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IMPROVED MODELS FOR THE EVOLUTION OF THE COMA CLUSTER OF GALAXIES

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and

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ABSTRACT

The analysis by Fitchett & Webster of the observations of the Coma cluster of galaxies has demonstrated that the center of the Coma Cluster consists of two subclusters. Therefore, it is important to construct realistic dynamical models of a galaxy cluster with two mass centers. Our previous *N*-body models for the Coma Cluster consisted of point masses or particles with simple interaction properties. In the current paper, we employ a more sophisticated *N*-body code, which includes dynamical friction, mass exchange, and mergers between galaxies. Our starting point is a model where the two subclusters form a binary system. The rest of the cluster galaxies are in nearly radial, bound orbits around the center of mass of the binary. The initial galaxy densities and velocities are chosen according to a particular cosmological model. At the end of the *N*-body simulation of 250 galaxies, we extract the projected galaxy surface density and radial velocity dispersion profiles as a function of the distance from the center of the mass of the cluster. With certain initial parameters, excellent agreement with observations is obtained. In such models, the use of the virial theorem in the standard way gives an overestimate of the cluster mass by a factor of about 3. Therefore, the true mass of the Coma Cluster should be smaller than the usually quoted value by the same factor. The mass-to-light ratio of the Coma Cluster should be about 100 in solar units, in agreement with the analysis of the X-ray data by Cowie et al.

Key words: dark matter — galaxies: clusters: individual (Coma) — galaxies: interactions

1. INTRODUCTION

In the currently popular cold dark matter (CDM) scenario of cosmological structure formation, structures of different scales start to develop more or less simultaneously. The small-scale structures condense first, and they are denser than larger scale structures. Therefore, rich clusters of galaxies may contain substructures on the galaxy group scale, as well as on the galaxy scale. The substructures may survive over periods of time that are comparable to the current age of the clusters (Crone & Geller 1995; Navarro, Frenk, & White 1997). The virialization time of a galaxy that contains $10^{12}\ M_{\odot}$ in the form of baryons is expected to be about 1.2×10^9 yr (Padmanabhan 1993). This could represent the virialization time of a supergiant galaxy that is now at the center of a galaxy cluster. The rest of the cluster will virialize gradually as the cluster collapses and builds itself up.

Substructures were first recognized in the Coma cluster of galaxies (Rood 1974). Coma Cluster has two exceptionally bright galaxies near its center: NGC 4874 and NGC 4889. These galaxies apparently mark the centers of two dark matter halos that are much more massive than ordinary galaxy halos (Valtonen & Byrd 1979). The evidence for subclusters comes from positional clustering in the sky (Fitchett & Webster 1987; Mellier et al. 1988; Escalera, Slezak, & Mazure 1992; Merritt & Tremblay 1994), from concentration of X-ray–emitting gas in the two potential wells (Briel, Henry, & Böhringer 1992; Watt et al. 1992; White, Briel, & Henry 1993; Vikhlinin, Forman, & Jones 1994; Arnaud et al. 2001), and from subclustering in the radial velocity space (Colless & Dunn 1996; Biviano et al. 1996).

Subsequently, a third subcluster has also been recognized in the Coma cluster of galaxies, centered on NGC 4839 (Mellier et al. 1988; Caldwell et al. 1993). It appears that none of the three subclusters mark the center of the Coma Cluster, but that they are independent dynamical units inside the overall cluster potential (Biviano et al. 1996). While NGC 4874 and NGC 4889 subclusters are probably close to the cluster center, the NGC 4839 subcluster is maybe just beginning to penetrate the Coma Cluster in an infall orbit (Colless & Dunn 1996; Neumann et al. 2001), or it may have already passed through the cluster (Burns et al. 1994; Beijersbergen et al. 2002).

The subclusters may not always be centered on exceptionally bright galaxies (Valtonen et al. 1985) as the case of NGC 4839 demonstrates. Many galaxy clusters have several subclusters (Stein, Jerjen, & Fedespiel 1997; Drinkwater, Gregg, & Colless 2001; Conselice, Gallagher, & Wyse 2001), although the subclusters are not so obvious in the light distribution of the clusters. Therefore, subclustering may be quite a general property, and the Coma Cluster may not be very exceptional in this respect.

