo. The most massive (and best resolved) satellites show a large variety of star formation histories (Fig. 4) in both cosmologies. Their star formation ceases a couple of Gyr after entering the halo of the primary galaxy. At $z = 0$, the stellar component of the dwarfs that entered the galaxy halo at $z \geq 0.5$ are supported by velocity dispersions, while those outside or that have just fallen in have recognizable disks, as expected if dynamical encounters are the major drivers of satellites morphologies as in the "tidal stirring" scenario (Mayer et al. 2001). In both models, the diffuse halos contain the oldest stars, but they also grow continuously until late epochs from material stripped after the last major merger, which gives rise to the bulge, and from the debris of disrupted satellites.

The amount of baryons (including stars and cold and hot gas) inside the virial radius is within a few percent of the original cosmic abundance. The X-ray flux at $z = 0$ is $\sim 0.5 \times 10^{42}$ ergs s^{-1} in both cosmologies; this value doubles if a metal abundance of 0.3 solar is assumed for the gas in the halo. This is larger than expected from observations; for example, the large disk galaxy NGC 2841 has a bolometric emission of only 1.3×10^{41} (Benson et al. 2000; Murali 2000). As expected with the weak feedback adopted and the long cooling times in the outer part of this relatively massive halo, a hot gas phase is always present within the virial radius, and X-ray luminosity evolution is weak to $z = 1$. The overabundance of halo baryons (in all its various subcomponents, hot gas, satellites, and diffuse stellar halo) is clearly a problem of both cosmologies. While the WDM galaxy has a substantially smaller stellar halo component, possibly in agreement with observations, its X-ray emission is high and very similar to the ΛCDM one. This is expected, as power reduces at subgalactic scales, and does not affect the total mass and the accretion rate of halo baryons. According to the existing literature and the work presented here, energy feedback, the reduced amount of small-scale power, and increased resolution tend to increase the size of galactic disks, but the amount of hot gas in halos of large galaxies is likely only sensitive to feedback. X-ray observations sensitive to sub-keV temperatures of nearby massive galaxies would set powerful constraints on the amount of energy injected by different processes into the baryonic component during the formation of the galaxy, as they currently do on the larger scale of small groups (Borgani et al. 2002), pointing to at least 0.5 keV per baryon. As an alternative, Toft et al. (2002) suggest that the excess X-ray emission could be reduced, allowing a detailed treatment of cooling by metal lines that would reduce the amount of hot gas left in the halo. Current global estimates of galaxy formation efficiency set it at about 10% (Bell et al. 2003), which is significantly lower than the high star formation efficiency in our runs, suggesting that ejection of baryons from the halos of disk galaxies is likely to be necessary to avoid excess X-ray emission from galaxy halos. The hot-gas component of the Milky Way has just recently been detected (see Sembach 2003), and future observations will provide useful constraints on its properties.

4. ROBUSTNESS OF NUMERICAL RESULTS: SOLVING THE ANGULAR MOMENTUM PROBLEM

The main finding of this work is that the angular momentum and consequently the scale length of the stellar disk formed in our simulations is comparable to that of real galaxies of similar luminosity. This result was not obtained adopting the usually advocated strong feedback to decrease the lumpiness of the gas being accreted, but rather using good mass and force resolution. Is then the addition of feedback still a necessary ingredient to obtain realistic galaxies? How much is the formation and evolution of disk stellar systems affected by limited resolution?

It is now widely recognized that 10^5–10^6 particles with a force resolution close or better than 1% $R_{\rm vir}$ are necessary to reliably simulate the formation and the internal structure of a single DM halo (Ghigna et al. 2000; Fukushige & Makino 2001). It is then unlikely that the much more complex formation of disk galaxies could be reliably simulated with significantly less particles. A comparison with our higher resolution DM-only runs shows that the mass function of DM subhalos becomes severely incomplete below 30–35 km s^{-1}. On the positive side, this implies that at our resolution we are resolving the mass range of the progenitor that contributes most of the mass in the accretion history of the central galaxy and most of the mass in the subhalo population. With more than 10^5 particles within the virial radius, our simulations accurately follow the evolution of the hot gaseous phase (see tests in Frenk et al. 1999; Borgani et al. 2002; Wadsley et al. 2004).

