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STAR FORMATION, SUPERNOVA FEEDBACK, AND THE ANGULAR MOMENTUM PROBLEM IN NUMERICAL COLD DARK MATTER COSMOGONY: HALFWAY THERE?

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ABSTRACT

We present a smoothed particle hydrodynamic simulation that reproduces a galaxy that is a moderate facsimile of those observed. The primary failing point of previous simulations of disk formation, namely, excessive transport of angular momentum from gas to dark matter, is ameliorated by the inclusion of a supernova feedback algorithm that allows energy to persist in the model interstellar medium for a period corresponding to the lifetime of stellar associations. The inclusion of feedback leads to a disk at a redshift $z = 0.52$, with a specific angular momentum content within 10% of the value required to fit observations. An exponential fit to the disk baryon surface density gives a scale length within 17% of the theoretical value. Runs without feedback, with or without star formation, exhibit the drastic angular momentum transport observed elsewhere.

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

1. INTRODUCTION

A fundamental assumption of the analytic work on disk formation of Fall & Efstathiou (1980) is that during protogalactic collapse the baryonic component conserves its specific angular momentum (AM). Pioneering *N*-body hydrodynamic simulations (Navarro & Benz 1991) showed that baryon cores, which develop naturally within cold dark matter (CDM) simulations, systematically lose specific AM to dark matter halos during merger events, contrary to the assumption of Fall & Efstathiou. As detailed in White (1994), the resolution of this perceived "numerical problem" is widely believed to be the inclusion of feedback from supernovae (although for an alternative view see Mac Low & Ferrara 1999), which is necessary in CDM cosmologies to avoid the cooling catastrophe (White & Frenk 1991). To date, simulations incorporating feedback—using a variety of algorithms to model the process—have been largely unsuccessful in preserving the specific AM of the baryons (e.g., Katz 1992; Navarro & White 1993; Navarro & Steinmetz 2000). Models in which the gas is artificially prevented from cooling before a "cooling epoch" (Weil, Eke, & Efstathiou 1998) have been considerably more successful. Alternatively, Domínguez-Tenreiro, Tissera, & Sáiz (1998) argue that the inclusion of star formation can help stabilize disks against bar formation and subsequent AM loss. Sommer-Larsen & Dolgov (2001) have shown that warm dark matter does not suffer as significant an AM deficit problem due to the reduction in short-scale power compared with CDM.

This Letter presents results of simulations that model star formation and feedback using an algorithm tested in detail in Thacker & Couchman (2000, hereafter TC00). We achieve significant success in reproducing fundamental properties of observed galaxies: the model galaxy does not suffer a catastrophic (∼80%) loss of AM relative to the dark matter and has a disk scale length comparable with those observed and in accord with theoretically predicted values (e.g., Mo, Mao, & White 1998).

2. NUMERICAL LIMITATIONS OF FEEDBACK MODELS

It is not currently possible to model individual star formation and feedback events in cosmological simulations of disk formation. The result of limited numerical resolution is a large disparity between the minimum simulation timescale and the true physical timescale associated with supernova feedback. Physically, following a supernova, the gas cooling time very rapidly increases to $O(10^7)$ yr over the time it takes the shock front to propagate. Thus, it is the timescale—$t_{\dot{E}}$—for the cooling time to increase markedly that is of critical importance. In the smoothed particle hydrodynamic (SPH) simulation, "stars" form and "supernova feedback" occurs in gas cores that are typically less than $h_{\rm min}/5$ in diameter ($h_{\rm min}$ being the effective spatial resolution). Any rearrangement of the particles in such a small region leads to a density estimate varying by at most ∼7%. Since the cooling time in the model is dependent on the local SPH density, any energy deposited into a feedback region only reduces the local cooling rate by increasing the temperature; the SPH density cannot respond on a timescale that in real supernova events would very rapidly increase the cooling time. A successful feedback algorithm in an SPH model must thus overcome the fact that $\rho_{\rm SPH}$ does not change on the same timescale as $t_{\dot{E}}$ and consequently that cooling times for dense gas cores at $T < 10^{6.5}$ K and $\rho > 2n_B$ cm^{-3} remain short (<10 Myr; as emphasized in Sommer-Larsen, Gelato, & Vedel 1999).