One of the interesting consequences of subclustering is that it may lead to the ejection of some of the member galaxies from the cluster via the three-body slingshot process. The neglect of the ejections in the analysis of the dynamical state of the cluster leads easily to an overestimate of the mass of the cluster (Saarinen & Valtonen 1985; Valtonen & Byrd 1986). The fact that the mass estimates based on X-ray observations tend to give lower mass values than the masses based on the radial velocities of the galaxies in the Coma Cluster (Cowie,

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Henriksen, & Mushotzky 1987; Rines et al. 2001) and in other rich clusters of galaxies (Girardi et al. 1996) suggests that some ejections may indeed take place. The studies using weak gravitational lensing support the X-ray–based mass determinations, while the velocity dispersion of the galaxies is typically too high by 50% for those masses (Smail et al. 1997).

One of the objections to the nonstatic models of the Coma Cluster and other rich clusters was presented by The & White (1990; hereafter TW90), who found that the observed velocity dispersion profile of the Coma Cluster cannot be reproduced by nonstatic models. The Coma Cluster is an important test case, since it has by far the most extensive set of observational data among all clusters of galaxies (see Biviano 1998 for a recent historical review of Coma Cluster observations). The aim of this paper is to study to what extent the claim of TW90 is valid.

2. NUMERICAL TECHNIQUES

The simulations in this paper have been carried out using the *N*-body code of Aarseth (1971) with certain modifications. We discuss the main modifications in the following.

2.1. *Dynamical Friction*

We assign every particle of index i the value of radius r_i. This together with its mass m_i uniquely defines the properties of the particle (for details, see Valtaoja, Valtonen, & Byrd 1989; Valtonen & Wiren 1994). When one galaxy enters another one, i.e., when the distance between two particles (r_{ij}) becomes less than or equal to the larger of the values of r_i and r_j, dynamical friction modifies the relative orbit of the pair. The calculation of dynamical friction was explained in detail by Valtonen & Wiren (1994). Test runs with two particles were carried out in order to test the proper functioning of the dynamical friction routine.

2.2. *Tidal Force and Mass Loss*

When a small galaxy enters a larger one, tidal forces become important at a certain distance from the center of the larger galaxy. The stars in the outer orbits of the small galaxy are pulled away, and the effective mass of the smaller galaxy is decreased. This mass decrease is included in the code, following the description of Valtaoja et al. (1989).

It is not a simple matter to describe the redistribution of the stars that have been pulled out of the smaller galaxy. In order to provide a simple algorithm, we have assumed that all the matter lost from the smaller galaxy ends up in the larger galaxy. Another simplification, which certainly should be improved upon when more is known about galaxy interactions, is the assumption that the shape of the density profile of a galaxy is not changed during the tidal interaction. With this assumption, crude as it may be, one may continue to describe the galaxies with only two parameters, m_i and r_i, even when mass is exchanged between them.

2.3. *Mergers*

Dynamical friction may bring two galaxies so close to each other that their centers are separated only by 1 kpc or less. At this stage the merger is considered complete, and we replace two particles by one, and the problem is reduced from an *N*-body to an $(N-1)$-body problem. From the way the mass loss is handled, it follows that the mass of the merged galaxy is the sum of its components. This method avoids close interparticle encounters, and thus it is not necessary to use regularization. We did not attempt to refine our merger algorithm for the purposes of this paper, although clearly not every encounter in reality would produce a merger. For example, cases where the two galaxies pass each other on tangential orbits with high velocities could conceivably not merge even in encounters where the centers pass within 1 kpc, although substantial damage would be acquired by both galaxies. A refinement of our merger algorithm is desirable in future work, but we believe that at least to the first order our basic results are not sensitive to the exact merger criterion that is used.

The modifications of the basic *N*-body code of Aarseth (1971) were tested first with the two-body problem, and then with the three-body problem. When satisfactory agreement with expected behavior was obtained, in comparison with, e.g., Valtaoja et al. (1989), the tests were extended to a 100-body problem. The latter were compared with the previous work of Saarinen & Valtonen (1985). We consider the algorithm to be a reasonable first approximation to the galaxy interactions.

