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Black Pits in Cluster Cores

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ABSTRACT

The relative radial velocities of multiple-nuclei galaxies, together with recent X-ray observations, suggest that the dark matter in the centers of rich clusters can have core radii ranging from the conventionally assumed value of ∼200 kpc down to as small as 10 kpc. We present a two-parameter (core radius and velocity dispersion) model of the cluster gravitational potential, describing a family of potentials corresponding to the two-parameter observed morphology of X-ray clusters. Because the dark matter can dominate the luminous matter down to such small scales, we consider a cluster of galaxies as a "black pit" in which the galaxies move as test particles. Using this model potential, we interpret the unusual optical morphology, often observed for brightest cluster member galaxies (Morgan's cD, D, and db classes), as a natural consequence of galaxy formation, tidal stripping, and merging in a pre-existing small core radius black pit. Dynamical friction is less efficacious in these small core radius pits, as observations seem to require. The central concentration of dark matter in cluster cores may explain the phenomenon of wide-angle-tail radio sources associated with brightest cluster members. The amount of gas and stars in a pit potential may vary widely, producing the richness variation observed in clusters. Optically under-illuminated pits (such as the Yerkes poor clusters) can still have their observed cD galaxies, small X-ray cores, and wide-angle tails caused by the dark matter. The most likely cause of the high density of dark matter in some cluster cores is the fragmentation of the cosmological dark matter. We make a number of predictions for observational tests of the black pit model.

1. INTRODUCTION

It has long been known that the centers of many D (elliptical nucleus plus extensive envelope) and cD (supergiant D) galaxies contain two or more distinct elliptical components. The extreme of this type is the dumbbell (db) galaxy (Mathews et al. 1964): two equally bright elliptical galaxies in a common envelope. These "compound" galaxies are particularly common amongst those bright galaxies that dominate the cores of rich clusters. At least one-third of the brightest cluster members in rich clusters are known to be compound (Rood and Leir 1979, Hoessel 1980, Schneider and Gunn 1982). In the course of a systematic study of the optical and radio properties of compound galaxies being carried out by one of us (LS), it has become apparent that the dynamical properties of compound galaxies differ in a quite striking way from those of the binary galaxies in small groups and in the field. In particular, it appears that the velocity differences between two or more galaxies contained within a common envelope (separation ∼10 kpc) and located near the centers of rich clusters are frequently ∼800 km/s (cf. Jenner 1974), about five times the median velocity differences normally found for isolated binaries (Faber and Gallagher 1979). This implies the presence of an unusually large density of dark matter within the central region of the cD.

The dynamics of cluster cores is usually discussed (see, e.g., Hausman and Ostriker 1979) in terms of "galactic cannibalism." In this picture, the luminous envelopes of D and cD galaxies comprise stellar debris stripped from galaxies that have been captured and ingested as a result of the action of dynamical friction in a self-consistent stellar potential. Compound galaxies are then presumed to contain the undigested central parts of normal elliptical galaxies that will eventually merge to form a single core. We propose an alternative picture in which the central cD galaxy in many rich clusters has been formed in a pre-existing potential well gravitationally produced by dark matter; a "black pit," which has a core radius some ten times smaller than that hitherto associated with the dark matter known to exist in these clusters. The dynamics of the cluster core is then approximately

that of test particles in an external potential well, which leads to conclusions quantitatively different from those of the galactic cannibalism model.

If these multiple nuclei are bound by the potential, then their redshift difference is (apart from projection effects) a direct local measurement of the logarithmic slope of that potential, or equivalently the Kepler velocity. In Section 3, we point out that in many clusters with dominant multiple-nuclei galaxies, this velocity appears to be similar on scales from 10 kpc to $\gtrsim 1$ Mpc, i.e., that the gravitational potential appears to be scale-free over several decades in radius. We produce a two-parameter model of such a "black pit" potential. One parameter measures the core radius of the dark matter and one the characteristic velocity of the dark matter potential. The core radius ranges from large values (hundreds of kpc) for "conventional" dark matter dominated clusters to small values (tens of kpc) for "extreme" black pits. The second parameter measures the velocity dispersion of clusters (250 km/s to 1500 km/s) at large distances.

Our model suggests that the external dark matter dominates the cD galaxy dynamics in extreme black pits. This will cause the measured velocity dispersion in a cD galaxy to rise with distance from the bright galactic core. In Section 4, we draw a number of consequences of our model for X-ray and radio observations. The X-ray-dominated (XD) clusters (Forman and Jones 1982, Jones and Forman 1983) are associated with extreme black pits. The black pit potential with its variable core radii can be compared with the more conventional King model potentials, with their fixed core radii, used to investigate hydrostatic and X-ray cooling core clusters. The wide-angle tailed radio sources, which emanate from dominant cluster galaxies, are probably caused by the inability of the radio jets to propagate supersonically to large distances in a black pit potential, particularly if a temperature inversion (cooling core) is present. It is natural, in our model, that the Yerkes "poor clusters" can have high-ΔV multiple nuclei, X-ray cooling cores, and wide-angle tails.

In Section 5, we argue that the universal dark matter is highly inhomogeneous, with the highest density concentrations corresponding to the extreme black pits. The galaxies and gas will settle into this nonuniform potential. As a result, some cD galaxies may still be forming (e.g., Perseus or A496) from gas flowing into the black pit. Clusters vary in galaxy content from the rich Abell clusters to the "poor cD clusters" of Morgan, Kayser, and White (1975). In our view, this variation reflects the total luminous content of the dark matter potential wells. The Bautz-Morgan cluster classification (which describes the degree of dominance of the central galaxy) measures how much of the gas and stars have fallen into the bottom of the central pit. Finally, the shape of the underlying dark matter potential, illuminated by the galaxy distribution, leads to the Rood-Sastry (1971) morphological classification of clusters.

2. COMPOUND GALAXIES

Matthews, Morgan, and Schmidt's (1964; hereafter MMS) article on the nature of galaxies associated with radio sources made some profound observations about the galaxies that inhabit the cores of clusters of galaxies. They found that in many Abell clusters, the brightest cluster member was not a normal elliptical or spiral galaxy, but instead a "D" or a "dumbbell" galaxy. These galaxies were so unusual morphologically that Morgan created special subclasses for them in his (Morgan, 1958) classification scheme.

The D galaxies "have an elliptical-like nucleus surrounded by an extensive envelope" (MMS, p. 40). If the envelope is 3–4 times the diameter of an ordinary cluster lenticular, the prefix "c" is added, denoting the now well-known cD supergiant galaxies. The dumbbells (db) are a group allied to the D galaxies, in which two separated, approximately equal nuclei, are observed in a common envelope. They may well be related to the galaxies which have one or more fainter companions in their envelopes, the dumbbells being the extreme cases of very close multiple galaxies when there are only two equal components" (MMS, p. 40).

