THE ASTROPHYSICAL JOURNAL, 521:L99–L102, 1999 August 20

A SIMULATION OF GALAXY FORMATION AND CLUSTERING

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Received 1999 April 28; accepted 1999 June 18; published 1999 July 8

ABSTRACT

We discuss early results from the first *N*-body/hydrodynamical simulation to resolve the formation of galaxies in a volume large enough for their clustering properties to be reliably determined. The simulation follows the formation of galaxies by gas cooling within dark halos of mass a few times $10^{11}\ M_\odot$ and above, in a flat cold dark matter universe with a positive cosmological constant. Over 2200 galaxies form in our simulated volume of $(100\ \mathrm{Mpc})^3$. Assigning luminosities to the model galaxies using a spectral population synthesis model results in a *K*-band luminosity function in excellent agreement with observations. The two-point correlation function of galaxies in the simulation evolves very little since $z = 3$, and it has a shape close to a power law over 4 orders of magnitude in amplitude. At the present day, the galaxy correlation function in the simulation is antibiased relative to the mass on small scales and unbiased on large scales. It provides a reasonable match to observations.

Subject headings: cosmology: theory — galaxies: formation — galaxies: kinematics and dynamics — hydrodynamics — methods: numerical

1. INTRODUCTION

Studies of galaxy formation have advanced at an unprecedented rate in the past few years. Data from the Keck and *Hubble Space* telescopes have revolutionized our view of the high-redshift universe (e.g., Steidel et al. 1998) and have led to claims that the main phases of galaxy formation activity may have now been observed (Baugh et al. 1999). From the theoretical point of view, modeling galaxy formation presents a formidable challenge because it involves the synthesis of a wide range of disciplines, from early-universe cosmology to the microphysics and chemistry of star formation.

Because of the strongly nonlinear and asymmetric nature of gravitational collapse, the problem of galaxy formation is best addressed by direct numerical simulation. The main difficulty stems from the huge range of scales spanned by the relevant processes, from star formation to large-scale clustering, which cannot all be simultaneously resolved with current simulation techniques. Two complementary strategies have been developed to deal with processes occurring below the resolution limit of a simulation. In one of them, a semianalytic model of the dynamics of gas and star formation is used, for example, in conjunction with *N*-body simulations of the formation of dark matter halos (Kauffmann, Nusser, & Steinmetz 1997; Kauffmann et al. 1999a, 1999b; Benson et al. 1999). This technique permits a large dynamic range to be followed, at the expense of simplifying assumptions, such as spherical symmetry, for the treatment of the dynamics of cooling gas and star formation. The alternative approach, which is the one adopted in this Letter, is to solve directly the evolution equations for gravitationally coupled dark matter and dissipative gas. This enables the dynamics of the gas to be treated with a minimum of assumptions, at the expense of a severe reduction in the accessible dynamic range. As in the semianalytic approach, a phenomenological model for star formation and feedback is required.

Eulerian and Lagrangian numerical hydrodynamics have been used to simulate galaxy formation. At present only the latter, implemented by means of the smooth particle hydrodynamics (SPH) technique, provides sufficient resolution to follow the formation of individual galaxies. For example, the best Eulerian simulations to date, such as those of Blanton et al. (1999), have gas resolution elements of ∼300–500 kpc, whereas the early SPH simulation of Carlberg, Couchman, & Thomas (1990) had a spatial resolution of 20 kpc. This together with the simulations of Katz, Hernquist, & Weinberg (1992), Evrard, Summers, & Davis (1994), and Frenk et al. (1996) were the first to resolve individual galaxies in relatively large volumes, allowing detailed studies of the distribution of galaxies and the dynamics of galaxies in clusters. However, the volumes modeled in this early work were much too small to allow reliable investigations of galaxy clustering at the present day. Galaxy clustering at high redshift has been investigated in the simulations of Katz et al. (1999).

In this Letter, we present the first results of a large *N*-body/SPH simulation of galaxy formation in a representative volume of a cold dark matter (CDM) universe, employing about an order of magnitude more particles than the largest previous study of this kind (Katz et al. 1996). Our simulation produced 2266 galaxies at the present day, compared to 60 in the simulation of Katz et al. (1992) and 58 in those of Katz et al. (1996), the only other large SPH calculations to have been evolved to the present. Earlier dark matter simulations by the Virgo Consortium (Jenkins et al. 1998) demonstrated the kind of biases required for CDM universes to provide a good match to observations of galaxy clustering. Here we show that these biases arise quite naturally.

