

KINEMATIC EVIDENCE OF SATELLITE GALAXY POPULATIONS IN THE POTENTIAL WELLS OF FIRST-RANKED CLUSTER GALAXIES

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ABSTRACT

We have measured the velocities of 38 centrally positioned galaxies ($r \ll 100$ kpc) relative to the velocity of the first-ranked galaxy in 14 rich clusters. Analysis of the velocity distribution function of this sample and of previous data shows that the population cannot be fit by a single Gaussian. An adequate fit is obtained if 60% of the objects lie in a Gaussian with $\sigma = 250$ km s⁻¹ and the remainder in a population with $\sigma = 1400$ km s⁻¹. All previous data sets are individually consistent with this conclusion. This suggests that there is a bound population of galaxies in the potential well of the central galaxy in addition to the normal population of the cluster core. We take this as supporting evidence for the galactic cannibalism model of cD galaxy formation.

Subject headings: galaxies: clustering — galaxies: formation

I. INTRODUCTION

As is well known the central most luminous galaxy in a rich cluster often possesses multiple nuclei. Recent work by Hoessel and his collaborators has quantified this phenomenon and shown that there is a significant excess of galaxies with $L \geq 0.06 L_*$ within $10 h^{-1}$ kpc (where $h = H_0/100$ km s⁻¹ Mpc⁻¹) of the center of the first-ranked galaxy (Hoessel 1980; Schneider, Gunn, and Hoessel 1983; Hoessel and Schneider 1985). Tonry (1984) and Hoessel and Schneider (1985) have shown that the galaxy surface density must rise by a factor of roughly 3 within this $10 h^{-1}$ kpc aperture compared to the average density of the cluster core, though these calculations are based on uncertain fits to the core population.

Cannibalism models for cD galaxy formation would predict that the excess galaxies lie in decaying circular bound orbits about the central galaxies (Ostriker and Tremaine 1975; White 1976; Hausman and Ostriker 1978). Arguing against this is the fact that in some of the more famous of these systems (e.g., NGC 6166 in A2199) the relative velocities of the nuclei with respect to the cD galaxy are far too large for them to be bound in the potential of the cD galaxies, which have typical velocity dispersions of around 300 km s⁻¹ at these radii (Tonry 1984; 1985*b*). The presence of these high-velocity nuclei has led Tonry (1984, 1985*a*) and also Merritt (1984), in a theoretical paper, to argue that a substantial portion of the excess population is in fact not bound to the central galaxy but is in radial orbits passing through the nucleus of the

cluster. More recently, measurements by Tonry (1985*b*) and Smith *et al.* (1985) of velocities in two sets of multiple nuclei drawn primarily from the Hoessel and Schneider sample, have been taken as evidence supporting this conclusion. In particular the velocity dispersion in each sample is around 800 km s⁻¹, which is comparable to the velocity dispersions in the parent clusters.

We shall argue in this *Letter* that in fact a substantial fraction of the multiple nuclei, about 60%, lies in a bound population in the potential well of the first-ranked cluster galaxy. The velocity dispersion of this component is about 250 km s⁻¹ and is comparable to the velocity dispersion of the central galaxy as measured by Tonry (1984, 1985*b*). Before proceeding, we review the difficulties in the previous interpretation.

The basic problem is to measure the velocity dispersion of an excess population against the projected normal population of the cluster core. If the central surface density is 3 times the normal value, roughly 2/3 of the nuclei are in the excess population and one-third are normal core galaxies. It is this large fraction of projected normal core galaxies which causes the difficulty. Even if the velocity dispersion of the excess population is quite small, we will still see many individual high-velocity nuclei drawn from the normal core population. Both Tonry (1985*b*) and Smith *et al.* (1985) measured only 19 nuclei redshifts, and, as we shall show subsequently, neither sample is large enough to discriminate between a single normal distribution with $\sigma \approx 800$ km s⁻¹ and two normal distributions with $\sigma_1 \approx 250$ km s⁻¹ and $\sigma_2 \approx 1400$ km s⁻¹, respectively, which would give a similar value of $\sigma = (1/3 \sigma_2^2 + 2/3 \sigma_1^2)^{1/2} = 840$ km s⁻¹, let alone the three populations (bound, normal, and extended radial orbit) invoked by Tonry (1985*b*). The problem can be properly ad-

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dressed only with a large sample which can distinguish between a single Gaussian and a bimodal population. A second problem which the Tonry (1985*b*) and Smith *et al.* (1985) papers fail to address is the need for a control population sampling the region outside the central $10 h^{-1}$ kpc, to allow determination of which features of the observed velocity distribution are in fact attributable to the central region alone.