We quote MMS to emphasize that twenty years ago it was clear to Morgan that the D, cD, and db galaxies were not the same entities as elliptical galaxies. Furthermore, since they were almost exclusively found at the centers of rich clusters, there was something different about the environment at the cluster center as compared to the cluster as a whole. In this section, we analyze some of the observational evidence collected since MMS on the nature of this environment.

2.1. *Existence of Binaries in Cluster Cores*

Leir and van den Bergh (1977) cataloged the multiplicity of the brightest cluster member (as seen on the Palomar Observatory Sky Survey plates — POSS) for 1889 of Abell's rich clusters. Rood and Leir (1979) performed a statistical analysis on these data and concluded that 23% of Bautz-Morgan Type I and I/II clusters had multiple-nuclei brightest cluster members. In all cases (28 multiple out of 112 clusters) these galaxies were Morgan's dumbbell type. Struble and Rood (1982) published a more detailed catalog of the 276 closest Abell clusters [Distance Class (D.C.) < 4]. This was later extended to D.C. 5 (Struble and Rood 1984) and D.C.

6 (Struble and Rood 1987). It should be emphasized that these multiple-nuclei central galaxies occur in all Bautz-Morgan type clusters, not just clusters with cD galaxies.

In their catalogs, Struble and Rood give the angular separation and morphological type of the three brightest galaxies in each Abell cluster. They note that in between 10% and 50% of the clusters, one of the three brightest galaxies is a "binary," the percentage depending on the Rood-Sastry (1971) morphological type of the cluster. These "binaries" are two bright galaxies within a connecting bridge or common envelope, "b-systems" in the Rood-Sastry (1971) classification. For each binary, Struble and Rood give the angular separation between the two components of the binary as well.

We have analyzed Struble and Rood's systematic database in an attempt to determine if the "binaries" are physical pairs or chance superpositions. For all clusters in their catalog with D.C. ≤ 3 and known cluster redshift (96 clusters), we converted the angular separations of the brightest cluster galaxies to physical projected separations in kpc, using Hubble's Law with a Hubble constant of 100 km/s/Mpc. We then constructed a histogram (with 50 kpc bins) of these physical separations (Figure 1a). If a cluster had no binaries among the three brightest galaxies, we used three separations. If there were one or two binaries among the three galaxies, we treated their data as giving the separations of the four or of the five brightest galaxies; therefore, we used six or ten separations, respectively. This procedure assumes that the two components of the binary are nearly equally bright [as was found for many of them by Rood and Leir (1979)]. However, our results do not depend crucially on the details of this procedure.

A similar separation analysis was performed by Hickson (1977a) on the 40–60 brightest galaxies in each of 64 nearby clusters. He discovered a nearly universal curve that fit the data (his Figure 6). He later expanded his analysis to 95 clusters (Hickson 1977b). We find that the Struble–Rood data on separations is fit well by the same shape curve (this paper Figure 1a), with two important differences. First, we find that the peak in the curve for the three brightest galaxies is at 300 kpc, whereas Hickson's curve for the fifty brightest galaxies peaks at 800 kpc (adjusted to $H_0 = 100$ km/s/Mpc). Second, there is a large spike at small separations in the Struble–Rood data for the three brightest galaxies. Although Hickson treated apparent binaries as single galaxies, there were so few of them among the 50 brightest galaxies that inclusion of their separations in his Figure 6 would have produced no excess at small separations above the noise (Hickson — private communication).

The straightforward interpretation of our Figure 1a is that: (1) there is significant spatial luminosity segregation between the three brightest galaxies and the fifty brightest galaxies in clusters, and (2) there is a distinct population of bright close binaries in cluster cores. We will not pursue the possibility of luminosity segregation at the bright end of the luminosity function. We simply offer our Figure 1a as new data in that controversial subject.

What we do want to discuss is the excess of close separations. This spike is quite sharp. In Figure 1b we re-bin the Figure 1a data in 10 kpc bins for projected separations less than 100 kpc. Struble and Rood find the average binary separation for the complete sample to be 17 kpc. The deficiency in Struble and Rood's counts inside 10 kpc, seen in Figure 1b, is caused by the overexposure and poor resolution of the POSS. We have attempted to correct for this by using Hoessel's (1980) observations with a SIT on the 1.5m Palomar telescope, of brightest members of Abell clusters. Having better resolution, he lists the subset of these galaxies which are multiple on scales less than 10 kpc (with $H_0 = 100$ km/s/Mpc); see his Table 6. Among the D.C. = 3 clusters he observed, he found 25% multiple inside 10 kpc. Applying this statistic to our subset of Struble and Rood's clusters, we obtain the dotted line in Figure 1b for the probable number of multiple nuclei inside 10 kpc. It is clear from Hoessel's observations that the percentages of multiple-nuclei brightest cluster members given by Leir and Rood (1979) and Struble and Rood (1982) are lower bounds only (cf. also Schneider, Gunn, and Hoessel 1983).

The bimodal distribution of Figure 1 seems to establish the fact that a separate population of multiple-nuclei galaxies inhabit cluster cores. Leir and Rood (1979) have calculated the chance probability of forming such a supergiant dumbbell galaxy in a cluster by superposition, for the case of the Bautz-Morgan Type I and I/II clusters. As mentioned above, for these clusters the two components of the multiple-nuclei galaxy are each among the five brightest galaxies in the cluster. Because the average separation of the bright galaxies is $\sim$20 times the average separation of the binaries (Figure 1), and because there are so few (< 5) bright galaxies, the probability of chance superposition is less than 1%. In any case, if chance superpositions of bright galaxies were producing Struble and Rood's binaries, one would expect a smooth (quadratic) rise from zero separation in Figure 1a, not a bimodal distribution (a point emphasized to us by J. S. Gallagher). This definitely is not seen. Thus, Morgan's belief that the dumbbells are a separate population of galaxies seems to be borne out.

2.2. *Velocity Differences of Cluster Core Binaries*

Having established the spatial peculiarity of the cluster core binaries, we turn to a consideration of their velocity properties. We have searched the astronomical literature for velocity measurements on the individual components of the Struble and Rood binaries. Table 1 lists the 15 pairs with D.C. ≤ 5 and measured radial velocities which we found. Since at least 95 of the D.C. ≤ 5 clusters have bright binaries (Struble and Rood 1982), observers should be able to quadruple our list in the near future. Our list itself significantly enlarges Jenner's (1974) earlier sample (see Table 1). Although these 15 out of 95 have been chosen in a highly unsystematic way by observers, we see no way in which the observers could have a priori biased the sample toward a particular velocity difference. We plot the radial velocity differences (ΔV) versus the projected spatial separation ($r_\perp$) for the 15 pairs in Figure 2. The median ΔV of our sample is $\sim$800 km/s and the median $r_\perp \sim 11$ kpc, i.e., the separations are similar to Struble and Rood's more complete sample of cluster core binaries.