2. THE SIMULATION

We have simulated a region of a CDM universe with the same cosmological parameters as the ΛCDM simulation of Jenkins et al. (1998): mean mass density parameter $\Omega_0 = 0.3$; cosmological constant $\Lambda/(3H_0^2) = 0.7$; Hubble constant (in units of 100 km s^{-1} Mpc^{-1}) $h = 0.7$ (hereafter we adopt this value, unless otherwise stated); and rms linear fluctuation am-

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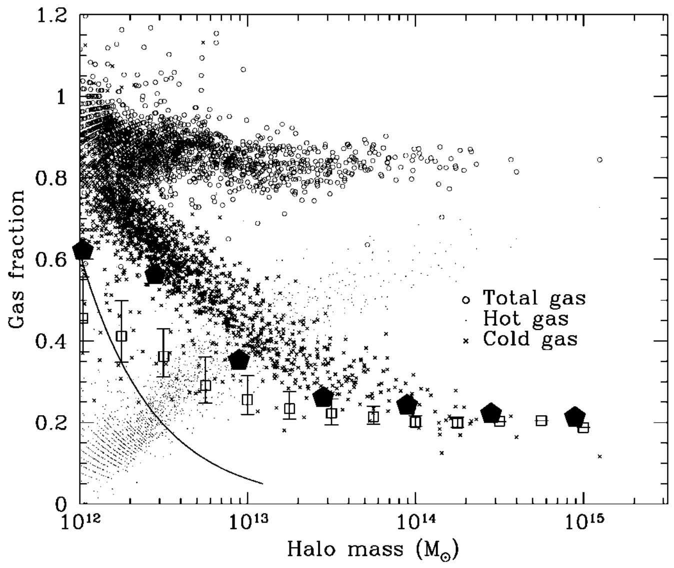

FIG. 1.—Ratio of gas mass to dark matter within the virial radius of each halo, in units of the mean baryon fraction in the simulation. The circles, crosses, and dots show results from the *N*-body/SPH simulation. The pentagons show results from a semianalytic model constrained to match the parameters of the simulation. The squares show results from a full semianalytic model. The circles show the total gas mass fraction, while the dots and crosses show the mass fractions of gas hotter and cooler than 12,000 K, respectively. The solid line shows the resolution limit of 32 gas particles.

plitude in 8 h^{-1} Mpc spheres, $\sigma_8 = 0.9$. The baryon fraction was set to $\Omega_b h^2 = 0.015$ from big bang nucleosynthesis constraints (Copi, Schramm, & Turner 1995). We assumed an unevolving gas metallicity of 0.3 times the solar value. The simulation was carried out using "parallel Hydra," an adaptive, particle-particle, particle-mesh *N*-body/SPH code (Pearce & Couchman 1998) based on the publicly released serial version of Couchman et al. (1995).

Our simulation followed 2,097,152 dark matter particles and 2,097,152 gas particles in a cube of side 100 Mpc. It required 12,492 time steps (and $\sim 10^5$ processor hr on a Cray-T3D) to evolve from $z = 50$ to $z = 0$. The gas mass per particle is $\sim 2 \times 10^9$ $M_\odot$ and, since we typically smooth over 32 SPH neighbors, the smallest resolved objects have a gas mass of 6.4×10^{10} $M_\odot$. We employed a β-spline gravitational softening, with a Plummer-equivalent comoving value of 50 kpc until $z = 2.5$. Thereafter, the softening remained fixed at $50/(1 + 2.5) = 14.3$ kpc in physical coordinates, and the minimum SPH resolution was set to match this value. With our chosen parameters, our simulation was able to follow the cooling of gas into galactic dark matter halos. The resulting "galaxies" typically have 50–1000 particles. With a spatial resolution of 14.3 kpc, we cannot resolve the internal structure of galaxies and we must be cautious about the possibility of enhanced tidal disruption, drag, and merging within the largest clusters. However, as we argue below, there is no evidence that this is a major problem.

As in all studies of this type, a phenomenological model is required to treat physical processes occurring below the resolution limit of the simulation. The first of these is the runaway cooling instability present in hierarchical clustering models of galaxy formation. At high redshift, the cooling time in dense subgalactic objects is so short that most of the gas would cool (and presumably turn into stars) unless other processes acted to counteract cooling (White & Rees 1978; Cole 1991; White & Frenk 1991). Since all the gas in the universe has clearly not cooled into dark matter halos, a common assumption is that feedback from early generations of stars will have reheated the gas, preventing it from cooling catastrophically.

