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COSMOLOGICAL VELOCITY BIAS

R. G. CARLBERG AND H. M. P. COUCHMAN
Department of Astronomy, University of Toronto
AND
P. A. THOMAS
Canadian Institute for Theoretical Astrophysics, University of Toronto
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ABSTRACT

Gravitationally bound objects, such as galaxies, that collapse from a cosmological background can exhibit both a correlation bias and, as shown here, a significant bias in their peculiar velocity dispersion with respect to the density field. The correlation bias, b_ξ, begins as a statistical enhancement that dwindles as relatively less overdense regions collapse. Ultimately, merging can diminish the correlation to less than that in the density field. Pairwise center-of-mass peculiar velocities of collapsed regions are reduced below that of the density field to a small extent by the removal of their internal velocity dispersion and by the tendency of galaxies to form preferentially near the bottom of group and cluster potential wells. More importantly, dynamical friction slows the objects and their associated halos as dynamical clustering develops, leading to a significant velocity dispersion bias, b_v, with respect to the density field. The detailed simulations of a cold dark matter cosmology reported here indicate that together these two kinds of bias can reconcile a galaxy correlation length of $5h^{-1}$ Mpc and a peculiar velocity dispersion of approximately 300 km s^{-1} with an $\Omega = 1$ cosmology, for a range of correlation biases. Values of $b_\xi \simeq 1$ and $b_v \simeq 0.5$ are favored using additional normalizing data. For the adopted star formation algorithm, the galaxies in the simulation are found to have properties similar to those of the dense cores of dark halos.

Subject headings: cosmology — galaxies: clustering — gravitation

I. INTRODUCTION

A strong prediction of inflationary cosmology (Guth 1981) is that the density of the universe should be very near the critical density of a Friedmann-Lemaître universe, i.e., $\rho/\rho_c \equiv \Omega = 1$. Estimates of Ω using galaxies find values around 0.2 (Davis and Peebles 1983; Bean *et al.* 1983). The estimators of Ω use overdensities as a function of length scale, often expressed in the form of a correlation function, and velocities of objects moving in these potentials. The value of Ω will be underestimated if galaxies form from the higher peaks of the density field (Kaiser 1984), although this solution lowers the predicted large-scale streaming velocities (e.g., Lynden-Bell *et al.* 1988). We show that galaxies can give a biased representation of the velocity dispersion of the density field that allows the contradiction between $\Omega = 1$ and the observations to be resolved for a relatively low correlation bias.

The highest overdensity regions of a given mass scale collapse first, and these first objects will initially be more strongly correlated than the density field (Kaiser 1984; Bardeen *et al.* 1986). If the galaxy correlation function overestimates the density contrast in the dark matter, then it leads to an underestimate of the mass density required to generate the observed velocities. Subsequent orbital evolution through dynamical friction can cause the galaxies in groups and clusters to decrease their mean orbital radius, such that the total mass of the association is underrepresented by the mass enclosed within the orbits of the galaxies (Barnes 1984; Evrard 1986; Carlberg 1988; West and Richstone 1988). Merging of objects in groups and clusters can ultimately drive their correlation function below that of the density field.

The random velocities of galaxies will never exceed the velocities of the dark matter making up a dominant, collisionless, background density field. The presence of a significant pairwise velocity dispersion bias was noted in Carlberg and Couchman (1989, hereafter CC89). A minimal bias is that the center-of-mass random velocities of virialized regions have their internal dispersions removed, although this effect is taken into account in the standard virial theorem estimate (Peebles 1980). Galaxies tend to form at locations somewhat more clustered than the underlying density field and hence will have somewhat smaller ($\approx$10%–30% reduction) velocities than average particles (Bardeen *et al.* 1986). The main purpose of this *Letter* is to show that the pairwise velocity dispersions of large units can be reduced by as much as 70% from those in the dark matter. The likely mechanism for the velocity reduction is dynamical friction, which even in a cosmology filled with collisionless particles introduces an effective dissipation for the velocities of collapsed regions as they and their associated halos fall toward each other.