3. THE CLUSTER MODEL

There is no unique way to set up the *N*-body system that we use to model the Coma Cluster. However, there are certain general principles that we consider to be important. We discuss the initial setup and input parameters of our simulation in the following subsections.

3.1. *The Cluster Center*

The surface density of galaxies in the Coma Cluster suggests that the center of the cluster has two gravitational potential wells, centered on the two supergiant galaxies NGC 4874 and NGC 4889. By applying the virial theorem to the galaxies in the two concentrations, one obtains masses of the order of $3–5 \times 10^{14}\ M_\odot$ in each subcluster (Valtonen & Byrd 1979; Fitchett & Webster 1987). The apparent separation of the subclusters is 360 kpc in the sky (using a Hubble constant $H_0 = 50$ km $^{-1}$ Mpc^{-1}), but it is likely that the true separation is considerably greater (Valtonen & Byrd 1979). Note that our models are based on Hubble constant $H_0 = 50$ km $^{-1}$ Mpc^{-1}, corresponding to $H_0^{-1} = 2 \times 10^{10}$ yr. Our models may be scaled to larger values of H_0 and to smaller H_0^{-1} by dividing the distance and mass scales proportionally to the change in H_0.

TW90 argued against two cluster centers. They noted that the X-ray map of the Coma Cluster (Sarazin 1986) shows no clear evidence of the bimodality that one might expect if there are two gravitational wells. More recent maps (e.g., the one by Arnaud et al. (2001)), have clearly brought out the substructure in X-rays. In addition, the bimodal distribution of diffuse light (Thuan & Kormendy 1977), as well as the bimodal distribution of galaxies (Quintana 1979) and their radial velocities (Fitchett & Webster 1987), make the central binary model more convincing. If the concept of the double potential well is accepted, then NGC 4874 should be the more massive of the two galaxies or subclusters (Valtonen & Byrd 1986), in agreement with X-ray observations.

The question of the relative orbits of the two subclusters needs to be answered next. Tremaine (1990) suggests that the Coma Cluster is an example of two clusters of galaxies in an early phase of merging. There are several points that argue against this interpretation. First, the general appearance of the cluster is very regular and relaxed. If it has resulted from a merger, it appears more likely that the merger of clusters took place a long time ago, when measured in terms of the crossing time of the central region. Secondly, the Coma Cluster is not unique in having two dominating central galaxies. It is a member of the B class of clusters (Rood & Sastry 1971) that make up about 10% of all rich clusters of galaxies. There appear to be timescale problems if one tries to associate all B-class clusters with recent cluster collisions (Rood 1988; Tremaine 1990).

Therefore, we place two supergiant galaxies with extensive dark halos in a bound orbit about each other. It is not essential to our model to know how the two supergiants become bound. Perhaps two clusters formed with one supergiant in each, and the clusters collided a long time ago, with the binary supergiant galaxy being the only visible remnant of the merger. Or perhaps galaxies formed initially in such a way that a few galaxies became very massive supergiants. In the gravitational clustering picture many of the very massive galaxies would have formed pairs with less massive galaxies clustered around them (Fig. 11*c* in Itoh, Inagaki, & Saslaw 1990).

We adopt the total mass of the central supergiant galaxies as $3.5 \times 10^{14}\ M_\odot$ (cf. Valtonen & Byrd 1979, 1986) and the mass ratio as 2 : 1. Their original relative orbit is circular, with orbital radius of 800 kpc. These values are in no way unique, but they are consistent with what we know about the central region of the Coma Cluster (Watt et al. 1992).

3.2. *The Rest of the Cluster Galaxies*

We do not know the original luminosity function of the Coma cluster of galaxies, and we know even less about the mass spectrum. In order to construct a reasonable mass distribution, we took the 250 brightest galaxies of the present-day Coma Cluster (Abell 1977) and assigned mass values to them. The masses of the supergiant galaxies were mentioned above. A constant mass-to-light ratio was used for the remaining 248 galaxies. In different runs, different M/L_V ratios were used: $M/L_V = 30 - 45$. The resulting total mass in the 248 galaxies was between 4×10^{14} and $6.2 \times 10^{14}\ M_\odot$.