Although a variety of prescriptions have been used to model feedback (e.g., Navarro & White 1993; Steinmetz & Müller 1995; Katz et al. 1996), this process remains poorly understood. In cosmological SPH simulations, gas can only cool efficiently in objects above the minimum resolved gas mass, in our case 6.4×10^{10} $M_\odot$. Thus, resolution effects alone act as a crude form of feedback. Semianalytical models of galaxy formation suggest that feedback is relatively unimportant on mass scales above our resolution limit. We do not, therefore, impose any prescription for feedback over and above that provided naturally by resolution effects. If the rate at which gas cools in the simulation is identified with the rate at which stars form, our adopted parameters give rise to a cosmic history of star formation in broad agreement with data from $z \simeq 4$ to the present (Madau, Pozzetti, & Dickinson 1998).

The second subresolution process that we must model is star formation and the associated coupling of different gas phases in the interstellar medium. Like feedback, this is a complex and poorly understood phenomenon. In some SPH simulations, groups of cooled gas particles have been identified with galaxies (the "globs" of Evrard et al. 1994). One disadvantage of this procedure is that dense knots of cold gas can affect the cooling of surrounding hot material because of the smoothing inherent in the SPH technique. To avoid this problem, an alternative strategy often used is to assume that gas that has cooled turns into collisionless "stars" according to some heuristic algorithm (Navarro & White 1993; Katz et al. 1996; Steinmetz & Müller 1995). This prescription effectively decouples the cooled gas from the hot component.

We have adopted an intermediate strategy intended as a compromise between the extremes of letting clumps of cool gas persist in the simulation and turning them into stars. As in the first case, we identify galaxies with groups of gas particles that have cooled below 10^4 K. However, when computing the SPH density of particles with temperatures above 10^5 K, we do not include any contribution from particles below 10^4 K. All other SPH interactions remain unaffected. As in the case in which cool gas is turned into stars, our model effectively decouples the galactic material from the surrounding hot halo gas, but unlike this case, "galaxies" in our model are made of dissipative material and thus are more resilient to tidal interactions and mergers than model stellar galaxies. Our model of the intergalactic medium can be regarded as a simple, first step toward a multiphase implementation of SPH, an important requirement when dealing with situations in which there are steep density gradients. The main effect of our treatment of cool gas is to prevent the formation of very massive galaxies in the centers of the richest clusters, as happened, for example, in the simulation of Frenk et al. (1996). Thacker et al. (1998) present a more detailed discussion of the effects of runaway cooling and the production of supermassive objects.

As a test of our techniques, Figure 1 compares the amount of cold gas in halos in our simulation with that predicted by the semianalytic model of Cole et al. (1999). Halos in the simulation were located by first identifying suitable centers using the friends-of-friends group finder of Davis et al. (1985) with a linking parameter $b = 0.05$ and then growing spheres around these centers out to the virial radius (defined as the

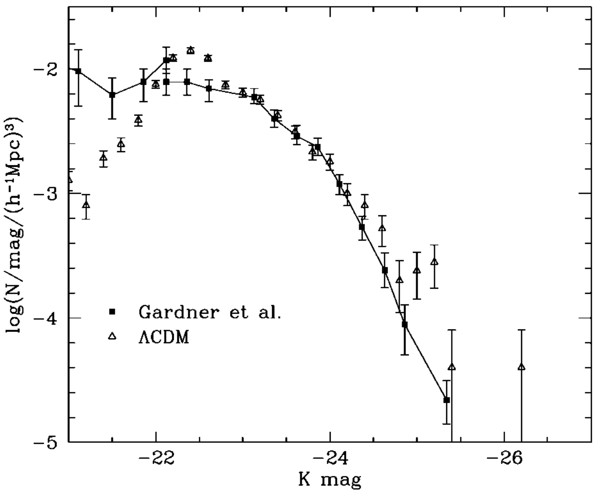

FIG. 2.—Comparison between the *K*-band galaxy luminosity function in the simulation with observations. The simulation data are shown by triangles, and the data from Gardner et al. (1997) by squares. A luminosity normalization factor of $\Upsilon = 2.8$ has been assumed. Poisson errors are shown.