This *Letter* reports an N-body cosmological simulation which incorporates a dissipative baryonic component. The model includes a more accurate description of gas cooling and star formation than in CC89 which allows the X-ray luminosity evolution to more confidently calculated, "galaxies" of "stars" to be more reliably identified, and, most importantly here, the redshift evolution of the velocity bias to be accurately traced. A simple model that adds dynamical friction to orbital evolution is then discussed in § IV. Throughout we assume $\Omega = 1$ and adopt $H_0 = 50$ km s^{-1} Mpc^{-1} at the current epoch.

II. A GALAXY FORMATION ALGORITHM

We have added a baryonic component to a cosmological N-body experiment to provide a physical basis for our identification for galaxies, although with hindsight we find similar results can be extracted from a purely dissipationless model. The mass in the model is carried by 262,144 particles with a total mass density corresponding to $\Omega = 1$ in a 40 Mpc box. Half of the particles are identified as gas and are assigned masses such that $\Omega_b = 0.05$. A dark matter particle has mass $3.21 \times 10^{10}\ M_\odot$, and a baryonic particle has mass $1.69 \times 10^9\ M_\odot$. The mass associated with the *stellar* component of an L_* galaxy of $2 \times 10^{10}\ L_\odot$ will be taken as 30 baryonic particles ($M/L = 2.5$).

Gravitational interactions between the particles were calculated using a PPPM type code having periodic boundary conditions (Hockney and Eastwood 1980; Efstathiou *et al.* 1985). Refinement of the Green's function allowed the mesh force to extend to 0.625 Mpc in our 40 Mpc box with rms errors under 1%. The direct particle-particle calculation takes over for shorter separations. The gravitational force is calculated for a Plummer potential with a softening length maintained at a physical length of 20 kpc. The time steps are set at 10 Myr each, as required for stability of the gasdynamics.

The gas interparticle forces are calculated using a smoothed particle hydrodynamics (SPH) code (e.g., Monaghan and Gingold 1983; Monaghan and Lattanzio 1985; Lattanzio *et al.* 1986; Katz and Hernquist 1989). In order to maintain resolution the smoothing length is shortened in high-density regions, $h_i = n_i^{1/3}$, where n_i is the SPH density estimate at the position of particle i. The value of h_i is not allowed to become smaller than 15 kpc as a match to the softening length. Pairwise forces are symmetrized by averaging quantities. The code was first tested using an adiabatic gas and found to provide well-defined shocks and accurately conserve energy in virialized regions. The gas here is cooled using a tabulated zero metallicity cooling function (Raymond, Cox, and Smith 1976). Increased metallicity makes relatively little difference to the results. The main drawback of this code is that it takes nearly twice the cpu time per step compared with gravity alone, and the SPH forces in the presence of cooling require reduced time steps, typically a factor of 3, compared with those for an adiabatic gas or collisionless particles.

The stellar component of observed galaxies is found to be approximately 50% self-gravitating (with a wide dispersion), the rest of the mass being ascribed to dark matter. Furthermore, as Gunn (1982) has argued, gas must be self-gravitating before it can efficiently form stars. This observation motivates the algorithm for star formation in this code: stars form when the local estimate of baryonic mass density is 50% of the total local mass density. Since the initial smooth baryonic density is 5%, this requirement demands that the gas cool sufficiently that its local density can be increased 38 times.

A strength of the current code is the dynamical range of the force calculations, over a factor of 1000, and the reasonably realistic (on large scales) gas cooling and star formation. The main deficiency is that there are too few particles in the simulation. This leads to some two-body relaxation, particularly irksome here where two different particle masses are involved.

III. VELOCITY BIAS

The CDM initial conditions (Bond and Efstathiou 1984) were evolved while the box expanded by a factor of 12, giving final results at a formal $b_\delta = 1.2$; i.e., at this time the *linear* extrapolation of the initial conditions gives $\sigma(16\ \mathrm{Mpc}) = 0.8$. Star formation begins at $z = 3$ and peaks near $z = 1.5$, declining by a factor of 2 at $z = 0$. The stars form exclusively at the bottom of potential wells, and many bursts of star formation are clearly associated with the compressions that occur during the collision of substructure. Galaxies are identified in the simulation by linking together all particles within either 60 or 125 kpc of each other; the larger length incorporates a few outlying star particles into the galaxies; otherwise, the two link lengths give very similar results. The velocity bias found below is insensitive to this "observational parameter." The galaxies so found have half-mass radii of 50–100 kpc, hardly adequate for resolution of internal dynamics, but sufficient for the cosmological dynamics discussed here. The galaxies contain 80%–90% of all star particles. These galaxies have kinematics and correlations very similar to the dense cores of the dark matter halos picked out with a link length of 50 kpc. A distinction is that the mass function of the dark matter cores is somewhat steeper at low luminosities than the "galaxy" mass function.