3. ALGORITHM AND INITIAL CONDITIONS

We model a standard CDM model: $\Omega_b = 0.1$, $\Omega_{\rm CDM} = 0.9$, $h = 0.5$, $\sigma_8 = 0.6$, and shape parameter $\Gamma = 0.41$ with the adiabatic Bond & Efstathiou (1984) CDM power spectrum. The same candidate halo as discussed in Thacker (1999) was selected for resimulation from a 100^3 dark matter–only simulation of comoving width 48 Mpc. The halo, of mass $1.66 \times 10^{12}\ M_\odot$, lies on a filament ∼2 Mpc long and does not have a violent merger history at low resolution.

Three SPH simulations were run: one with no star formation or feedback (NSF), one with star formation but no feedback (NF), and one with both star formation and feedback (energy smoothing [ES]; see below). The initial conditions for each simulation were prepared by creating four mass hierarchies in radial shells within the 48^3 Mpc^3 (comoving) simulation volume. The central high-resolution region is 6 Mpc in comoving diameter and has a total mass of $7.8 \times 10^{12}\ M_\odot$ and a particle number of 2 × 65,454 yielding particle masses of $1.2 \times 10^7\ M_\odot$ and $1.1 \times 10^8\ M_\odot$ for gas and dark matter, respectively. The minimum "glob" and dark halo mass resolutions are 52 times higher,

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corresponding to the number of SPH neighbors. The dark matter particle mass is small enough to avoid spurious two-body heating of the gas particles (Steinmetz & White 1997). Only the high-resolution region includes SPH particles, which were given an initial temperature of 100 K. The particle positions were drawn from a "glass," and the power spectrum was truncated at the Nyquist frequency of each hierarchy. A Plummer softening length of $\epsilon = 3$ kpc was chosen, and the minimum SPH smoothing length was $h_{\rm min} = 3.52$ kpc.

The star formation and feedback algorithms are described in detail in TC00; the key features are summarized here. Radiative cooling is included for a gas of metallicity 0.01 $Z_\odot$. The star formation rate (SFR) is calculated using a Lagrangian Schmidt law: $\dot{M}_* = (4\pi G\rho_g)^{1/2}\, c^* M_g = c^* M_g/t_{\rm free\,fall}$. The SFR normalization (or star formation efficiency) was set to $c^* = 0.06$, 50% higher than the Local Group estimate of Gnedin (2000). Each gas particle carries an associated "star mass" and can spawn two star particles, each half the mass of the original gas particle. This procedure leads to a delay between star formation and the associated feedback (see TC00 for a full discussion). After spawning the first star particle, the gas particle mass is decremented accordingly. The ES algorithm (ESa in TC00) smooths 5×10^{15} ergs g^{-1} of feedback energy over the SPH neighbor particles after a star formation event and allows this energy to persist in an adiabatic state for a time $t_{1/2} = 30$ Myr, after which the energy is allowed to radiate away. The 30 Myr period is motivated to coincide with the lifetime of stellar associations (Gerritsen 1997) and is longer than the 5 Myr value used in TC00. Star formation is allowed only in regions where the baryons are partially self-gravitating, $\rho_b > 0.2\rho_{\rm DM}$, and the local flow is converging ($\boldsymbol{\nabla}\cdot\boldsymbol{v} < 0$).

It is worth noting that since the adiabatic period in the ES algorithm, $t_{1/2}$, is not a function of resolution, the (resolution-dependent) Courant condition does not guarantee a sufficiently short time step for feedback regions to expand. We have found that $dt < 0.1t_{1/2}$ is necessary. This criterion imposes a maximum time step length of 2 Myr, although in practice the time step is limited by other criteria. At lower resolution, this criterion would become significant, which may partially explain the comparatively poor results for the ES feedback algorithm observed in TC00, where the algorithm was observed to have only a minor impact on AM values.