That the average ΔV is very high can be seen by comparing our cluster core binary sample with a morphologically similar elliptical galaxy binary sample taken from the field. For a comparison sample, we have used the isolated binary catalogs of Karachentsev (1974), Turner (1976), and Peterson (1979). To obtain a uniformly observed sample, we chose those pairs, identified as elliptical pairs in the three catalogs, which had been reobserved by Tifft (1981) in his comprehensive binary redshift survey. This isolated field binary sample has a median $\Delta V \sim 150$ km/s and a median $r_\perp \sim 11$ kpc (the median ΔV for the three catalogs is 125 km/s; Faber and Gallagher 1979). Therefore, both the cluster core and isolated field binary samples have the same median $r_\perp$, but the median ΔV of the cluster core sample is $\sim$5 times as large as that of the isolated field binary samples. The ΔV of the field binaries is just what one would expect for an orbital velocity if the only matter interior to the orbit was the bright stellar matter. This stellar matter leads to a mean velocity dispersion inside elliptical galaxies of $\sigma_0 \sim 200$–300 km/s (Tonry and Davis 1981). Evidently, there is a great deal of additional dark matter inside the orbits of the cluster core binaries.

To estimate the mass, we apply Peterson's (1979) methods to our cluster core sample using Struble and Rood's (1982) determination of the distribution of close binaries in the cluster core: $N(r_\perp) \sim r_\perp^{-2.3}$ (compared to $r_\perp^{-0.5}$ for isolated binaries). Lines of constant $M_T \sim r_\perp (\Delta V)^2$ are shown for in Figure 2 for our 15 samples. Peterson's analysis indicates that the most probable actual spatial separation of the cluster core binaries is $1.25\, r_\perp$. The average total mass inside the orbit is $M_T \simeq 2 \times 10^{12} M_\odot$, using the median values of ΔV and $r_\perp$. (We find Peterson's $\langle F_p \rangle = 0.35$.) This mass is 10 times Peterson's value for isolated field binaries at the same separation. This implies a mass-to-light (B band) ratio of $\sim$300 in the central cusp (< 20 kpc) of the db-dominated rich clusters, similar to that for the cluster as a whole (Faber and Gallagher 1979). This implies that the dark matter which binds the cluster on large scales (Zwicky 1933) can continue to dominate gravitationally down to very small scales.

Finally, we note that the center of mass of a cD or db compound galaxy appears to be essentially at rest in the cluster core, even though the components of the compound galaxy are moving rapidly. Guthrie (1978) found that for six cD clusters, the mean radial velocity difference between the cD galaxy and its cluster is $\sim$200 km/s. Quintana and Laurie (1982) reach a similar conclusion for both cD clusters and db-dominated clusters. They find some evidence for the same phenomenon in D-dominated clusters, but the evidence is less conclusive there.

2.3. *Continuity of Cluster Potential*

The previous two subsections use the available observational evidence to argue that there is a significant excess of bright, high relative-velocity close binary galaxies in cluster cores. Two types of explanation have been offered for this excess. In the first (see, e.g., Hintzen 1979), it is argued that the two galaxies are just passing each other on their way across the cluster and that is why their velocity difference is typical of a cluster velocity dispersion. However, this picture is incompatible with the dramatic bimodal distribution of separations seen in Figure 1. The second view is that these binaries are "supermassive" galaxies (e.g., Minkowski 1961, Chincarini et al. 1971, Wolf and Bahcall 1972, Jenner 1974, and Schneider et al. 1982). Evidently, these galaxies have massive dark matter halos attached to them which other elliptical binaries do not.

We propose a third explanation. Since we know dark matter is needed to bind clusters on scales of 100–1000 kpc (e.g., Faber and Gallagher 1979), we argue that the core radius of that dark matter can become even smaller in some clusters. Our view is that the high ΔV dumbbells and cD's are in the extreme clusters, in which the core radius of the dark matter is as small as 10–20 kpc, one-tenth the traditional value. If our view is correct, we expect tracers of the underlying cluster potential to show a continuity from large scales to small scales in these extreme clusters.

A direct measure of the cluster potential is given by the dynamics of particles moving in that potential. The velocity dispersion of galaxies in the cluster is normally used to probe this dark matter potential on scales between 100 kpc and 1 Mpc. Typical one-dimensional velocity dispersions σ in Abell clusters range (Struble and Rood 1982) from 250 km/s to 1500 km/s with a median value of 700 km/s. This has been interpreted as showing that the density of dark matter on cluster scales is roughly ten times the matter density associated with individual galaxies (Faber and Gallagher 1979).

We extend this method by using the local relative velocity of compound galaxies ΔV to probe the potential ϕ on scales $\lesssim$100 kpc where there are too few bright galaxies to use a statistical measure like σ easily. The circular Kepler velocity,

$$V_C = \left(\frac{\partial \phi}{\partial \ln r}\right)^{1/2} \tag{1}$$

measures the local slope of the cluster potential. The exact relation between ΔV and V_C depends on the eccentricity of the orbits of the nuclei and on projection effects. For those Abell clusters in our sample whose velocity dispersion has been measured (Struble and Rood 1982), we can then replot (Figure 3) the differential velocity data from Figure 1 to compare ΔV (at $\sim$10 kpc) with σ (at $\sim$500 kpc).

First, we note that the median value of σ is roughly the same as the median value of ΔV in our sample, $\sim$750 km/s. Second, all of our high ($\Delta V > 700$ km/s) velocity compound galaxies are in clusters with velocity dispersion higher than 700 km/s. Three of the four low ΔV cases are in low-σ clusters. Figure 3 thus seems to indicate that in clusters whose dominant galaxy has multiple nuclei, the characteristic velocity (σ or ΔV) is roughly constant, or equivalently the potential is scale-free, on lengths from 10 kpc to 1 Mpc. This complements a similar conclusion, based on weighing virialized clusters in the Center for Astrophysics redshift survey, by Press and Davis (1981). However, it is also clear that this cannot be true for radii much smaller than $\sim$10 kpc because the central velocity dispersions of cD galaxies (measured in their inner $\sim$2 kpc) are typically only $\sim$300–400 km/s (Malamuth and Kirshner 1981). Therefore, on some smaller scale the central bright matter of the cD or db must gravitationally dominate the dark matter.

