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Rich Cluster Simulation: Dynamics and Mass Estimates

B. C. Bromley, M. S. Warren, W. H. Zurek

Theoretical Astrophysics, MS B288, Los Alamos National Laboratory Los Alamos NM, 87545

P. J. Quinn

Mt. Stromlo Observatory, Canberra, Australia

Abstract

We present an analysis of a simulated rich cluster dominated by cold dark matter. Here we focus on the dynamics of collapsed dark matter halos within the cluster. We use projected positions and velocities of both dark matter and halos to assess several conventional measures of cluster mass. The results indicate that the measures give reasonable results for dark matter particles but cause overestimates of cluster mass when applied to halos. In searching for the source of the discrepancies, we find that tidal disruption and dynamical friction do not induce significant bias in the projected velocity dispersions. However, an antibias in the spatial distribution of halos relative to that of the total mass appears to be most problematic for cluster mass estimates. We conclude that over and above the usual concerns about the applicability of virial equilibrium to clusters, any bias can adversely affect cluster mass estimates and one must question their reliability as applied to observed clusters.

1 Introduction

Galaxy clusters have played a key role in the effort to determine the nature of matter in the Universe and the value of the cosmological density parameter Ω. The dynamical mass of clusters has particularly important cosmological implications, as first recognized when Zwicky (1933) deduced presence of dark matter in the Coma cluster. Several estimators designed to yield cluster mass from projected galaxy velocities have been introduced by Bahcall & Tremaine (1977) and Heisler, Tremaine & Bahcall (1985). These authors assessed such measures in numerical N-body simulations with 20 or less point-like galaxies. Subsequently, West & Richstone (1988) performed tests with simulations of $N = 10^4$ particles, and Carlberg (1994) examined virial mass estimated in a cluster simulation of 10^6 mass particles. The conclusion from these more recent studies was that virial measures underestimate cluster mass.

Ideally, mass estimates should be tested with simulations that include the large-scale gas dynamics of the baryons as well as high mass resolution to track the interaction of extended galactic halos with the rest of the cluster. However, work on gas dynamics within clusters (e.g., Evrard 1990) indicates that cooling processes may be neglected in the large-scale intracluster gas — the baryonic component may be effectively dissipationless. Thus as an approximation, dissipative effects may be neglected when one proceeds to higher and higher mass resolution.

Here we present the results of a million-particle high-resolution simulation of a cluster with dissipationless cold dark matter The cluster is dominated by a single massive core interspersed with smaller collapsed halos which may be associated with galaxies. We track the dynamical evolution of the halos, as well as that of their constituent dark matter particles. Our principal aim here is to test conventional measures of cluster mass based on projected positions and velocities, as might be available to a distant observer. We first use the mass particles to test the assumptions, such as virialization, upon which these measures rest. Then, we focus upon the application of the mass measures to the halos. At issue are the effects of tidal disruption and dynamical friction, and the extent to which the halo phase-space distribution is biased with respect to that of the total mass.

2 Numerical Method

The simulation of the cluster began with selection of a primordial overdense structure, the seed for a present-epoch cluster, from a palette of random realizations of the cosmic density field. Each realization was generated as a Gaussian field variate with a COBE-normalized CDM power spectrum in an $\Omega = 1$ universe. The selected initial field was a 1-in-500 event; it contained a 2.5-σ overdensity in the middle 1/9th of the simulation volume.