4. RESULTS

The simulations were integrated to $z = 0.52$, which required 15,930 (15,900; 17,440) time steps for the ES (NF; NSF) runs, respectively, requiring between 9 and 14 days on a four-node Alphaserver ES40. Minimum time step values were $dt_{\rm min} = 0.12$ Myr for all simulations, and average values were $dt = 0.44$ (0.44; 0.40) Myr. At $z = 0.52$, the virial radius was $r_{200} = 203.4 \pm 0.4$ kpc, and particles from the second mass hierarchy had reached $1.5r_{200}$, preventing reliable further integration. The relaxation argument in Thomas & Couchman (1992) implies that four particles per softening volume is necessary to avoid two-body heating in the dark matter at $z = 0.52$, which is satisfied in the densest regions of the simulation. At this epoch, there were 14,546 (14,466; 14,403), 8350 (5805; 12,713), and 13,193 (17,264; 0) dark matter, gas, and star particles within r_{200}. At this SPH resolution, shock processes should be represented with moderate accuracy within the halo (Steinmetz & Müller 1993). Halo, disk, and bulge masses are summarized in Table 1. Disk edges are found using a surface density cut as in TC00, with a slightly lower limit of 7×10^{12} $M_\odot$ Mpc^{-2} due to the increased mass resolution. At $z = 0.52$, the disk edges defined in this way were at 29 (19; 13) kpc. A comparison of the gas content shows that at this epoch the ES galaxy has 3.1 times more gas than the NF run.

TABLE 1
HALO, DISK, AND BULGE MASSES AND BULGE-TO-DISK RATIOS FOR THE SIMULATIONS

Run	M_h ($\times 10^{12}$ $M_\odot$)	M_b ($\times 10^{10}$ $M_\odot$)	M_d ($\times 10^{10}$ $M_\odot$)	Bulge : Disk
ES	1.56	6.69	3.94	1.69 : 1
NF	1.55	6.54	3.26	2.01 : 1
NSF	1.55	7.98	2.15	3.71 : 1

Although the first gas cores are in place by $z = 9$, star formation begins at $z = 5.6$ and the first feedback events occur at $z = 3.95$. A peak SFR of 51 $M_\odot$ yr^{-1} is reached for the NF run at $z = 2.75$, while for the ES run the peak is 27 $M_\odot$ yr^{-1} at $z = 3.42$. Due to feedback, the ES SFR is suppressed by up to 35 $M_\odot$ yr^{-1} compared to the NF run between $z = 3.4$ and $z = 1.6$. At $z = 0.52$ the average SFRs over the previous 0.4 Gyr are 1.67 $M_\odot$ yr^{-1} for the ES run and 0.96 $M_\odot$ yr^{-1} for the NF run. By $z = 1$ in the ES run, 98% of the bulge mass is in place, and formation of the extended gas disk begins largely after this epoch. The morphology of the ES galaxy is type S0; i.e., the system has a distinct disk and bulge component, while the NF galaxy is closer to E7, with a thin gaseous disk embedded within it.

4.1. *Effect of Feedback on Overcooling*

In Figure 1, we plot the mass filling factor for the gas $f_m(n, T)$, defined as the fraction of mass per unit logarithmic interval at density n and temperature T. The integrated, constant density, cooling curves are also shown to separate gas which can cool from that which cannot. The $z = 3$ plot for the NF run shows hot, low-density (halo) gas ($T \sim 10^6$ K, $n_B \sim 10^{-5}$ cm^{-3}), cooled gas cores ($T \sim 10^4$ K, $n_B > 10^{-3}$ cm^{-3}), and cold void gas ($T < 10^4$ K, $n_B < 10^{-6}$ cm^{-3}). The ES simulation develops a new hot, high-density phase, which at $z = 3$ has $T \simeq 10^6$ K, $n_B \simeq 0.01$ cm^{-3}, and $\log f_m \simeq -1.3$, indicating that only a small amount (about the same as the hot halo) of the gas is in this phase. The "bridge" ($f_m > -2.0$) between the hot high-density phase and the hot low-density phase (to the left of the cooling line) shows that some of the gas is being heated sufficiently and rising high enough in the halos to have $t_{\rm cool} > 5$ Gyr. This highlights the point that gas does not have to be blown away to make it unavailable for disk formation. However, it is clear from the $z = 1$ plot that the predominant evolutionary pathway for feedback is recycling of gas back into the cold, high-density phase for which cooling times remain less than 1 Gyr.