In this *Letter* we use an extended sample containing 75 nuclei to demonstrate that the multiple nucleus population is indeed bimodal. The new data consist of 36 additional redshifts taken together with the Tonry and Smith *et al.* samples and some previous measurements compiled by Smith *et al.* With this much larger sample we show that a single Gaussian is *not* an acceptable fit to the data, but that the bimodal distribution discussed above is. In addition, we use the new and more homogeneous data to demonstrate that a control sample of 22 objects with $r \geq 20$ kpc shows substantially higher velocity dispersion ($\sim 1400 \text{ km s}^{-1}$) than the $\sim 800 \text{ km s}^{-1}$ obtained for the 14 galaxies with $r \leq 20$ kpc.

II. DATA

Galaxy positions and redshifts for a large sample of galaxies in cluster cores were obtained, serendipitously, during the course of spectroscopic studies of the cool gas in the centers of rich X-ray luminous clusters (Hu, Cowie, and Wang 1985). Full details of the observation and reduction procedure and extensive discussion of the cluster properties may be found in this paper. A list of the properties of the clusters and the observed galaxies is given in Table 1.

Fifty-nine independent objects which fell within the slits were bright enough (typically $\mu_V \leq 23 \text{ mag arcsec}^{-2}$) compared to the background light of the central galaxy for redshifts to be unambiguously measured using a cross correlation procedure described in Paper I, with subsequent confirmation by the direct measurement of several individual absorption- or emission-line features. The accuracy of the redshift measurements from both internal and external checks is $\sim 100 \text{ km s}^{-1}$ for most of the objects, but can be as much as 250 km s^{-1} at the fainter end. In each case, positions of the

TABLE 1
PROPERTIES OF CLUSTERS WITH OBSERVED REDSHIFTS

ID	RS	BM	R.A.(1950)	DECL.(1950)	$(l^{\text{II}}, b^{\text{II}})$	z_{cD}	NEIGHBORING GALAXY ^a	
							Separation (h^{-1} kpc)	Velocity (km s^{-1})
A85	cD	I	00 ^h 39 ^m 18 ^s	-09°34'35"	(115, -72)	0.0558	83	-2410
							41	-2680
							25	180
A133	cD	I	01 00 15	-22 08 30	(149, -84)	0.0572	3	-150
A262	C9	III	01 49 50	+35 54 20	(137, -25)	0.0162	15	-240
							12	-300
A401	cD	I	02 56 13	+13 23 00	(164, -39)	0.0741	20	600
A496	cD	I:	04 31 19	-13 21 22	(209, -37)	0.0328	126	-30
							16	30
							11	-60
							29	120
A644	cD	III:	08 15 00	-07 21 22	(230, +15)	0.0704	45	-870
							17	-390
							84	60
A754	cD	I	09 06 06	-09 25 36	(239, +25)	0.0553	46	-60
A978	F	II	10 17 56	-06 16 56	(250, +40)	0.0542
A1126	B _b	I-II	10 51 10	+17 06 35	(228, +61)	0.0844	6	1390
							12	0
A1775	B _b	I	13 39 30	+26 37 56	(31, +78)	0.0753	23	-1780
							28	120
							11	90
							43	360
							28	-270
A1795	cD	I	13 46 34	+26 50 28	(33, +78)	0.0632	13	300
							36	-90
							54	-870
							8	-2350
							117	-1450
							44	210
A2029	cD	I	15 08 27	+05 56 35	(6, +51)	0.0772	43	-1630
							63	-1480
							80	2310
							60	1450
							4	-60
A2052	cD	I-II	15 14 12	+07 12 26	(9, +50)	0.0340	36	-3020
A2142	B _b	II	15 56 16	+27 22 32	(44, +49)	0.0911	8	120
							8	120
							214	1420

^a Measured in frame of cD with redshift shown.

object along the slit were measured and confirmed on the Palomar prints or on CCD exposures of the fields. Finding charts may be found in Paper I. The data are given in full in Table 4 of Hu, Cowie, and Wang (1985) and summarized here in Table 1. Of the objects, 14 are the central (most luminous) galaxy of the cluster, 38 are other galaxies, and seven are foreground stars. After eliminating the foreground stars, one spiral galaxy at very low redshift, and one high-redshift ($z \approx 0.3$) object, we are left with a sample of 36 galaxies plus the central galaxies in the clusters. The total area covered by the slits was only 8.3 arcmin^2 so the expected number of projected galaxies to $m_V = 19.5$ is only about 0.5 (Abell 1977).