The velocities in our model are scaled to σ_∞, the radial velocity dispersion at large distances of the dark matter (i.e., in the cluster); the distances are measured in terms of the core radius r_c of the central galaxy, i.e., the radius at which the surface brightness has fallen to half its central value. Thus, the dimensionless radius variable is $\mu = r/r_c$. There are two dimensionless parameters in our model: $\alpha = a/r_c$, where a is the core radius for the logarithmic potential of the dark matter alone. We expect that $10 \lesssim \alpha \lesssim 100$. The other dimensionless parameter is $\Sigma = \sigma_\infty/\sigma_0$, where σ_0 would be the local central velocity dispersion of the central galaxy if the galaxy were in isolation. A large survey of elliptical galaxies (Tonry and Davis 1981) finds $100 \lesssim \sigma_0 \lesssim 400$ km/s. Combining this with Struble and Rood's (1982) compilation of cluster velocity dispersions, we obtain $1 \lesssim \Sigma \lesssim 10$. Thus, both of our dimensionless parameters have roughly the same range—a factor of ten.

The gravitational potential associated with the density law (Equation 2) is:

$$\phi = \sigma_\infty^2 \left[\underbrace{\ln\left(1+\frac{\mu^2}{a^2}\right)}_{\text{dark matter}} + \underbrace{\frac{9}{\Sigma^2}\left(1-\frac{\operatorname{arcsinh}(\mu)}{\mu}\right)}_{\text{bright matter}} \right] \tag{2}$$

where ϕ is normalized to zero at $\mu = r = 0$. The first term leads to a scale-free logarithmic potential for large distances ($\mu \gg a$ or equivalently $r \gg a$). In the intermediate distance range, $1 \leq \mu \leq \alpha$, the gravitational potential derives from a combination of bright and dark matter. At small distances ($\mu \ll 1$), the potential flattens to zero with its source becoming the self-gravitation of the stars in the galactic nucleus. In Figure 4, we present a model with $\alpha = 33.3$, $\Sigma = 4.8$.

This picture of the cluster potential maintaining its properties over several decades in scale and then smoothly joining on to an elliptical galaxy core also seems most natural for two other observational tracers: the cD envelope and the cluster X-ray emission. We return to a discussion of these tracers in Section 4.

3. THE GRAVITATIONAL POTENTIAL

The preceding section on observations leads us to model a cluster of galaxies as a self-gravitating ball of dark matter, whose gravitational potential has a constant logarithmic slope (characteristic velocity) from 1 Mpc down to some core radius, which can range from 10 kpc to 200 kpc. This suggests that we model a cluster as having a two-parameter (characteristic velocity and core radius) logarithmic potential. This would reproduce the classic dark matter results for large core radius and offer an explanation of cD and dumbbell clusters for small core radius.

3.1. *The Scale-Free Model*

The simplest model which can accommodate these facts is obtained by adding together two spherically symmetric density distributions: the first representing the dark matter at large distances (chosen to give a scale-free logarithmic potential) and the second representing the bright matter in the central galaxy at small distances (chosen to give an approximate King law):

$$\rho = \left(\frac{\sigma_\infty^2}{2\pi G r_c^2}\right)\left[\underbrace{\frac{3\alpha^2+\mu^2}{(\alpha^2+\mu^2)^2}}_{\text{dark matter}} + \underbrace{\frac{9}{2\Sigma^2}(1+\mu^2)^{-3/2}}_{\text{bright matter}}\right] \quad (3)$$

The gravitational acceleration $g(r)$, circular orbital velocity $V_c(r)$, and velocity dispersion $\sigma(r)$ can now all be obtained by standard integration of $\rho(r)$. In addition, the "mass" interior to a given radius is obtained by:

$$m(r) = \int 4\pi r^2 \rho(r)\, dr \quad (4)$$

yielding $m(\mu) \sim \mu$ for $\mu \gg \alpha$.

3.2. *Velocity Dispersion*

The local physical value of $\sigma(r)$ is not directly observable. Rather, observers measure the line-of-sight integration of luminosity-weighted quantities. In the central part of the galaxy ($\mu \ll 1$), the volume light emissivity $j(r)$ is assumed to be the bright matter density in equation (2) divided by the mass-to-light ratio (M/L):

$$j(\mu) = \left(\frac{L}{M}\right)\rho(\mu) = \left(\frac{L}{M}\right)\left(\frac{9\sigma_0^2}{4\pi G r_c^2}\right)(1+\mu^2)^{-3/2} \quad (5a)$$

for $\mu \ll 1$.

At larger distances in cD or db clusters, the bright matter merely illuminates the dark matter potential. Therefore, we choose

$$j(\mu) \sim \mu^{-2.7} \qquad \mu \gg \alpha \quad (5b)$$

making the surface brightness $I(\mu) \sim \mu j(\mu) \sim \mu^{-1.7}$ roughly match the observations (Oemler 1976; Kormendy 1977; King 1978; Hoessel 1980). In the intermediate region ($\alpha \leq \mu \leq 1$), we matched (5a) and (5b) to give a continuous $j(\mu)$. We plot the "observed" surface brightness profile $I(r)$ and velocity dispersion $\sigma(\mu)$ for one example in Figure 4. In addition, we have convolved the result with a Gaussian "seeing disk."

The major observational constraint on our model is that the observed velocity dispersions (Malamuth and Kirshner 1981) in the central bright cores of cD's are like those of normal elliptical galaxies (Faber and Gallagher 1979; Tonry and Davis 1981): i.e., less than 400 km/s. The observed central velocity dispersion depends upon integrating along the line of sight: $\int_0^\infty j(r)\sigma(r)\, dr$.

This will only be dominated by the light from the more slowly moving stars in the core as long as σ rises sufficiently slowly with radius, which in turn requires that V_c also rises slowly. Specifically, if $j(r)$ falls more slowly than r^{-2} (as in most galaxy models), then V_c can rise no faster than $r^{1/2}$. We have constructed a large number of models in the manner just described and find that in general:

$$r_c \leq \left(\frac{\sigma_0}{V_c(r)}\right)^2 r \quad ; \quad 3r_c \leq r \leq 30 r_c \quad (6)$$

If the galaxy core radius is indeed large, then so must be the scale length of the logarithmic potential (outside of which $V_c \gtrsim \sigma_\infty$). This approximate result is not particularly sensitive to the details of the model as long as the surface brightness profile resembles that of real galaxies.