4.2. *Angular Momentum and Disk Scale Length*

Navarro & Steinmetz (2000) argue, following work by Mo et al. (1998) and using the observations of Mathewson, Ford, & Buchhorn (1992) and Courteau (1998), that the ratio of specific AM between disk and halo components, c_j, should be given by

$$c_j = \frac{j_d}{j_h} \simeq \frac{0.023}{\lambda}\frac{\Delta}{200}\left(\frac{V_c}{V_{200}}\right)^2 \qquad (1)$$

at $z = 0$, where Δ is the average overdensity within the virial radius, V_c is the disk circular speed, V_{200} is the circular speed at the virial radius, and λ is the spin parameter of the halo.

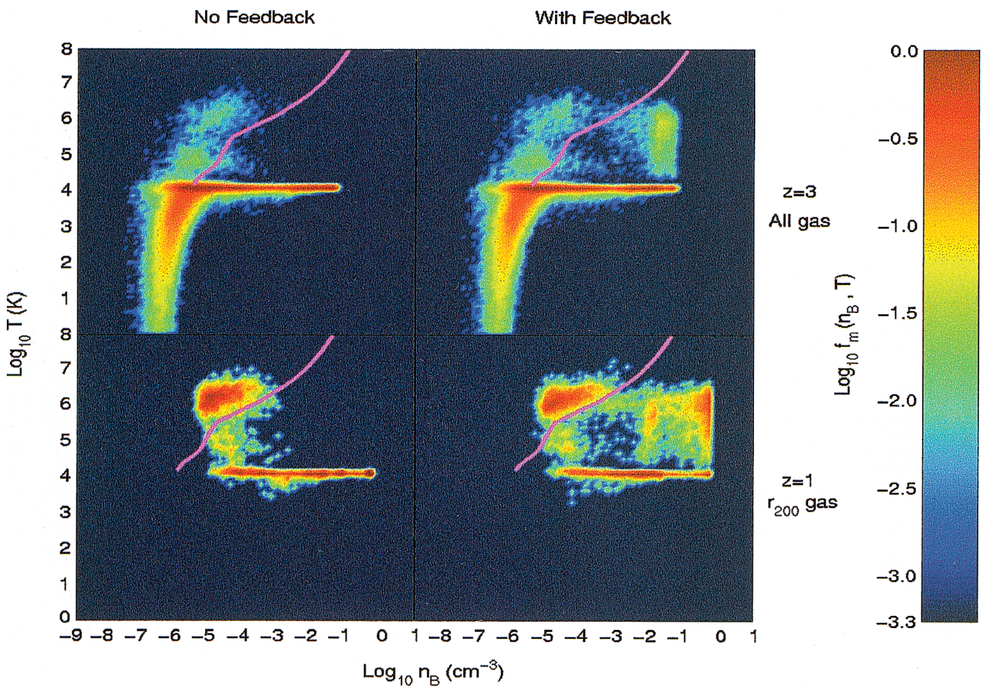

FIG. 1.—Density-temperature filling functions for the NF run (*left*) and ES (*right*) at $z = 3$ (*top*) and $z = 1$ (*bottom*). The magenta lines separate gas that can cool (*below the lines*) and cannot cool (*above the lines*) by $z = 0$ at each epoch ($t_{\rm cool} = t_0 - t$).

Thus, if a disk galaxy within a halo of overdensity 200 has the same V_c as V_{200} and $\lambda = 0.05$, then the disk component preserves one-half of its initial specific AM. For the ES simulation, $V_{200} = 191$ km s^{-1}, $\lambda = 0.075$, and $V_c = 258$ km s^{-1} at $r = 40$ kpc, which, extrapolated to $z = 0$, predicts $c_j = 0.55$. Parameters for the NF run are identical (to within 2%).