Initially, all of the 248 galaxies were given radial velocities away from the center of the supergiant binary. The galaxies were placed in an expanding shell between an inner radius R_i and outer radius R_o from the binary center. The values of R_i and R_o were varied in different runs. Table 1 gives the parameters of the experiments that were carried out. Column (1) is the run number. Column (2) describes the type of initial conditions used. "OS" refers to the model of Olson & Silk (1979) and "SV" to the model of Saarinen & Valtonen (1985). In the latter model, the galaxies were scattered uniformly in the shell bounded by radii R_i and R_o, and the velocities were using the Hubble law with distance measured from the center of the cluster and allowing for a small random velocity component drawn from a Gaussian distribution with a 50 km s^{-1} dispersion.

Olson & Silk (1979) calculated the evolution of primordial inhomogeneities in the expanding universe. They found that in a marginally bound shell around the center of perturbation the radial dependence of density is $\rho(r) \propto r^{-8/7}$. We use this density profile at the beginning of the experiment between radii R_i and R_o. The starting time t_0 of the cluster integration is set in such a way that the galaxies are at their turning points at R_i but still expanding away in the shell between R_i and R_o. The OS model gives a unique value for the radial expansion speed as a function of distance from the center. The expansion speed is zero at $r = R_i$ and nonzero further away.

In the OS model, the determination of the velocity field proceeds as follows: (1) Choose a value for R_i. (2) Calculate the starting time from

$$t_0 = \frac{\pi}{2^{3/2}} \frac{R_i^{3/2}}{(GM_i)^{1/2}}. \tag{1}$$

Here M_i is the mass within the radius R_i, i.e., the central binary mass. G is the gravitational constant. (3) Solve the parameter θ from

$$\frac{\theta - \sin\theta}{(1 - \cos\theta)^{3/2}} = t_0 \frac{[GM(r)]^{1/2}}{r^{3/2}} \tag{2}$$

for every radial distance $R_i \le r \le R_o$. The quantity $M(r)$ is the cluster mass contained within radial distance r. (4) Finally, calculate the radial velocity V from

$$V = \frac{r}{t_0} \frac{\sin\theta(\theta - \sin\theta)}{(1 - \cos\theta)^2}. \tag{3}$$

For details, we refer to Olson & Silk (1979).

Starting from time t_0, the evolution of the cluster was followed up to 2×10^{10} yr. It is expected that subclusters of a few times $10^{14}\ M_\odot$ form around redshift $z = 3$, while the cluster formation goes on via infall of gas and galaxies up to the present time (Evrard et al. 2002). This leaves about 17 billion yr of dynamical evolution to calculate (using $H_0 =$ 50 km s^{-1} Mpc^{-1}).

TABLE 1
PARAMETERS OF THE NUMERICAL EXPERIMENTS

Run (1)	Type (2)	Mass ($10^{14}\ M_\odot$) (3)	R_i (Mpc) (4)	R_o (Mpc) (5)	Friction (Yes/No) (6)
1	OS	4.0	0.8	1.4	Yes
2	OS	4.0	1.5	2.5	Yes
3	OS	4.6	1.0	2.0	Yes
4	OS	4.6	2.0	3.0	Yes
5	OS	6.2	3.0	5.0	Yes
6	OS	6.2	3.0	5.0	No
7	SV	4.0	0.8	3.0	Yes
8	SV	4.6	0.8	3.0	Yes
9	OS	4.6	0.8	3.0	No
10	OS	4.6	1.0	1.8	No

NOTE.—"OS" refers to Olson & Silk (1979), and "SV" refers to Saarinen & Valtonen (1985).