The final angular momentum of a stellar galactic disk is set first by the details of hierarchical accretion onto the parent halo and the subsequent cooling of high angular momentum gas. Once a disk of baryonic material is formed, disk instabilities could redistribute the original angular momentum of the disk both internally and to the DM halo (Weinberg & Katz 2002; Valenzuela & Klypin 2003). Both stages are potentially affected by numerical viscosity (present in the SPH approach to describe shocks) and numerical relaxation introduced by noise in the global potential due to small particle numbers. These effects reduce the angular momentum of the disk by artificial dissipation and by transfer to the halo component, respectively.

To measure the importance of the numerical effects mentioned in the above paragraph independently of the hierarchical buildup, we built an isolated galaxy system (following Springel & White 1999) with the same structural parameters (mass, profile, fraction of mass in the disk and in the bulge, relevant scale lengths, and fraction of cold gas in the disk) as our ΛCDM galaxy at $z = 0.6$, i.e., soon after the formation of the disk; results can likely be extended to the ΛWDM galaxy. All components were made of "live" particles. The galaxy was evolved in isolation for 6 Gyr. We ran different versions of it, changing the number and accordingly the mass and softening of the stellar, DM, and gas particles (see Fig. 5). Softening for the different component in the different realizations was scaled as $\epsilon_{\rm test} = \epsilon_{\rm cosmo}(m_{\rm test}/m_{\rm cosmo})^{1/3}$, where $\epsilon_{\rm cosmo}$ and $m_{\rm cosmo}$ were the softening and masses used in the main cosmological runs for each component.

In our lowest resolution realization (25 times fewer particles than in our cosmological runs), the number of halo (DM) particles and particles representing stars in the disk goes below a few thousands and the disk (defined as all the particles originally assigned to the disk component) loses almost 70% of its initial angular momentum over 8 Gyr. A disk structure is not visible at the final (present epoch) time (Fig. 5, *short-dashed line*). Angular momentum loss is greatly reduced, as first the number of DM particles and then the number of particles in the stellar disk is increased (*long-dashed and dot-dashed lines*). At the resolution of our cosmological runs (*solid line*), the loss is down to only 10% across most of the disk, reaching 30% in the inner 2 kpc. Even in this isolated model, a bar forms in the disk. Finally, we verified that when the collisionless components are well resolved, gas angular momentum loss due to artificial viscosity becomes less than 10% over several Gyr if the disk gas component is represented by at least a few thousand particles (in agreement with Navarro & Steinmetz 2000). We expect numerical effects will continue to decrease as the numerical resolution (both spatial and chronological) is increased.

To verify that our findings are applicable in a full cosmological context where the hierarchical build is included, we also run a low-resolution realization (with one-eighth of the particles and twice as large an ϵ as the cosmological ΛCDM galaxy described above). In this situation, additional resolution problems could be present, as the first individual structures that form are necessarily made of small particles. Artificial viscosity could show up not only in cold gas lumps but also in poorly resolved shocks, and numerical effects could cascade down as the galaxy main body is assembled. This also implies that at the same mass and force resolution, the ΛCDM galaxy with its larger substructure mass range is intrinsically harder to simulate than the ΛWDM one. As expected, because of the low number of particles and the very poor spatial resolution by $z = 0$ in this low-resolution run, cold gas and stars within 20 kpc have lost 90% of their initial angular momentum compared to the DM and no strong stellar disk component is present, although the central part of the stellar distribution is rotationally supported. This low-resolution run is in qualitative agreement with Eke et al. (2001), where no disklike morphology was observed in their simulated galaxies. Our results imply that the disk galaxy described in TC01 (their run was stopped at $z = 0.5$) would likely show a much weaker disk component if evolved to the present time.