In Figure 2, we plot the specific AM of the halo, galaxy (bulge + disk), and dense cores at $z = 0.52$ for both simulations.

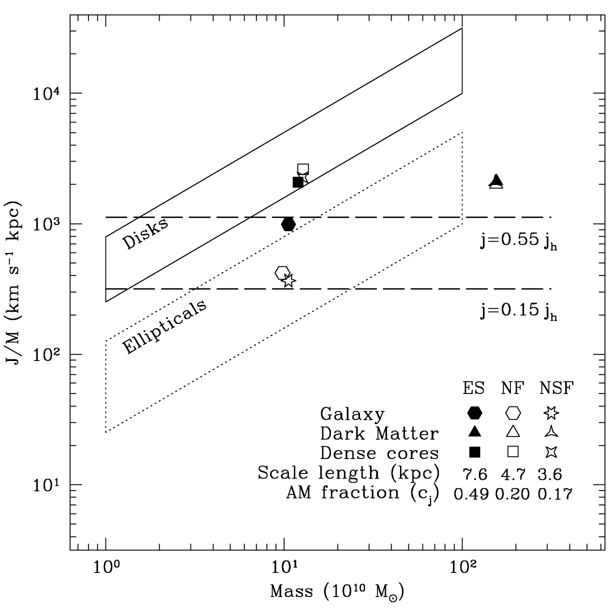

FIG. 2.—Specific AM for various components of the simulations at $z = 0.52$. The ES simulation achieves a j-value close to the combined observational and theoretical constraint $j_d \simeq 0.55 j_h$. Boxes are inferred from data assembled by Fall (1983). Scale lengths are derived from the exponential fits to the disks described in the text and values of $c_j = j_d/j_h$ are also given.

The most significant result is that the specific AM of the entire ES galaxy is only 10% lower than the predicted value of $c_j = 0.55$. Both the NF and NSF runs have minimal amounts of AM. This does not agree with the findings of Domínguez-Tenreiro et al. (1998), who argue that star formation can help prevent the formation of an AM-robbing bar. However, since the NSF simulation does not form a bar, our argument is not conclusive. As expected, the bulge components (not plotted) exhibit an extreme deficit of specific AM ($j_{\rm bulge} \sim 0.01 j_h$) having been formed primarily from first generation infall that has been subjected to little feedback (even in the ES run). The dense cores, defined as all the baryons within r_{200} satisfying $\delta_b > 2000$ (i.e., the galaxy plus satellites), have a high specific AM value because they include the contribution of one large core at $0.8 r_{200}$ (160 kpc) that heavily biases the $\boldsymbol{r} \times \boldsymbol{v}$ calculation. A large fraction of this AM will be shed as the core merges with the central galaxy. The presence of this satellite highlights the argument of Binney, Ortwin, & Silk (2001): if one can expel the low-AM core, then baryons falling in from large radii, which naturally have a large specific AM, will produce a galaxy with a large specific AM value.

Mo et al. (1998) have constructed an analytic model of disk formation that assumes a negligible exponential disk embedded within an isothermal dark halo. They parameterize the fraction of specific AM retained within the baryons in terms of c_j and find a disk scale length given by

$$R_d = \frac{\lambda G M_h^{3/2}}{2 V_{200} |E_h|^{1/2}} c_j . \qquad (2)$$

For our simulated halos, $|E_h| = 3.45 \times 10^{52} J$, which implies $R_d = 13.2 c_j$ kpc. Using the c_j-values in Figure 2, the ES disk has an expected scale length of ~6.5 kpc, while for the NF and NSF runs the value is ~2.5 kpc. Least-squares exponential fits to our disks (measured from ϵ to the disk edge) give $R_d = 7.6$ (4.7; 3.6) kpc.