radius within which the mean overdensity is 323; see Eke, Cole, & Frenk 1996). Only halos with more than 50 dark matter particles were considered, of which there are 2353 in the simulation, spanning over 3 orders of magnitude in mass. The simulation results (*crosses*, Fig. 1) are compared with two versions of the semianalytic model. In the first (*pentagons*), the parameters of the semianalytic model were set so as to mimic the conditions in the simulation as closely as possible. The mass resolution of the semianalytic model was degraded to that of the simulation, and the feedback was switched off. The agreement between the simulation and modified semianalytic model indicates that there are only minor differences in the cooling properties of the gas calculated with these two different techniques. The second comparison is intended as a test of how well the artificial "feedback" produced by resolution effects compares with the physically motivated feedback prescription used in semianalytic models. In this case (*squares*), the parameters of the semianalytic model were set so as to obtain a good match to the faint end of the galaxy luminosity function, as discussed by Cole et al. (1999). The agreement with the simulation in this case is moderate. Clearly, feedback in the semianalytic model prevents cooling within galaxy halos more efficiently than do resolution effects in the simulation, but the difference is only about 50% for halos similar to that of the Milky Way.

3. RESULTS

The ability of gas to cool is a strong function of the mass of the host halo. Figure 1 shows the fraction of hot and cold gas within the virial radius of each halo, normalized to the mean baryon fraction of the simulation (10%), as a function of halo mass. In small halos just above the resolution limit (*solid line*), most of the gas cools, but the fraction of cold gas decreases rapidly with halo mass as the cooling time for the hot gas increases. In large halos, most of the gas never cools. The crossover occurs at a halo mass of $\sim 10^{13}\ M_{\odot}$. Because of the generally asymmetric and chaotic nature of halo formation, a few low-mass halos have baryon fractions in excess of the universal mean, but in most galactic halos the baryon fraction ranges between 80% and 100% of the cosmic mean. On the scale of galaxy clusters, the baryon fraction is 85%, similar to the values obtained by White et al. (1993) and Frenk et al. (1999).

We identify "galaxies" in our simulation with dense knots of cold gas. These are very easy to locate except in the minority of cases in which a merger is ongoing or the galaxy is experiencing significant tidal disruption or ablation within a cluster halo. To find galaxies, we used the friends-of-friends group finder with a linking length of $0.0164(1 + z)$ times the mean comoving interparticle separation. This selects material with overdensity greater than $\sim 10^5$ at $z = 0$. The galaxy catalog is almost unaffected by large changes in the maximum linking length. At the end of the simulation, there were 2266 resolved galaxies within the volume.

We can assign a luminosity to each galaxy in our simulation using the stellar population synthesis model of Bruzual & Charlot (1993). For this purpose we assume that at each model output, a fraction $1/\Upsilon$ of the gas that has cooled since the previous output turns into stars in an instantaneous burst with a Salpeter initial mass function. Because the output times were relatively infrequent, this procedure works best for *K*-band luminosities.

In Figure 2 we compare the resulting *K*-band galaxy luminosity function with the observational data of Gardner et al. (1997). The shape of the model luminosity function agrees well with the data, and the model and observed functions match well if we set the luminosity normalization factor $\Upsilon = 2.8$. This implies that only 35% of the cold gas has been turned into visible stars, with the rest remaining in dense gas clouds and brown dwarfs or hidden in some other form. The associated mass-to-light ratios are about twice as large as those measured for elliptical galaxies, but these numbers (which are similar to those required by Katz et al. 1996) should be treated with caution. Not only is our star formation prescription very crude, but our model ignores the effects of metallicity and obscuration by dust. Furthermore, as the comparison with the full semianalytic model indicates, too much gas has probably cooled in our simulation because of our neglect of feedback processes. In spite of these reservations, the agreement in Figure 2 is very good and suggests that our simulation provides a realistic description of the formation of bright galaxies.

The relatively large volume of our simulation allows a reliable measurement of the clustering properties of galaxies and their relation to the clustering properties of the mass. The galaxy and mass two-point correlation functions at various epochs are plotted in Figure 3. The mass correlation function agrees very well with the results of our earlier, dark matter–only simulations which followed a cubic region of side 342 Mpc using 16.8 million particles (Jenkins et al. 1998). The clustering amplitude of the mass grows by a factor of about 30 between the two epochs shown in the figure, $z = 3$ and $z = 0$. By contrast, the galaxy correlation function hardly evolves at all between $z = 3$ and $z = 0$.