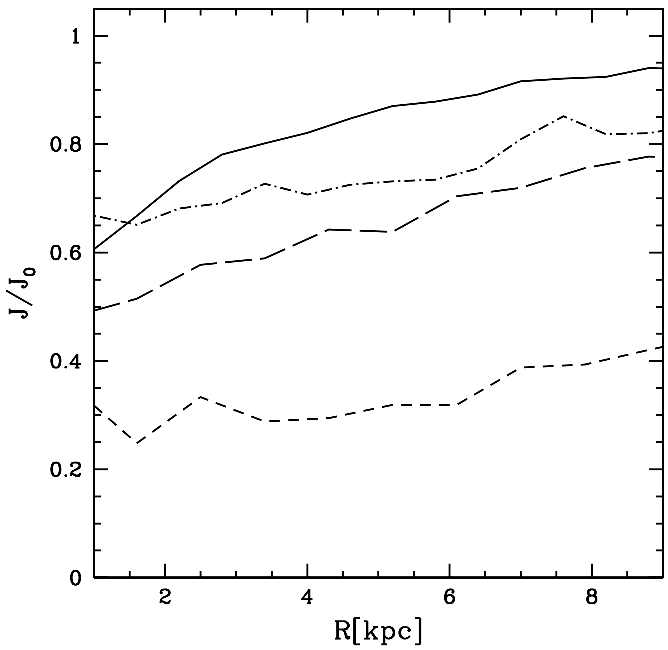

FIG. 5.—Angular momentum loss in an isolated disk galaxy model with structural parameters as our ΛCDM run at $z = 0.6$. This model was run for 6 Gyr (equivalent to the present time). The y-axis is the fractional angular momentum loss for all the baryonic material in the disk; the x-axis is the radius. *Solid line*: $N_{\rm DM} = 100{,}000$, $N_{\rm star} = 200{,}000$, and $N_{\rm gas} = 5000$ (same as in the cosmological run). Our choice of spawning a large number of star particles (typically 6 per gas particle) in the cosmological run reduces internal heating of the stellar disk. *Dot-dashed line*: Values are as above, but $N_{\rm DM}$ and $N_{\rm star}$ are reduced by a factor of 5. *Long-dashed line*: $N_{\rm star}$ is reduced by a factor of 25. *Short-dashed line*: $N_{\rm DM} = 4000$, $N_{\rm star} = 8000$, and $N_{\rm gas} = 1000$. At the lowest resolution, the disk undergoes the catastrophic angular momentum loss reported in early simulations.

To show the effects of resolution on a galaxy with different mass and merging history from that in our main runs, we resimulated to $z = 2$ (with similar techniques as described for the main runs) a small dwarf-galaxy–sized halo ($9 \times 10^{10}\ M_\odot$) at the outskirts of our Milky Way–sized halo at 8 times better mass resolution. As the number of DM particles within $R_{\rm vir}$ (gas particles were increased accordingly) increased from ~3000 to almost 2.5×10^4 and with softening set at 0.5 kpc, the stellar component of this dwarf galaxy became more rotationally supported as v/σ changed from 0.46 to 0.77, and a gaseous disk became apparent. The shape and amplitude of the SFR(z) did not change substantially, showing that we are qualitatively capturing the events that drive star formation in the small galactic satellites of our main runs.

To summarize, at the best resolution for our main runs numerical effects are likely responsible for the angular momentum loss in the ΛWDM disk (∼10%). As described in § 3, the ΛCDM disk loses significantly more angular momentum than its equivalent in the ΛWDM. The only difference in the two runs are the initial power spectra, with ΛCDM having significantly more substructure under 50–100 Km s^{-1}. This result suggests that *at the current resolution* and as suggested by early works, the intrinsic clumpiness of the hierarchical formation process leads to significant angular momentum loss, likely through interactions between the infalling lumps (Lake & Carlberg 1988) before the disk has formed. However, at our resolution, this angular momentum loss is far from catastrophic, as the fraction of mass contained in surviving sublumps within a larger parent halo is only of the order of 15% (Ghigna et al. 2000). A large fraction of mass is tidally stripped from the subhalos as soon as they first go past pericenter (Mayer et al. 2001). This material typically loses only a small fraction of its initial angular momentum (Colpi et al. 1999). If this high fraction of stripped material is also typical of the gas accreted by the disk, then most of it actually forms from diffuse material cooling from the hot halo, rather than from individual lumps.