We illustrate this constraint with typical numbers. Suppose that in a two-component high-velocity cD, the larger galaxy has sunk to the bottom of the potential well formed by the dark matter and the smaller galaxy is in circular orbit about it. For the moment, regard the orbiting galaxy as a test particle. Let the orbital speed be 1000 km/s and the orbital radius be 10 kpc. If the central velocity dispersion of the larger galaxy is 300 km/s, then by relation (6) its core radius must be smaller than 900 pc. In Figure 3, we illustrate this point using parameters appropriate to a cD in a rich cluster. Note that the observed velocity dispersion increases with radius from the cluster center.

Our model can accommodate a spread in the types of observed clusters; see Table 2. For convenience, we will divide them into two main classes. The "conventional" dark matter potentials have large core radii ($a \sim 100$ kpc, $\alpha \sim 100$) and represent clusters such as Coma, in which there are no high-velocity multiple-nuclei cD's. The velocity dispersion of the central ellipticals drops off as one moves away from the center of the galaxy. The other class is the "extreme" black pits, with which this paper is mainly concerned. These have small core radii for the dark matter ($a \sim 10$ kpc, $\alpha \sim 10$), often have high-ΔV multiple-nuclei cD's, and should have rapidly rising velocity dispersions as one moves out into the cD envelope. Presumably, there is a continuum of dark matter core radii between these two classes. Furthermore, given a value of the core radius α for the dark matter, the slope of the potential can vary using the parameter Σ.

3.3. *Tidal Radius*

Merritt (1983) has recently reemphasized Gunn's (1977) point that the cluster tidal forces play a crucial role in stripping halos (made of bright or dark matter) from cluster galaxies. Merritt shows that there are two important effects caused by the tidal force: (1) galaxies passing through the region of maximum tidal force (the cluster core radius) will be tidally limited to a sufficiently small size that they cannot carry much dark matter with them; (2) a "safe harbor" exists inside the cluster core radius which will allow a large cD envelope to develop without tidal limitation. His analysis is based on a conventional dark matter potential, modeled by a King formula with a cluster core radius of 125 kpc.

We have extended his analysis to our black pit potential (Equation 2) to determine the effect of our much smaller core radii. The basic "U" shape of his Figure 1 is preserved, although our functional form is different. If we choose the same black pit core radius as Merritt uses for the King cluster radius, $a = 125$ kpc, we find that our scale-free potential produces a similar tidal limit as his King model potential, namely 15 kpc. However, as the dark matter core radius (a) decreases, the tidal radius also decreases. For an extreme black pit, such as graphed in Figure 4, the tidal radius becomes essentially equal to the galaxy's core radius of $\sim$ kpc. This would seem to predict that there should be compact galaxies with star-like images near high-ΔV dumbbells and cD's. There is some observational evidence for such galaxies in A1775 (Richter 1981). In any case, it is going to be impossible for normal-sized galaxies to populate the inner ($\sim$100 kpc) regions of clusters with a small core radius ($a \sim 20$ kpc) potential. This is presumably why the core radii of the galaxy distribution of clusters is found to be a universal number between 125-250 kpc (see, e.g., Bahcall 1975; Dressler 1981). That is, the galaxy distribution core radii will yield no information about the true core radius of the gravitational potential, because of tidal disruption in clusters with small gravitational potential core radius.

Because our $r_\perp$ also becomes large as $r \to 0$, a "safe harbor" from tidal limitation also exists in our black pit potential as it does in Merritt's potential. This allows for tight multiple nuclei to exist in the central region of a cD galaxy without being tidally destroyed. In addition, since the cD envelope is sitting in the potential well, it also is not subject to tidal limitation. We note that there are three distinct ways in which the stellar envelope of D and cD galaxies can be built in our model. First, as Merritt has emphasized, the envelope may have been formed during cluster collapse. It seems likely that the cluster-filling diffuse stellar light seen in non-cD clusters (e.g., Coma) and extreme cD clusters (e.g., A2670) originates this way (Merritt, 1983). Second, our extreme black pit potential will strip much more visible matter from galaxies passing through the cluster core than Merritt's large core radius model. Finally, as discussed in Section 4, some clusters have X-ray cooling cores, which can deliver up to $\sim 200\ M_\odot$/yr of gas to the cluster core. This is then available for making new stars.

The consequences of tidal limitation, predicted by Merritt's analysis, have been partially verified by unpublished three-dimensional computer simulations carried out by Miller (1982, private communication). He followed the stellar distribution of galaxies in various orbits through a cluster potential resembling a black pit. Galaxies passing through the region of maximum tidal force ($r \sim a$) were severely stripped and perhaps totally disrupted. However, if two galaxies were allowed to oscillate inside the pit core radius ($r \lesssim a$), they were able to pass through each other many times with essentially no particle exchange. Miller (private communication) believes there were two reasons for this surprising result. First, all the tidal stresses are compressive in this region, and second, the galaxies are moving at high speed compared to their internal stellar velocities.

In summary, the tidal properties of our potential seem to give a natural explanation for the morphology of galaxies in cluster cores. The inhabitants of the central "safe harbor" of the pit are Morgan's D, cD, and db galaxies. A single nucleus in the bottom of a pit with an accumulated envelope will look like a D galaxy. If two nuclei inhabit the pit, with one more massive (sinking quickly to the bottom of the well), then the compound galaxy will be classified morphologically as a dumbbell of type db(D,E) (Mathews, Morgan, and Schmidt 1964; Wirth, Smarr, and Gallagher 1982). If the components have similar masses, the classification will be db(E,E). In our view, the similar pit potential is what associates (MMS, p. 40) the db with the D galaxies. If a D galaxy envelope grows to the point that its size is large compared to cluster lenticulars, then it will become a cD. If a number of galaxies get tidally stripped in a small core radius black pit, then a "nest" of galaxies can be created. Examples are A2199 (Minkowski 1961) and A407 (Schneider and Gunn 1982), in which many (4 and 9, respectively) galactic nuclei are orbiting at high speed in a "luminous matrix." Our model also provides a natural explanation for White's (1978a) conclusion that D and cD galaxies are found in local density concentrations in all B-M cluster types. These galaxy concentrations illuminate the deepest part of the underlying dark matter potential.

3.4. *Dynamical Friction*

The existence of multiple nuclei has often been cited in support of the picture of galactic cannibalism (Ostriker 1978; Hausman and Ostriker 1979). Here one assumes the gravitational potential is generated only by the stars in the cD galaxy, thus leading to low velocities (∼200 km/s) for galaxies near the cD nucleus. One difficulty, first noted in a different context by Toomre and Toomre (1972), is that the dynamical estimate of the time for two galaxies to merge is roughly a factor of five smaller than the observational estimate. This discrepancy is particularly pronounced for the 23% Bautz-Morgan Type I and I/II clusters which have multiple cores containing two of the brightest galaxies in the cluster (Rood and Leir 1979). In these cases, the typical cD core will have made no more than two captures, and so the merger time ought to exceed one-fifth the cluster age, ∼2 Gyr (Rood and Leir 1979). However, the conventional estimate for the merger time is ∼0.4 Gyr (Tremaine 1981). Our model alleviates this difficulty because the components are stripped galaxy cores orbiting as test particles at comparatively high speeds in the "black pit" background potential.