The difference between the clustering growth rates of galaxies and mass is a manifestation of "biased galaxy formation," the preferential formation of galaxies in high peaks of the primordial density field. It was already seen in the first simulations of cold dark matter models by Davis et al. (1985), in which galaxies were put in "by hand" near high peaks of the initial density field. It is also very clear in the SPH simulations of Evrard et al. (1994) and Katz et al. (1999) and can even be inferred from the *N*-body–only simulations of Bagla (1998)

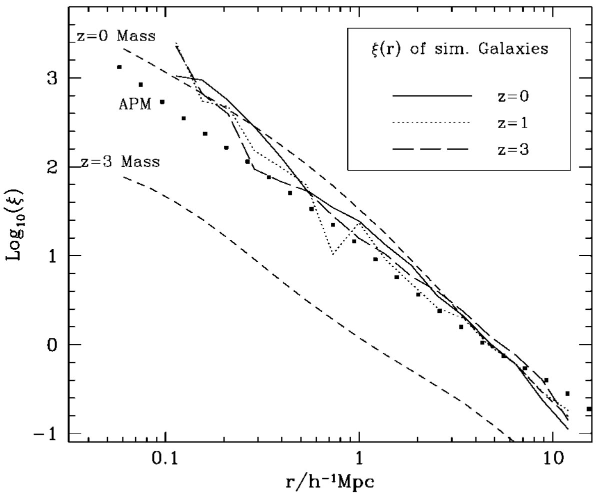

FIG. 3.—Mass and galaxy correlation functions. The dashed lines show the mass correlation functions at $z = 3$ and $z = 0$. The solid, long-dashed, and dotted lines show the galaxy correlation functions in the simulation at the indicated redshifts. The squares show the observed, real-space correlation function, estimated by Baugh (1996), from the APM survey.

and Colin et al. (1998). Semianalytic techniques have been used on their own (Baugh et al. 1998) or combined with *N*-body simulations (Kauffmann et al. 1999b) for detailed study of the clustering evolution of galaxies, while specific applications to high-redshift Lyman-break galaxies are to be found in Baugh et al. (1999) and Governato et al. (1998). The latter models provide an excellent description of the strong clustering discovered by Adelberger et al. (1998).

In Figure 3 we also plot the observed, real-space galaxy correlation function at $z \simeq 0$, estimated by Baugh (1996) from the Automatic Plate Measuring (APM) survey (*squares*). This may be compared with the $z = 0$ results in our simulation (*solid line*). On scales larger than a few hundred kiloparsec, the agreement is good. (The differences at $r \gtrsim 10\ h^{-1}$ Mpc are due, for the most part, to finite volume effects, as we have verified by comparison with the larger simulations of Jenkins et al. 1998.) Beyond $\sim 1\ h^{-1}$ Mpc, the galaxy correlation function is close to the mass correlation function. On smaller scales, galaxies are less strongly clustered than the mass, or antibiased, an effect that persists until separations of $\sim 100\ h^{-1}$ kpc. At small separations, the model correlations lie above the APM data. Over nearly 4 orders of magnitude in amplitude, the model galaxy correlation function is close to a power law within the errors, even though the mass correlation function is not. An essentially featureless galaxy correlation function was also obtained for the same cosmological model in the semianalytic model of Benson et al. (1999) and, for some parameter combinations, in those of Kauffmann et al. (1999a).

4. CONCLUSIONS

The simulation presented here is the first to resolve galaxy formation in a large enough volume to allow a reliable study of the demographics and clustering of galaxies. Our results are encouraging: the resulting luminosity function and correlation function of galaxies are broadly consistent with observations. Furthermore, the correlation function of bright galaxies in the simulation changes little since $z = 3$, in agreement with results from semianalytic studies and with available data at high redshift. Further progress will require a more detailed treatment of the astrophysics of galaxy formation, particularly of the processes of star formation and feedback.

This work was carried out as part of the program of the Virgo Consortium using the facilities of the Computing Centre of the Max-Planck Society in Garching and the Edinburgh Parallel Computing Centre. This work was supported by the EC network for “Galaxy Formation and Evolution” and NATO CRG 970081. We thank Carlton Baugh and Shaun Cole for providing unpublished results from their semianalytic models.

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