4. RESULTS

4.1. *The Virial Mass*

The virial mass is determined in the same way as observers would do it. There are many methods to choose from, but we have only used the method of Schwarzschild (1954). Previous work (e.g., Saarinen & Valtonen 1985) has shown that different methods give rather similar values in a case like ours. In Figure 1, we plot the ratio of the virial mass to the known total mass as a function of time in two different experiments. Naturally, the result depends on the direction from which the cluster is viewed. Our coordinates are such that the binary moves initially in the *xy*-plane. In the comparison with the Coma Cluster, we should probably take a projection that

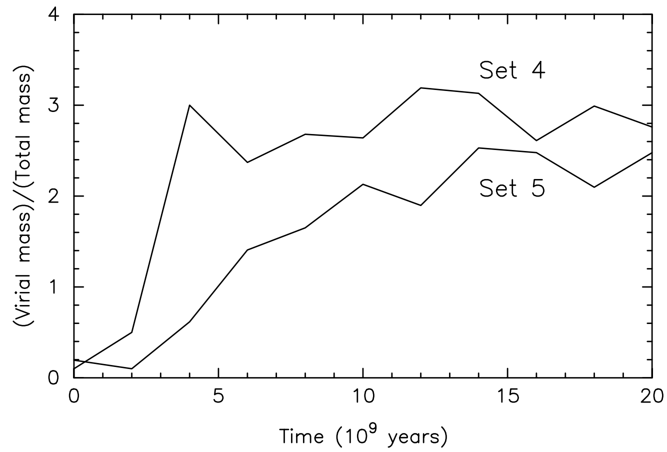

FIG. 1.—Calculated virial mass normalized to the known total mass of the cluster as a function of time (runs 4 and 5).

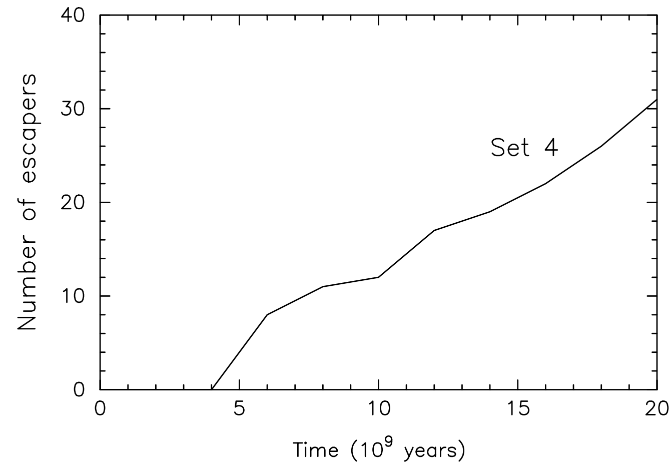

FIG. 2.—Number of escaped galaxies as a function of time in run 4. The total number of galaxies at the beginning of the simulation, apart from the central massive binary, was 248.

includes the z-axis, i.e., we are likely to be looking at the binary nearly edge-on (Valtonen & Byrd 1979).

We note that generally the virial mass is too large by a factor of 2–3. It does not seem to matter what kind of initial conditions we use, or whether we include dynamical friction or not. Whatever the details of the evolution of the Coma Cluster are, it is likely that the mass estimates based on the virial theorem are excessive by a similar factor of 2–3. Part of this excess comes from the predominance of nearly radial orbits in our model. However, the essential feature in these models is the binary nature of the central region, which is responsible for much of the deviation from a true virial equilibrium.

4.2. *The Number of Escapers*

One of the causes for the overestimate in the virial mass determination is the inclusion of gravitationally unbound, escaping galaxies. Our definition may be compared with the definition of "interloper" galaxies in observations, used by, e.g., Katgert et al. (1996); and Mazure et al. (1996). They iteratively identified and removed interloper galaxies from their observed clusters using the following criterion for true cluster membership: the observed line-of-sight velocity had to be consistent with either a bound galaxy in a radial orbit around the cluster center or a bound galaxy in a circular orbit around the cluster center. Galaxies with inconsistent velocities were removed and the cluster potential calculated again, and the process repeated iteratively. This alternative definition of nonmember galaxies has been shown to work well in simulated data (van Kampen 1994). Naturally, the interloper elimination algorithm eliminates escaping background and foreground galaxies, and the hope is that only the virialized cluster is left behind. While it is hard to estimate how successful that method is, we can unambiguously identify the escaping galaxies in our simulation. Figure 2 shows the number of escapers in one of our runs as a function of time. Typically, the escapers form about 10% of the projected cluster galaxy population at the end of the run.