The main result of the simulations is shown in Figure 1, where the three-dimensional pairwise velocity dispersions of the dark matter particles and galaxies with two different mass limits are shown as a function of redshift. One velocity unit scales to 1002 km s^{-1}. The velocities plotted are averages over separations ranging from 1 to 3.2 Mpc. The three-dimensional pairwise velocity dispersion, the quadrature sum of the radial and tangential components, is used to increase the signal to noise ratio. Figure 1 clearly shows that as galaxies appear near $z \simeq 1$, their pairwise velocities quickly drop below those of the individual collisionless dark matter particles. The M_* and heavier galaxies in these experiments have a velocity bias $b_v = 0.5$ at the time chosen to be the current epoch. The velocity bias of the large heavy halos, $M \simeq 10^{13}\ M_\odot$, is even greater, nearly $b_v = 0.3$. The mass dependence of this effect may be somewhat overestimated by these experiments which do not adequately resolve galaxy scales. The data show an approximate inverse relationship between b_ξ and b_v, that is, we can identify collapsed objects that have ξ_{gg} or ξ_{hh} ranging from $3\xi_{\rho\rho}$ (very massive halos) to $0.5\xi_{\rho\rho}$ (low-mass galaxies or halos), whose b_v range from 0.3 to 0.8, respectively. In spite of this bias in the velocity dispersion, the mean infall velocity of the gal-

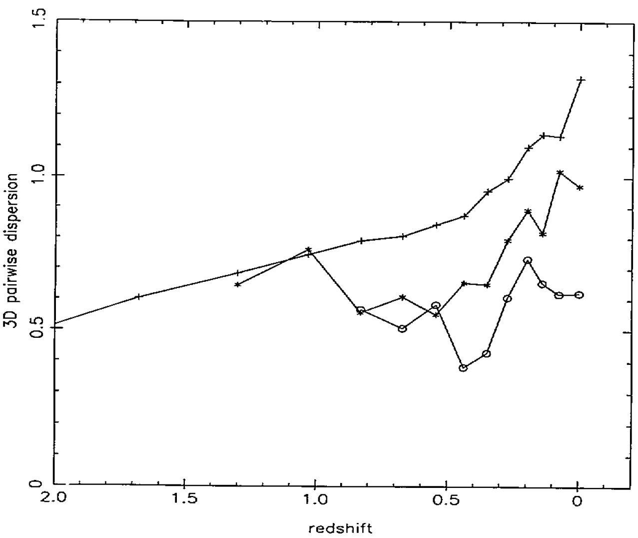

FIG. 1.—The pairwise peculiar velocity dispersions for dark matter (*plus signs*), $M > M_*/2$ galaxies (*asterisks*), and $M > M_*$ galaxies (*open circles*). The data are averaged over the comoving radial range of 1–3.2 Mpc. Shortly after galaxies appear in measurable numbers, their velocities being to drop below those of the dark matter particles.

axies remains a fairly accurate tracer of the dark matter flow velocity.

IV. DYNAMICS

In this N-body experiment the correlation function of the galaxies at the time chosen as the current epoch is not significantly biased with respect to that of the dark matter. On the other hand, the pairwise velocity dispersion of the galaxies dramatically underestimates that in the dark matter. There are several possible sources of the bias that can be discounted. First, the internal dispersion of the galaxies ranges from 20% to 35% of the pairwise dark matter velocity dispersion, so the reduction to the center of mass velocities by removing the internal dispersion of galaxies is only 10%–25%, roughly a factor of 3 less than required to explain the effect. Measurement of the cross-correlation between galaxies and dark matter, $\xi_{g\rho}$, shows that it is essentially identical to $\xi_{\rho\rho}$, thus removing the possibility that galaxies are located in a significantly different potentials than is the dark matter.