The present sample is well suited to studying the central core ($r \leq 3'$) dynamics of the clusters. It is complete to a limiting magnitude of $m_V \approx 19.5$ and is relatively free of selection effects, since the slit orientations were not chosen for this purpose. The sample of clusters was chosen primarily on the basis of X-ray gas properties (high central gas density) and forms a relatively homogeneous population compared to previous samples. As can be seen from Table 1, almost all the clusters are of Bautz-Morgan type I and have Rood-Sastry classification cD. Most are of richness class 1 or 2. Only one of the clusters (A262) departs significantly from the otherwise homogeneous sample of rich centrally condensed spiral poor clusters. Omission or inclusion of A262 does not affect the results discussed below. The sample does include three binary clusters (A1126, A1775, and A2142), where there are two central galaxies of comparable magnitude and size, and it seems likely that the dynamics of these clusters differ from those dominated by a single central galaxy. However, the incidence of multiple nuclei does not appear to depend sig-

nificantly on cluster type (Hoessel and Schneider 1985), so that the present clusters should constitute a satisfactory sample for studying this phenomenon.

III. THE VELOCITY DISTRIBUTION FUNCTION

In Figure 1a, we show the velocity of each galaxy in our present sample versus radial position, where both quantities are measured in the frame of the central galaxy. (As an ad hoc procedure, for the binary cases, we have chosen the galaxy around which the X-ray emission peaks to be the central galaxy.) Exclusion of the binary clusters reduces the velocity spread in the galaxies and suggests that the binaries are dynamically more complex. However, the major point to note from Figure 1a is the "swarming" of many of the galaxies in a low-velocity population near the origin.

A second way of making this point is to plot the spatial distribution of the higher velocity galaxies. In Figure 1b we show a comparison of the spatial distribution for galaxies with $v \geq 300 \text{ km s}^{-1}$ and compare it with that for all the galaxies. The higher velocity galaxies are consistent with being drawn from a Hubble law distribution and show no signs of the central excess which is clearly present in the lower velocity component. Thus, the initial picture we have is of a uniformly distributed high velocity dispersion component superposed on a low velocity dispersion component which is centrally concentrated.

What is the significance level of these results? If the 14 galaxies of our sample inside $20 h^{-1} \text{ kpc}$ were drawn from a normal population the velocity dispersion would be $750 \frac{1160}{360} \text{ km s}^{-1}$ (subscripted and superscripted values are 95% confidence limits). We may note in passing that the comparable