4.3. *Projected Surface Number Density of Galaxies*

The similarity of our model to the Coma Cluster cannot be constrained by the virial mass or the number of escaping galaxies. However, one of the most easily observable properties of a cluster is its surface number density of galaxies. We use the data given by Kent & Gunn (1982) for the Coma Cluster and compare them with our model runs. The comparisons are shown in Figure 3. We see that it is not difficult to fit the density profile in most cases, in agreement with the conclusions of TW90.

4.4. *Velocity Dispersion Profile*

TW90 found it impossible to fit the values of the radial velocity dispersion at different distances from the center of the Coma Cluster with their bimodal models. Since the work of TW90 the number of known redshifts in the Coma Cluster has increased considerably. We have included the new observational data in Figure 4 where we compare them with the model results. We selected all the galaxies from the NED that were within 3° of R.A. = $12^h59^m48^s.7$, decl. = +27°58′50″ (J2000.0) and within ±3100 km s^{-1} of 6925 km s^{-1}, the systemic velocity of the Coma Cluster. We found in total 924 galaxies.

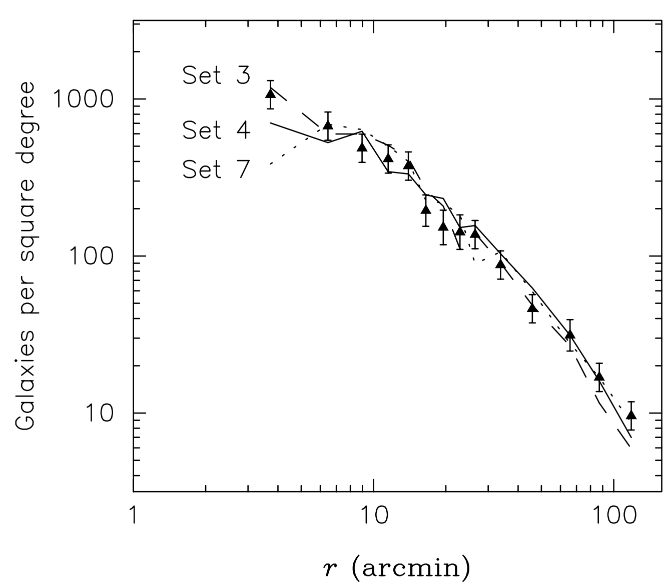

FIG. 3.—Surface number density of galaxies brighter than $M_V = 16.5$ in the Coma Cluster according to Kent & Gunn (1982; observations are shown with filled triangles and associated error bars). Model surface densities from cluster models at 2×10^{10} yr that are viewed in the binary plane are also shown. The model data have been scaled upward because of a different magnitude limit [runs 3 (*dashed line*), 4 (*solid line*), and 7 (*dotted line*)].

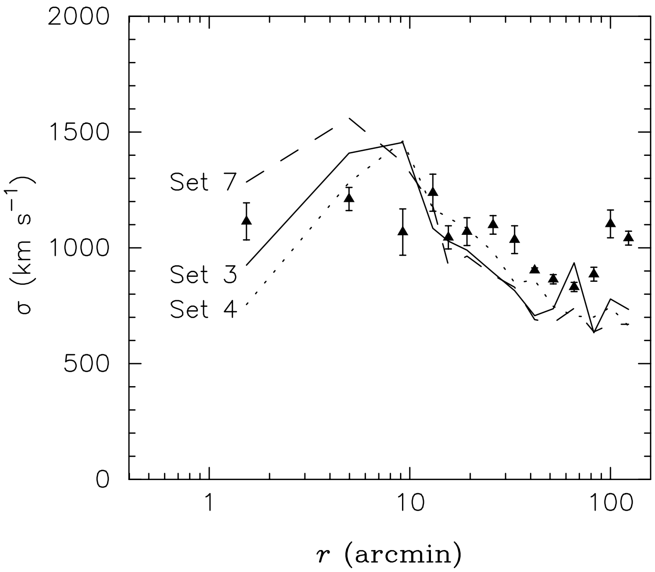

FIG. 4.—Velocity dispersion σ_r in the Coma cluster of galaxies (observations are shown with filled triangles and associated error bars). Model velocity dispersions from the cluster models at 2×10^{10} yr, viewed in the binary plane, are also shown [runs 3 (*solid line*), 4 (*dotted line*), and 7 (*dashed line*)].