Our results suggest that the large angular momentum loss or the lack of well-defined stellar disks reported in early works might have resulted from poor force or mass resolution. The tests done with the isolated galaxy model suggest that two-body heating by massive halo particles would be the main cause of angular momentum loss at low resolution if small softenings were used. As done in some previous works, two-body heating can be suppressed by using a larger softening without increasing the number of particles. However, even softenings as small as the values used here are barely enough to resolve the disk and avoid spurious results for its morphological evolution; suppression of disk self-gravity by a softening larger than the disk scale length would inhibit processes such as bar formation that are essential ingredients in disk formation and evolution (Romeo 1992, 1994; Weinberg & Katz 2002; Valenzuela & Klypin 2003; Mayer & Wadsley 2004).

We also evolved another isolated galaxy model with the same structure and numerical resolution as the ΛCDM galaxy, but with a stellar disk only 50% as massive. This disk does not show the bar instability present in the other runs, and its angular momentum loss is slightly lower. This experiment also implies that disk-satellite interactions have only a limited effect on the development of the bar instability and in the angular momentum loss of the disk.

Finally, it is likely that our adopted feedback recipe is too simplistic, and although it models the build up of the disk population well, it does not stop star formation at high redshift in small halos, creating an excess of massive satellites in the ΛCDM galaxy. The paucity of cold gas in our final state suggests that our star formation algorithm is likely too efficient, at least compared to the universal value of 10% or less (Bell et al. 2003), although it is difficult to quantify such a statement with only one run.

5. SUMMARY AND DISCUSSION

We simulated the formation of a disk galaxy in a cosmological context to the present time with a high force and mass resolution. Without resorting to strong feedback recipes, we successfully formed an object with bulge-to-disk mass ratios, scale lengths, current star formation, disk age, and dynamical properties representative of those observed in present-day massive spirals. Our results show that the large angular momentum loss reported in some early works was in at least in part due to insufficient mass or force resolution. High resolution plays a significant role in correctly simulating the formation of disk galaxies in a cosmological context, independently of the SN feedback recipe adopted. We estimate that at a resolution of $\sim 10^5$ particles within $R_{\rm vir}$ for each of the DM, gas, and stellar components, numerical effects still account for 10% of the disk angular momentum loss during its formation and evolution.

WDM improves on the standard ΛCDM model in a few aspects, namely, it reduces the number of satellites, and the galaxy forms with a smaller bulge and almost no stellar halo component. Within the simulation its disk is more gas-rich at the present time and has colder kinematics (lower $v_{\rm rot}/\sigma$). However, WDM fails to solve the issue for which it was introduced: WDM does not make substantially more-extended disks.

The presence of a substantial fraction of hot gas in the halo, independent of the cosmology adopted, results in an X-ray emission higher than estimates for galaxies of similar v_c to those in our study. Numerical and semi-analytical results (e.g., Borgani et al. 2002; Babul et al. 2002) show that significant energy injection leading to an entropy floor of 50–100 keV cm^{-2} is needed on the mass scale of small groups (just a factor of 10 higher than the mass of the galaxy in our study) to reduce the fraction of hot baryons and reconcile models with the observed X-ray luminosity-temperature relation. However, additional numerical studies including cooling and detailed star formation are needed.

There is little evidence for SN energy injection of this magnitude in dwarf galaxies (Martin 1999), but it is possible that a combination of SN and active galactic nucleus activity linked to bulge formation (Binney et al. 2001) could simultaneously reduce the baryon fraction in the halo and quench early star formation in the disk and the satellites, making a large fraction of them "dark." If energy injection is required regardless of cosmology, then the need to invoke nonstandard DM models will be substantially weakened.

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