Velocity bias appears to be mainly a consequence of dynamical friction as galaxies and their associated halos undergo dynamical clustering shortly after formation. A simple model which demonstrates the importance of dynamical friction on the velocities is to approximate the dynamics of galaxy clustering as two identical galaxies with dark halos falling together, ultimately to merge. The galaxies and halos are approximated as singular isothermal spheres, in which $\rho(r) = \rho_0(r_0/r)^2$, and the one-dimensional velocity dispersion is $\sigma^2 = 2\pi G\rho_0 r_0^2$. The effective mass for dynamical friction is approximated as the integral of the density between the two centers, $M_h(r) = 4\pi \int_0^r \rho(r) r^2\, dr$, where r is the separation. In the presence of Chandrasekhar's dynamical friction (e.g., Binney and Tremaine 1987) the orbital separation then evolves as

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{GM_h(r)\mathbf{r}}{r^3} - 4\pi G\rho(r) \ln \Lambda M_h(r) \times \left[\operatorname{erf}(X) - \frac{2}{\sqrt{\pi}} X_e^{-X^2}\right] \frac{\mathbf{v}}{v^3}, \quad (1)$$

where $\mathbf{v}$ is the velocity, $X = v/(2^{1/2}\sigma)$, and $\ln \Lambda$ is taken to be 1. A solution of this equation is shown in Figure 2. The dimensionless scaling of this solution gives a circular velocity in the halo of one unit. The two orbits began at separations $r = 4$ and 8, both with an initial tangential velocity of 0.3 units. In the absence of friction, both of these orbits would attain a velocity at pericenter of about 0.9 unit. The orbits shown are an approximation to those in true cosmological clustering with continuing infall, but do reasonably represent those seen in N-body experiments (e.g., Carlberg 1982). These purely gravitational models are scale free; thus, they could be scaled to the current clustering strength and dark matter velocity dispersion.

As illustrated in Figure 2, dynamical friction decreases the radial velocity with decreasing separation, the well-known tendency to circularize orbits. The same trend of decreasing radial velocity with decreasing separation is seen in the simulation galaxies identified here, and in Figures 10 and 11 of CC89. Completely the opposite trend is seen in the collisionless dark matter particles, where the pairwise velocity dispersions decline with increasing separation over most of the same radial range.

Dynamical friction is of sufficient strength and has the correct qualitative features to account for the velocity bias seen in our experiments. The major problem in refining this theory is to accurately allow for the total mass of the galaxies and their associated dark halos, and to follow the reduction in effective mass as the halos are tidally disrupted as the galaxies cluster. This problem is left to a subsequent paper.

V. DISCUSSION AND CONCLUSIONS

The major result of this *Letter* is contained in Figure 1, showing that the pairwise velocity of galaxies drops below that of the collisionless dark matter particles to create a large velocity dispersion bias. The physical source of the velocity bias is largely the dynamical friction which slows the galaxies and their associated dark halos as dynamical clustering pulls them together.

The dual bias means that a range of b_ξ can be compatible with both $\Omega = 1$ and the current clustering measurements, thus lessening the value of galaxies as a constraint on the amplitude of the primeval density perturbation spectrum. Other data, such as the redshift of star formation ($z \simeq 1.5$) and the X-ray temperatures of the gas in large dark halos would favor a $b_\xi \simeq 1$. Values of b_ξ near 2 combined with our simulation data would imply star formation peaking near $z \simeq 0.5$ and would