We divided them into radial bins and calculated the velocity dispersion in each bin with respect to the average cluster velocity. We estimated the uncertainty in the velocity dispersion by forming 10 samplings of the velocity dispersion at a given radius by slightly changing the inner and outer bin radii while keeping the bin center fixed. The uncertainties reflect 1 σ differences from the average velocity dispersion in the 10 different realizations. Three degrees was chosen as the outer boundary due to the fact that beyond that radius the separation of the Coma Cluster from the Coma supercluster becomes ambiguous, and 3100 km s^{-1} reflects the fact that it includes galaxies up to 3 σ away in the Gaussian distribution of the galaxy velocities around the cluster center.

The innermost two to three points in Figure 4 are strongly influenced by the central supergiant binary. These points are very sensitive to the details of the models, for example, to the way the supergiant binary galaxies accumulate their companion galaxies, the detailed mass distribution of these supergiants, the detailed dark matter content of the companion galaxies, etc. The models have not been refined to this level of detail.

The last two points in Figure 4 may not reflect the true dynamical state of the cluster. They are more likely representative of the surrounding supercluster, and the velocity dispersion may arise from separate subclusters at somewhat different cosmological distances from us (Mellier et al. 1988). The last points lie definitely beyond the traditional r_{200} boundary of the Coma Cluster, which is at about 70′ radius (Rines et al. 2001). However, the slope between 10′ and 80′ is correctly reproduced. The systematic offset in the velocities depends on the projection of the model, as well as the masses and the orbital radius of the central binary. These scalings and projections can be made easily. The slope of the profile is more dependent on the dynamics of the system.

TW90 pointed out that their models tended to give a velocity dispersion that is too low at large distances from the cluster center. It is true also for some of our models, while others give a very nice fit to the data (e.g., runs 3, 4, 5, and 7). It is interesting that the inclusion of dynamical friction, as well as a more sophisticated starting model, clearly improve the agreement with the observations. Thus, it appears that the main objection to the bimodal cluster model by TW90 is simply the result of an overly simplified method of calculation.

5. DISCUSSION

In this section we briefly summarize our arguments and other recent progress in the field that favor a bimodal structure in the Coma Cluster and compare them with the original work of TW90.

Direct observational evidence, specifically from the X-ray data, have improved and now support the view that there is an important bimodal component near the center of the cluster. These data were inadequate at the time TW90 made their arguments against a bimodal structure.

TW90 emphasized that the cluster models which are based on the massive central binary do not agree well with observations of the radial velocities in the Coma Cluster. The same result was obtained also in the earlier work of Valtonen et al. (1985). However, the present modeling shows that this argument is valid only in the simplified models of the classical or semiclassical *N*-body problem. When dynamical interactions between galaxies are taken into account in a more realistic way, as we have done in the current paper, the agreement with observations is remarkably good.

TW90 also argued that the inferred properties of the supergiant galaxies of the Coma Cluster are somehow unnatural. The dark matter (or low-luminosity, to be exact) halos would be more extensive than in any other known galaxy, and the velocity dispersion in their outer parts would be much higher than the observed dispersion in the centers of the supergiant galaxies. Valtonen & Byrd (1979) also proposed celestial bodies that were not known at that time in their original binary model. However, the existence of subclusters inside dark matter halos has now been established observationally, and they are well understood in the CDM scenarios of structure formation.

A recent observation in favor of slingshot ejections from a dominant central binary in the Coma Cluster is the finding of overall rotation in the innermost 1 Mpc radius of the Coma Cluster. The rotation is retrograde relative to the sense of rotation of the NGC 4874–NGC 4889 binary (Biviano et al. 1996). Since retrograde orbits are more stable against being ejected, they are preferentially left over in the slingshot process when it is applied to randomly oriented orbits. While galaxies in direct orbits escape, galaxies with retrograde orbits can remain relatively close to the binary.

Since our models agree well with observations, it is highly likely that the cluster mass estimates based on the traditional virial theorem give an excessively large value for the total mass of the Coma Cluster. The corrected value for the mass-to-light ratio of about 100 in solar units agrees with a detailed analysis of the X-ray data by Cowie et al. (1987).

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