Thus, a major difference in the prediction of the galactic cannibalism model versus the black pit model occurs in the structure of a cD. A cD galaxy is composed of a number of previously independent galaxies in the cannibalism picture. Because of the longer infall time scales in the black pit model, the observed multiple nucleus may be the first such pair formed. Furthermore, much of the cD was formed in the black pit model either by tidal stripping of the outer envelope of passing ellipticals or by gas flowing into the black pit potential and creating stars there. This fundamental difference will lead to widely differing observational predictions for: (1) color gradients in the cD galaxy and envelope; (2) the magnitude differences between the brightest cluster members; (3) the issue of homologous merging; (4) the true core radii of cD's; and (5) the surface brightness of cD's. Schweizer (1981) has recently argued that galactic cannibalism seems to be in conflict with observations and numerical simulations on several of these issues. Valentijn (1982) claims that the color gradients in cD's are compatible with continued star formation in an X-ray cooling core, but not with accretion of stars from other galaxy cores. Future work will be needed to refine the predictions of the black pit model, if it withstands more direct observational tests.

An alternative viewpoint to that presented here (Gallagher and Ostriker 1972; Richstone 1975, 1976; Dressler 1979; Schneider and Gunn 1982; Richstone and Malamuth 1983) is that the dark matter cluster potential was not preexisting. Instead, it evolved from dark matter stripped from the outer parts of individual galaxies in the cluster after the galaxies were formed. As the galaxies interacted, their dark halos were removed by tidal forces, thus enhancing the background density and the efficacy of dynamical friction. A detailed model of this process to explain the 9-nuclei galaxy V Zw 311 in A407 has recently been worked out (Schneider and Gunn 1982).

There seem to be two problems with this idea in the present context.

Firstly, the mass in a self-gravitating isothermal sphere of velocity dispersion σ and with density greater than some given value ρ is proportional to $\sigma^3\rho^{-1/2}$. Now the velocity dispersion in the pit is presumably similar to the initial orbital velocity dispersion and is typically four times the velocity dispersion of a normal bright galaxy. Furthermore, the galaxy will presumably be stripped down to a density comparable with the surrounding density. As the density of the tidally stripped material cannot be increased (in the absence of dissipation), the pit would have to be constructed from at least $4^3 = 64$ galaxies whose nuclei would have sunk to the center. We do not observe this many galaxy cores within a cD galaxy.

Secondly, the overall mass-to-light ratio of a typical cluster is over 300 in solar units. If most of the cluster potential is formed out of dark matter stripped from galaxies, then if these galaxies are anything like our own, they would have had to have initial radii > 200 kpc, far larger than we have evidence for in nearby galaxies, and far too large to have survived in the original galaxy cluster (cf. Merritt 1983). Nonetheless, for a multiple system like V Zw 311 (A407) or NGC 6166 (A2199) (Minkowski 1961) to be stable, there must be a high density of background matter. If, as we argue, it cannot come from the galaxies, then it must predate the galaxies (cf. also White and Rees 1978).

4. OBSERVATIONAL IMPLICATIONS

4.1. *Optical*

As stated above, in our model the cD galaxies are signatures of an underlying small core radius black pit potential. The cD stellar envelope is more a property of the cluster potential than of the central galaxy, which happens to be at the center of the potential well.

The direct observational evidence for small core radius dark matter pits is not yet totally compelling because of the small sample of objects used in constructing Figure 1a. Clearly, the first priority is to measure ΔV and $r_\perp$ for a complete sample of compound galaxies. Comparing these quantities with the sizes and central velocity

dispersions of the associated rich clusters should lead to a more realistic model potential well and a better understanding of the constraints imposed by it. However, we feel that the data of Figures 1 and 2, together with the circumstantial evidence outlined above, make a sufficiently strong case for the existence of black pits that it is worth exploring further optical, X-ray, and radio observational implications of this idea.

We can hope to learn much more about the dynamical properties of nearby cD galaxies by carrying out detailed photometry and spectrophotometry of the envelope. The rate of falloff of the light in the envelope should be correlated with the falloff of other observational tracers, in particular the X-ray luminosity and, at larger radii, the galaxy falloff.

The core radii of cD galaxies are usually stated to lie in the range of 1–5 kpc, larger than the corresponding core radii of normal elliptical galaxies (Oemler 1976; Hoessel 1980). However, Schweizer (1979, 1981) has recently argued that when the effects of seeing are properly taken into account, the true cD core radii are frequently much smaller, as our model requires for extreme black pits [see Section 3.2]. Here, the space telescope may be able to make an important contribution, because it will not be limited by atmospheric seeing.

Further studies of the velocity dispersion of the envelope as a function of radius (Carter 1979; Dressler 1981) should provide a probe of the potential well that is less sensitive to projection effects than the compound galaxy velocity difference data. (In fact, if the potential is spherically symmetric, then sufficiently accurate measurements of $\sigma(r)$ and the surface brightness $I(r)$ can be inverted to solve for the potential directly.) Dressler's (1981) study of A2029 shows that the velocity dispersion in that cD increases with radius, although more slowly than in our extreme models constructed to accommodate the high ΔV multiple nuclei clusters (cf. also Faber, Burstein, and Dressler 1977).

We emphasize that the total amount of gas in a "black pit" potential may vary widely. Black pits with little original gas and therefore few galaxies should exist. Indeed, we believe this to be the case in the Yerkes (Morgan et al. 1975; Albert et al. 1977; White 1978a) poor clusters which contain cD's. As Bahcall (1980) has shown, the MKW clusters form a smooth continuation of the Abell clusters. Their smaller richness, galaxy surface density, and total X-ray luminosity are all consistent with smaller total amounts of gas in a pre-existing black pit potential.

4.2. *X-ray*

The hot intergalactic gas will settle in the gravitational potential of the dark matter, with its density and temperature determined by hydrostatic equilibrium. If X-ray cooling is negligible, then the X-ray luminosity profile will reflect the shape of the potential far more reliably than the light distribution of the galaxies. In the conventional picture, the dark matter which binds the X-ray gas follows a King model with the core radius similar to that of the bright galaxies in the cluster (Bahcall 1975; Dressler 1981), about 125–250 kpc. In this picture, all clusters without cooling cores would have flat-bottomed, large core radius X-ray distributions like Coma or A2256 (Jones and Forman 1983).