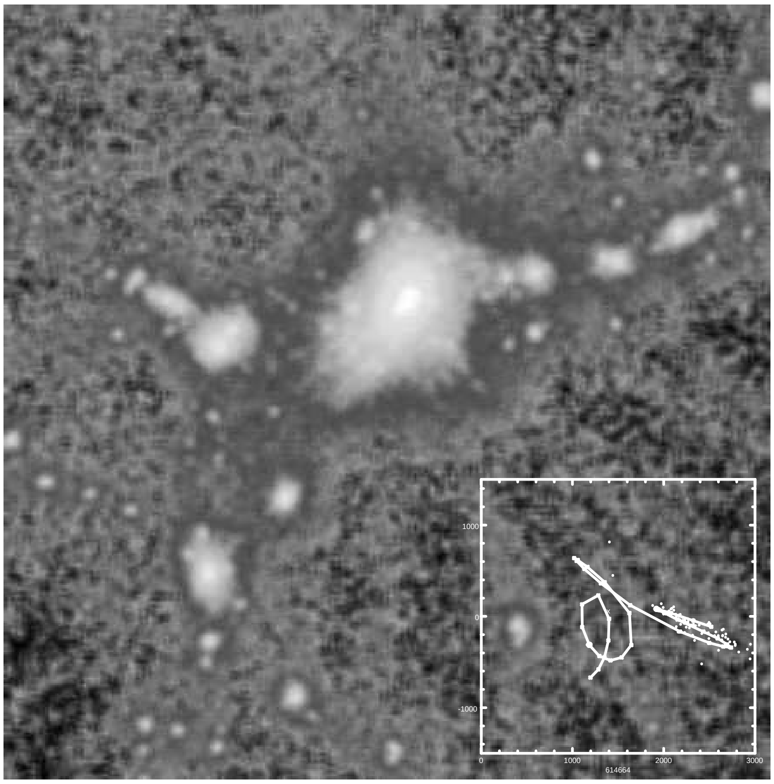

FIG. 1.—: The cluster at $z = 0$ and a typical halo orbit (inset).

Force calculation for this 1.1×10^6 particle system was performed using a tree code with spatial resolution of 5 kpc (see Warren 1994). The final output (Fig 1), obtained after 3000 computational timesteps, has a radius of 15 Mpc and a Hubble parameter of 50 km/s/Mpc. The evolved cluster had a mass of approximately 5×10^{14} $M_\odot$within the Abell radius.

In the simulation, aggregates of dark matter particles were identified as galaxy halos with the algorithm described by Warren et al. (1992). The constituent particles of a set of 40 halos were tagged and tracked from a redshift of $z = 0.85$ to the present epoch ($z = 0$). The inset in Figure 1 illustrates a typical trajectory over this period of time.

3 Cluster Mass Estimates

We examine three conventional cluster-mass measures (Bahcall & Tremaine 1981; Heisler et al. 1985; Binney & Tremaine 1987) for a cluster of N galaxies and a radius R:

$$\text{Isothermal Mass}: \; 2R\sigma_1^2/G;$$

$$\text{Virial Mass}: \; 3\pi N\sigma_1^2/2GR_H \; ;$$

$$\text{Projected Mass}: \; 32\alpha \left\langle v_\parallel^2 r_\perp \right\rangle / \pi G$$

in these expressions, σ_1 is the dispersion in the line-of-sight velocities $v_\parallel$, $r_\perp$ and R_H are radial distance from the cluster center and the mean harmonic radius, respectively, both measured in the sky plane of a distant observer, The factor of α in the projected-mass measure ranges from 1 for isotropic orbits to 2 for radial orbits.

These mass estimates are applied to the CDM particles in the simulation and are shown in Figure 2a as a function of plane-of-sky radius $r_\perp$. Evidently, the virial and projected mass estimates are in fair agreement with the true mass within the projected Abell radius. The isothermal mass estimate works well only within the central region of the cluster.