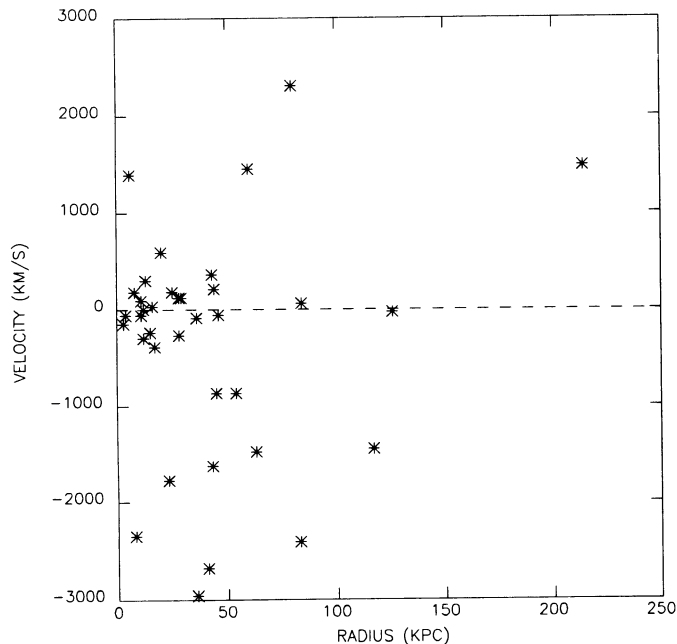


FIG. 1a

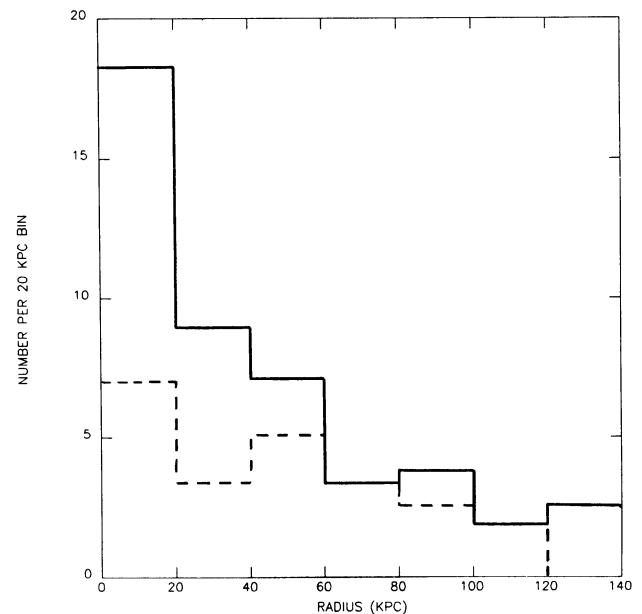


FIG. 1b

FIG. 1.—(a) Shown are the velocities of the galaxies from the sample listed in Table 1 in the frame of the central most luminous galaxy vs. radial position measured from the peak surface brightness of the central galaxy. (b) The number of galaxies, corrected for the fractional slit coverage, in each $20 h^{-1} \text{ kpc}$ bin (solid line) is compared with the number of galaxies with absolute velocities in excess of 300 km s^{-1} in each bin (dashed line).