4.3. *Rotation Curve and Density Profiles*

The large size of the stellar bulge makes an accurate determination of the stellar disk rotation curve difficult. As a compromise, we concentrate on the gas disk rotation curve where star formation is ongoing. In Figure 3, we show the tangential velocity of the gas in the ES run, compared to the expected rotation curve, which has been softened using the S2 softening shape (see TC00 for details). Rotation curves for the runs are broadly similar, peaking at 327 (312; 340) km s^{-1}. The NF run has the lowest central density, as the rapid creation of stars during the formation process results in a comparatively diffuse central core, which is an unavoidable artifact of the "low" resolution of our models. Radial dark matter density profiles are almost identical, with $\rho(r) \propto r^{-2}$ interior to $r = 6$ kpc, similar to the results of Tissera & Domínguez-Tenreiro (1998). A run without baryons has a profile that matches the Moore et al. (1999) fit.

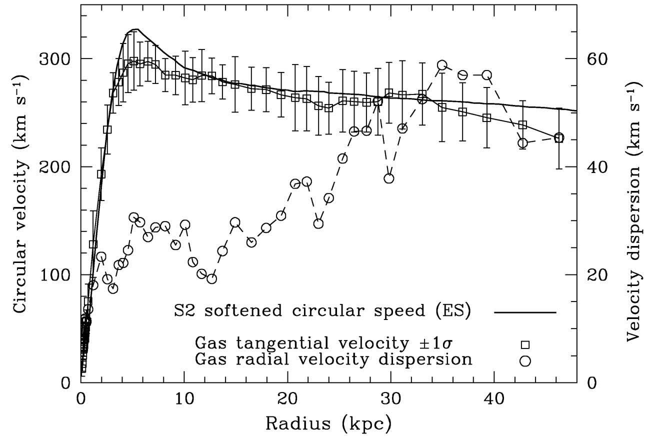

FIG. 3.—Tangential velocity and radial velocity dispersion for the ES galaxy at $z = 0.52$, averaged within 104-particle Lagrangian bins. The tangential velocities compare well with the expected circular speed.

5. SUMMARY AND DISCUSSION

Attempts to model star formation and feedback in a consistent way in previous cosmological simulations of galaxy formation have had limited success because the minimum simulation timescale far exceeds the characteristic physical feedback time. This mismatch prevents feedback energy from coupling effectively to the system—energy that is therefore unavailable to regulate star formation in the merging hierarchy. We have shown that by including a model for supernova feedback in our simulation that allows energy to persist for a timescale of 30 Myr, we have overcome this obstacle. The technique has resulted in the preservation of half of the specific AM content of the baryons in the galaxy during collapse, 10% lower than the value required to reproduce observed disks at $z = 0$. (Some part of this deficit may be viewed as being due to the high V_c/V_{200} ratio in standard CDM.) The disk scale length in the run with feedback is found to be within 17% of that predicted on theoretical grounds assuming the same fraction of specific AM loss. The inclusion of star formation alone does not help the AM problem for this halo. Furthermore, without feedback, there is a rapid exhaustion, by $z \sim 0.5$, of the gas supply for star formation: the overcooling problem in CDM cosmologies. Reducing the star formation efficiency is not a solution, as the specific AM values will remain similar to the NSF run.

The effects of varying resolution are difficult to conjecture. The assumption of the appropriate—but fixed—physical timescales is a barrier to the development of a resolution-independent model. It is worth noting, however, that our feedback prescription will always produce feedback regions of a characteristic temperature between 10^5 and 10^6 K (see TC00). At higher resolution, the first halos form with lower escape velocities and are consequently more susceptible to the effects of feedback, perhaps helping reduce the high central mass concentration evident in Figure 3. Authoritative answers await higher resolution simulations. We plan to conduct a simulation with twice the linear resolution and 8 times the mass resolution. We are also conducting a "survey" simulation using this feedback model at lower resolution, comparable to Evrard, Summers, & Davis (1994).

The galaxy that we have simulated is large and represents a relatively rare galactic event, and it is unwise to extrapolate the success of this particular model halo to a more general endorsement of CDM cosmogonies. The key result of this Letter, however, is that hierarchical structure formation is not an antirequisite for the successful formation of disks: the adoption of a plausible physical model for feedback can indeed regulate star formation and avoid catastrophic AM loss.

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