However, the Einstein X-ray Observatory has revealed (Forman and Jones 1982; Jones and Forman 1983) that many cluster X-ray sources have small core radii (<150 kpc), with the X-ray brightness peak centered on a stationary, optically bright galaxy. These so-called X-ray dominant (XD) clusters are most simply explained, in our view, as being clusters having a small core radius black pit potential. In fact, if one solves for the X-ray surface brightness of an isothermal gas in our logarithmic pit potential (Equation 2), one obtains exactly the formula (1) which Jones and Forman (1983) use to fit the X-ray observations. Their "a" is our "a" and the σ^2 in their β is our σ_∞^2 in Equation (2).

Reducing the core radius a of the black pit potential raises the central density of the gas sitting in it. Quantitative models show that for many smaller core radius pits, this density exceeds the critical density (e.g., Fabian and Nulsen 1977) at which X-ray bremsstrahlung cooling becomes important on a timescale short compared to the Hubble time. Thus, we expect many of our small core radius pits to possess cooling cores, which seems to be the case for many of the XD clusters (Jones and Forman 1983).

The continuous distribution of X-ray cluster core (Figure 4 of Jones and Forman 1983) between tens and hundreds of kpc seems to validate our model, which allows the core radius of the cluster potential to vary over a great range. It is in great contrast to the almost universal fixed core radius of ∼125–250 kpc observed in the galaxy distribution in clusters. As we have argued in Section 3.3, this result is self-consistent in our model, because Merritt's (1983) tidal radius analysis, applied to the pit potential, predicts galaxies are tidally destroyed in the central regions ($\lesssim$ 100 kpc) of small core radii potentials. The X-ray gas is obviously not subject to this tidal constraint; it therefore can more faithfully illuminate the shape of the potential.

However, establishing the absolute value of a particular cluster core radius, based on Einstein observations,

may not be possible. First, the angular resolution of the IPC is not sufficient to determine how "spiked" the central X-ray brightness distribution is. A good example of this is shown in Figures 9 and 10 of Forman and Jones (1982) for the cluster A85, where both high-resolution (HRI) and low-resolution (IPC) X-ray observations were made of the same cluster. Second, the fits used by Jones and Forman (1983) assume hydrostatic equilibrium. However, many of the small core radii XD clusters have X-ray excesses (Jones and Forman 1983), which indicates X-ray cooling. Since in a cooling core the number density n increases while the temperature T decreases, it is not clear how the X-ray brightness profile $\sim n^2 T^{1/2}$ will be affected. Detailed calculations are needed to provide a proper theoretical fit to the X-ray data.

The second parameter of our model, the slope of the potential (σ_∞), is proportional to the velocity dispersion of the galaxies and to the X-ray temperature of the isothermal gas sitting in the potential. Again, the X-ray data requires just this parameter to describe the "dynamical evolution" of the cluster (Forman and Jones 1982, Jones and Forman 1983). In our shallow dark matter potentials (low σ_∞), the relative importance of the local self-gravity of galaxies is enhanced over the dark matter's gravity, leading to a "clumpy" or "unevolved" appearance in the X-ray emission. In steep potentials (high σ_∞), the dark matter totally dominates everywhere, leading to a smooth "evolved" appearance of the emission.

Therefore, we conclude that our simple two-parameter model (equation 2) for the gravitational potential of clusters of galaxies explains the existence of the observed two-parameter morphology of X-ray emission from clusters. In fact, our Table 2 summarizing the predictions of our theoretical model is essentially identical to Table 3 (Forman and Jones 1982), which summarizes the observed properties of X-ray clusters.

However, we emphasize that our theoretical interpretation of the observed two-parameter morphology is, in a sense, opposite to that of Jones and Forman (1983) and others (e.g., Valentijn 1982). They argue that the XD class of X-ray clusters have "central dominant galaxies" which cause the XD phenomenon. We argue, on the other hand, that a continuous cluster potential, whose source is the dark matter, dominates not only the large-scale cluster but also the central region as well.

Indeed, we believe the evidence collected by Jones and Forman (1983) strongly supports our view. They find that ∼80% of their X-ray cluster sample is XD. However, only a small fraction of their sample clusters, ∼35%, have optically dominant (Bautz-Morgan type I or I/II) galaxies at the center of the X-ray distribution. In the XD clusters in which there is no optically dominant galaxy (e.g., Virgo), nonetheless one of several optically equivalent galaxies sits at the center of the cluster X-ray distribution. It seems to be the simplest interpretation to accept the observations at face value: the central galaxy is a normal galaxy which happens to be sitting in the center of the cluster potential well. Thus, in our view the XD clusters are not "dominated" by a central galaxy, but are simply those clusters with a small core radius for the dark matter.

A natural explanation for this difference in optical and X-ray properties of clusters is to assume that the halo of the central galaxy in the pit is built up by accreting the X-ray emitting gas in a cooling core (e.g., Silk 1976). The cD clusters (BMI) will be ones in which the process has gone to completion, creating an extended envelope of stars by continuing star formation (Valentijn 1983). Therefore, we expect all cD clusters to be XD, as has been observed (C. Jones, private communication). The XD clusters without a clearly optically dominant galaxy, such as Virgo, are still in the process of slowly building up the central galaxy by accretion. An intermediate stage of this process is Perseus (see e.g., Fabian et al. 1981; Wirth et al. 1982). Thus, in our view, the Bautz-Morgan classification measures how much gas has been accreted into the central pit, rather than directly measuring the geometry of the underlying gravitational potential. This concurs with Struble and Rood's (1982) observation, discussed in Section 2.3, that the existence of tight binaries, another indicator of a small core radius potential, can occur in all Bautz-Morgan types.

In Bautz-Morgan III clusters, there is no optically dominant galaxy and the determination of the dynamical center of the cluster can be rather uncertain. As an example, we take the very well-studied Hercules cluster A2151. In optical, the center of A2151 is often considered to be NGC 6047, a supergiant elliptical (E0 by Humason et al. 1956) about the same size as NGC 4869 in Coma. In radio, Jaffe and Perola (1974) also single out NGC 6047 as the central radio source, 4C17.66, in A2151. However, neither the relative optical brightness of galaxies nor the presence of a radio source is a direct tracer of the center of the underlying gravitational potential. In our black pit theory we have two direct tracers: high ΔV compound galaxies and a peaked X-ray emission. In the central region of A2151 is NGC 6041(a,b), a bright dumbbell galaxy in a common optical envelope. The velocity difference between the two components is high, 800 km/s (Tarenghi et al. 1979). As seen in Figure 3, this is close to the velocity dispersion of the cluster as a whole, 887 km/s (Tarenghi

et al. 1979). Therefore, our model predicts that a small core radius pit is centered on these galaxies. If this pair is not a superposition, then we expect the X-ray emission to peak up around this dumbbell system. If Einstein HRI observations show this to be true, then we will have identified the dynamical center of the Hercules cluster.