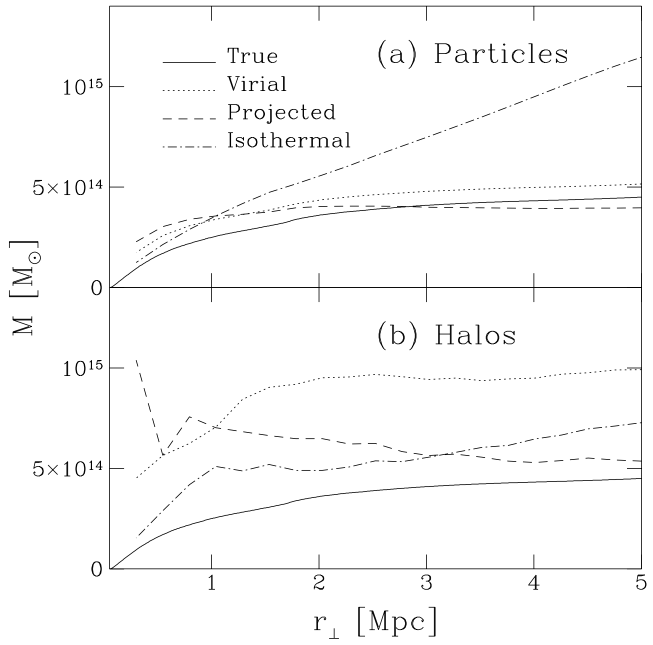

FIG. 2.—Cluster mass measures from (a) total mass and (b) halos as a function of plane-of-sky radius $r_\perp$. The cluster was defined to include all objects within 7.5 Mpc of the center of mass.

When applied to the halo population, the mass estimates fare considerably worse (Fig. 2b). In general, the mass is overestimated by 40% to 250% for 1 Mpc $< R <$ 3 Mpc. We now examine possible sources of the discrepancies.

The mass and force resolution of the simulation is sufficiently high that we may expect to see the effects of tidal forces and dynamical friction on the halo trajectories. We found that tidal effects were not significant even in those orbits that passed very near the cluster core, as only 5% of the halos were disrupted.

The more subtle phenomenon of dynamical friction, which may result when halos have a large internal degrees of freedom, can produce a velocity bias in the halo trajectories (Carlberg 1994). Here, we do not find evidence for a significant bias in the one-point halo velocity distribution. For example, the 1D halo velocity dispersion as a function of plane-of-sky radius from the cluster core traces the dispersion profile for particles over a broad range of $r_\perp$. Thus, a velocity bias is not the source of error in the mass measures discussed above.

However a spatial bias is detected. Evidence appears in R_H, the mean harmonic radius in the sky plane. The profile of R_H for halos lies significantly above that for particles, indicating that halos are more dilute in their contribution to the cluster potential. An increase in R_H at fixed velocity dispersion strengthens the magnitude of the inferred gravitational potential and drives the virial and projected mass measures upward from the true value. We conclude that spatial bias is the principal source of error in these measures.

4 Conclusion

The small smoothing scale of 5 kpc for the force calculation and the large number of particles distinguish this experiment from previous numerical simulations of dissipationless cluster dynamics. We find that conventional mass measures based on projected velocities and positions are in reasonable agreement with the actual mass when simulation particles are used. However, these same measures generally overestimate the cluster mass when applied to halos. The overestimate is linked to the spatial antibias of the halo distribution. A halo velocity bias, such as might be expected if tidal disruption and dynamical friction were dominant processes, was not detected. These conclusions compare favorably, in qualitative terms, with analyses of x-ray and optical data: Lubin & Bahcall (1993) argue for an absence of a velocity bias, while Eyles et al. (1991) find that galaxies are antibiased in clusters and dynamical masses are overestimated. We strongly caution that the spatial antibias in our data may be artificially enhanced by the halo finding algorithm and by the dissipationless assumption.

Our results are at odds with the findings of Carlberg (1994) who ran a similar simulation but with nearly 50% lower force resolution. Carlberg cites a significant velocity bias that causes underestimates in the virial mass measures. The discrepancy may stem in part from the force resolution and in part because halos were tagged at an early epoch ($z \approx 2$)—such objects may not be representative of the halo population at $z = 0$. This discrepancy serves as a reminder that cluster mass measures are highly sensitive to the uncertain details of biasing in dense regions and that the mass estimates must be interpreted accordingly.

In closing, we note that the spatial antibias of galaxies in clusters has ramifications for other cosmological measures. An example is the pairwise radial velocity dispersion, σ_{12}. Even if galaxies are exact tracers of the cosmic velocity field, σ_{12} inherits a bias simply because of the high-velocity galaxies in the dense clusters are under-represented compared with the slower objects in the field. This effect can be of considerable importance for cosmological information derive from σ_{12}, as discussed at this conference (see Zurek, Bromley & Warren) and elsewhere (Zurek *et al.* 1994).

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