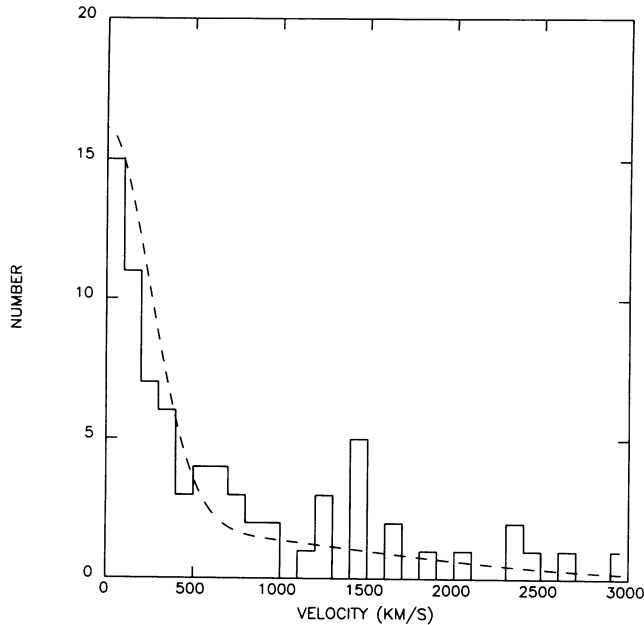


FIG. 2a

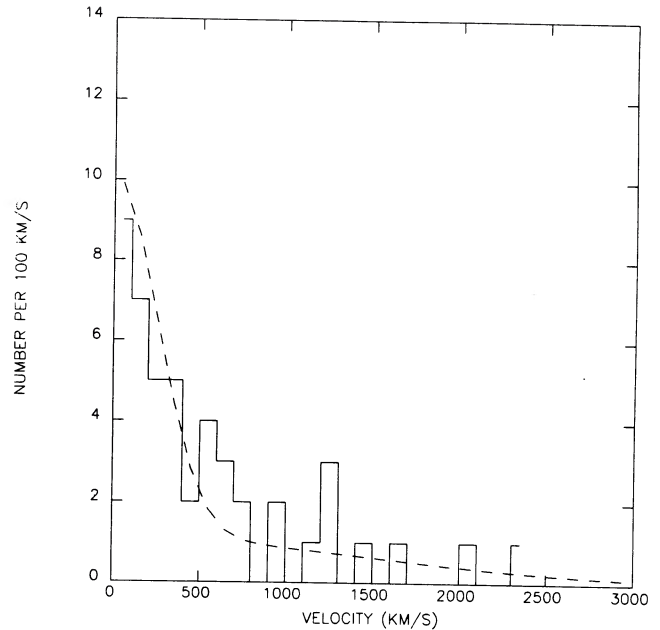


FIG. 2b

FIG. 2.—(a) The velocity distribution function of the entire sample of 75 objects. The dashed line shows a fit where 60% of the galaxies have $\sigma = 250$ km s^{-1} and 40% have $\sigma = 1400$ km s^{-1} . (b) The velocity distribution function of the sample of 47 objects inside $20 h^{-1}$ kpc. The same fit is shown.

value for the Smith *et al.* (1985) sample is 830^{+1030}_{-680} km s^{-1} and for the Tonry (1985*b*) sample is 760^{+1120}_{-580} km s^{-1} . (The similarity of the results suggest that despite the facts that these previous samples are much more inhomogeneous in their sample of clusters and that there is a small difference in limiting magnitude all three data sets are seeing the same population.) For the 22 galaxies in our sample outside $20 h^{-1}$ kpc we obtain 1420^{+1960}_{-1170} km s^{-1} which is significantly higher than the value inside $20 h^{-1}$ kpc population. Thus, when compared to a proper control sample, the central galaxy population contains a significantly larger fraction of low-velocity objects.

We next combined the present data with all the previous measurements to form a larger sample. Where overlap occurred we preferred Tonry's measurement, then Smith *et al.*'s, and then our own. The final sample contains 75 objects and its distribution is shown in Figure 2a. With this large sample we can now clearly distinguish the presence of the low-velocity population.

We first tested whether this data could be fit with a single normal distribution. Binning the data into six velocity bins, each with an expectation value of 12.5 galaxies, we found a minimum χ^2 of 22 for $\sigma = 800$ km s^{-1} . Since for 4 degrees of freedom the 5% critical value is $\chi^2_0 = 11.7$ we may reject the hypothesis of a single Gaussian at the 95% confidence level. We next fitted the distribution with the sum of two Gaussians allowing both velocity dispersions and the fractional contribution of each component to vary. The best fit gives 60% of the population in a component with $\sigma = 250$ km s^{-1} and 40% in a population with $\sigma = 1400$ km s^{-1} . The χ^2 for this fit is 2.6 compared with a 5% critical value of $\chi^2_0 = 6.0$ for 2 degrees of freedom. Thus this model is a good fit to the data. It is shown

as the dashed line in Figure 2a. The data within $20 h^{-1}$ kpc is shown in Figure 2b and is also well fitted by the same bimodal model but not by a Gaussian. As a final step we tested the bimodal fit against each of the individual data sets (Tonry, Smith *et al.*, and our own data for galaxies within $20 h^{-1}$ kpc). In each case, it provides a better fit than the single Gaussian though because of the small samples neither hypothesis can be rejected. However, the important point to note is that *none of the individual samples is inconsistent with the presence of the substantial low-velocity population which is found in the total data set.*

IV. CONCLUSIONS

The presence of the low-velocity population with a velocity dispersion comparable to that of the first-ranked cluster galaxy (~ 300 km s^{-1}) at these radii (Tonry 1985*b*) suggests that we are seeing a bound population of satellites in the potential well of the galaxy. The presence of these objects, with a surface density 1.5 times that of the normal core population, produces a net rise in surface density by a factor of 2.5 and can approximately account for the observed excess of multiple nuclei without invoking the presence of galaxies on radial orbits. We note that the presence of the low-velocity satellite population is in strong qualitative agreement with the predictions of the cannibalism model of cD galaxy formation (e.g., Hausman and Ostriker 1978), but we postpone a detailed discussion of this point to a subsequent paper.

One problem of the present result is the high velocity dispersion (1400 km s^{-1}) of the best-fit second component.

This is high compared with typical values of velocity dispersions in the clusters typifying the sample. These are around 800 km s^{-1} or so (Smith *et al.* 1985; Tonry 1985*b*). Acceptable values for the second component σ can be as low as 1000 km s^{-1} , and there are a number of effects which might raise the measured σ . These include interlopers, binary clusters, and the central cluster velocity dispersion being larger than the average value (as is the case in Coma [Kent and Gunn

1982]). However, this particular point clearly requires further study.

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