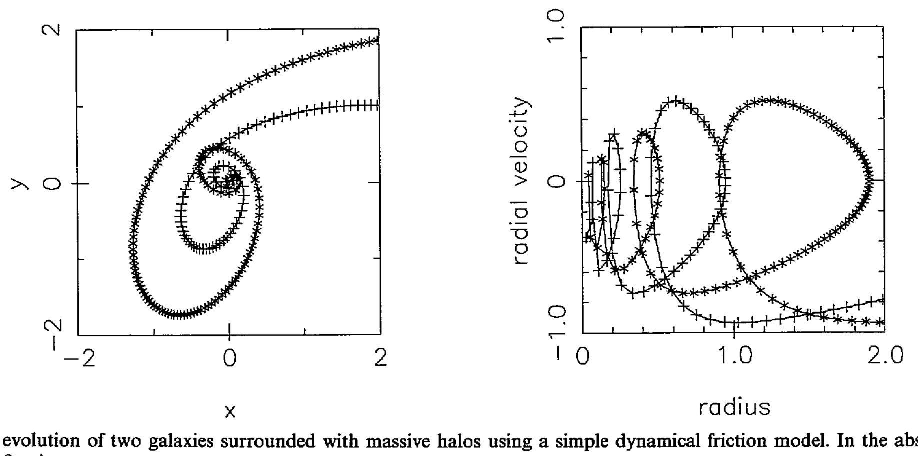

FIG. 2.—The orbital evolution of two galaxies surrounded with massive halos using a simple dynamical friction model. In the absence of friction, the radial velocities would rise to 0.9 units.

cause excessive radiative cooling of cluster gas. Independent of these simulations, $b_\xi = 2$ in a CDM universe give improbably low bulk flow velocities (Lynden-Bell *et al.* 1988).

Inasmuch as the properties of the galaxies and clusters in the $\Omega = 1$ CDM cosmology simulation reported here are a good match to those observed, this model implies that the available data are consistent with the true value of Ω being equal to 1.

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REFERENCES

Bardeen, J. M., Bond, J. R., Kaiser, N., and Szalay, A. S. 1986, *Ap. J.*, **304**, 15.
Barnes, J. 1984, *M.N.R.A.S.*, **208**, 373.
Bean, A. J., Efstathiou, G., Ellis, R. S., Peterson, B. A., and Shanks, T. 1983, *M.N.R.A.S.*, **205**, 605.
Binney, J., and Tremaine, S. 1987, *Galactic Dynamics* (Princeton: Princeton University Press).
Bond, J. R., and Efstathiou, G. E. 1984, *Ap. J. (Letters)*, **285**, L45.
Carlberg, R. G. 1982, *M.N.R.A.S.*, **199**, 1159.
———. 1988, *Ap. J.*, **324**, 664.
Carlberg, R. G., and Couchman, H. M. P. 1989, *Ap. J.*, **340**, 47 (CC89).
Davis, M., and Peebles, P. J. E. 1983, *Ap. J.*, **267**, 465.
Efstathiou, G., Davis, M., Frenk, C. S., and White, S. D. M. 1985, *Ap. J. Suppl.*, **57**, 241.
Evrard, A. 1986, *Ap. J.*, **310**, 1.
Gunn, J. E. 1982, in *Astrophysical Cosmology*, ed. H. A. Bruck, G. V. Coyne, and M. S. Longair (Vatican City: Pontifica Academia Scientiarum), p. 253.
Guth, A. 1981, *Phys. Rev. D.*, **23**, 347.
Hockney, R. W., and Eastwood, J. W. 1981, *Computer Simulations Using Particles* (New York: McGraw-Hill).
Katz, N., and Hernquist, L. 1989, *Ap. J. Suppl.*, **70**, 419.
Lattanzio, J. C., Monaghan, J. J., Pongracic, H., and Schwarz, M. P. 1986, *SIAM J. Sci. Stat. Comput.*, **7**, 591.
Lynden-Bell, D., Faber, S. M., Burstein, D., Davies, R. L., Dressler, A., Terlevich, R. J., and Wegner, G. 1988, *Ap. J.*, **326**, 19.
Monaghan, J. J., and Gingold, R. A. 1983, *J. Comput. Phys.*, **52**, 374.
Monaghan, J. J., and Lattanzio, J. C. 1985, *Astr. Ap.*, **149**, 135.
Peebles, P. J. E. 1980, *The Large Scale Structure of the Universe* (Princeton: Princeton University Press).
Raymond, J. C., Cox, D. P., and Smith, B. W. 1976, *Ap. J. (Letters)*, **204**, L290.
West, M. J., and Richstone, D. O. 1988, *Ap. J.*, **335**, 532.

R. G. Carlberg and H. M. P. Couchman: Department of Astronomy, University of Toronto, Toronto, Ontario, Canada, M5S 1A1

P. A. Thomas: Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, England