We briefly discuss the implications of our model for M87 (Sumi and Smarr, 1986) since it is so well studied that it may be a good test of our model. Jones and Forman (1983) use M87 as the prototype of an "unevolved cluster" with an X-ray dominant galaxy. In our model (Table 1), this means a moderate σ_∞ ($\sigma_{\rm Virgo} = 700$ km/s) and a small core radius black pit. It is well established that M87 has a cooling core X-ray halo (see e.g., Canizares et al. 1982a). This fact has been used to argue that M87 is a supermassive galaxy (Fabricant et al. 1982) or a pressure-confined cooling core with a normal-sized elliptical galaxy in the center (Binney and Cowie 1981). Our model unites these two pictures by separating the gravitational potential of the dark matter [$M(r) \propto r$, equation (4), which yields the huge "mass" of M87] from the normal-sized elliptical galaxy at the bottom of the pit. We predict that the X-ray spectral lines will produce a temperature-vs-radius plot best fit by a cooling flow in a scale-free potential similar to equation (2). A final test will be to compare the predictions of that potential with observations of: (1) the stellar (or globular cluster system) velocity dispersion out to large radius, (2) the X-ray surface brightness profile, and (3) the optical surface brightness profile.

Finally, the pre-existing pits may be optically underilluminated. However, the dark matter potential would still be able to confine the X-ray gas. These black pits would produce the XD morphology seen in poor clusters (Kriss et al. 1980; Kriss et al. 1983) or small groups (Schwartz et al. 1980). Furthermore, we would expect some of these poor clusters to have X-ray cooling cores (Canizares et al. 1982b) caused by the central concentration of dark matter.

4.3. *Radio*

The black pit model provides a new explanation (compare with Burns, Eilek, and Owen 1982) for the existence of wide-angle-tail (WAT) radio sources (Owen and Rudnick 1976), which emanate exclusively from dominant cluster galaxies. Examples include: A2634/3C465 (Burns, Eilek and Owen 1982; van Breugel 1980), A2220/4C53.37 (Burns and Owen 1980), A400/3C75 (Owen, private communication; Cornwall et al. 1982), and a non-Abell rich cluster/4C47.51 (Burns 1981). These WATs often have strong inner hot spots at small distances (5–50 kpc) from the central nucleus of the radio galaxy. It is outside of these hot spots that the wavy, broad, plume-like behavior of a WAT is seen. The abrupt changes in direction or width often observed immediately after the hot spots (e.g., 3C465, 1602+240, 4C47.51, 4C53.37, 3C75, etc.) are explained naturally if we interpret the inner hot spots as strong shocks that slow the jet from supersonic to transonic velocity. Such a shock can also give the jet an abrupt turn of direction if the shock is oblique (Norman, Smarr, and Winkler 1985).

In this interpretation, the WATs are the same phenomenon as the "close doubles" (Rudnick and Owen 1977), which are the other class of extended radio sources associated with dominant cluster galaxies. The close doubles are two hot spots separated by the same distance (5–50 kpc) as the inner hot spots of WATs. As extreme examples, A1795 (van Breugel et al. 1984) has only 1 kpc from nucleus to major hot spots, M87 has 2 kpc, A426 (Perseus) has 6 kpc (Pedlar et al. 1983), and A2199 (3C338) has 7 kpc (Burns et al. 1983). In fact, because of the low surface brightness of tails in WATs, a low dynamic range map of a WAT could appear to be a "close double."

Even though WATs have close hot spots, one must remember that most (75–90%) of cD radio sources are unresolved (Valentijn and Bijleveld 1983), even on these small scales (<25 kpc). Therefore, they are even more extreme than the well-known WATs. Thus, we believe the crucial morphological characteristic of radio sources in the centers of clusters is the very small length scale of their jets.

In our model, the small length scale of the jet is caused, directly or indirectly, by the small length scale of the gravitational potential in the extreme black pits that dominant cluster galaxies inhabit. This could be caused by (1) the high escape velocity from the bottom of the pit, (2) the change in slope of the potential (and therefore in the pressure gradient) at the core radius of the pit, (3) the temperature inversion in the X-ray cooling cluster centers (Sumi and Smarr 1986, Sumi 1986), or (4) the cold, dense gas at the bottom of the cooling cores through which the jet must bore through. Detailed hydrodynamical calculations are planned (Norman, Smarr, and Winkler, private communication) to determine the effect these environmental factors have on jet propagation.

We note that our view that the Yerkes poor cD clusters are also small core radius black pits would imply that one might also expect WATs in some of them. Indeed, the poor cluster AWM4 has such a WAT with very close (5 kpc) inner hot spots (Burns et al. 1981). Our model

may even explain Fomalont and Bridle's (1978) WAT (0915+320), which they found emanating from the dominant elliptical galaxy of a bright group. Such groups can be confined by an unseen potential well.

Finally, our model may bear on the observation (Stocke 1977; Wirth, Smarr, and Gallagher 1982) that in db(D,E) compound radio galaxies, it is almost always the D galaxy that is the radio source. In our model, the D galaxy is the one at the bottom of the pit and would receive most of the accreting gas to fuel the radio emission (cf. on fueling Valentijn and Bijleveld 1983).

4.4. *Combined Observations*

We emphasize that observations in different wavelength bands (e.g., X-ray, optical, and radio) should reveal correlations. Our model allows quantification of the conclusions of Burns, White, and Hough (1981) that it is the same underlying gravitational potential which produces the cD galaxy, the X-ray emission, and activates and replenishes the cD radio source. In this regard, the correlations in the trivariate luminosity function for cD galaxies recently found by Valentijn and Bijleveld (1983) are very suggestive. We hope that our model will stimulate further careful observational work on this crucial question.

To aid in this observational effort, we have assembled a list (Table 3) of 70 nearby (with redshift $z < 0.08$) Abell clusters which we believe are the most likely to be small core radius black pits. We use the tracers of extreme pits which we have described before: namely, clusters whose brightest member is a cD, db, or tight multiple nuclei galaxy, and clusters which are X-ray dominant. The cD's are chosen from Valentijn and Bijleveld (1983), the multiple nuclei galaxies from an optically selected list compiled by Smarr, and the XD clusters from Jones and Forman (1983). This list is not complete, but it contains enough candidates to make statistical tests on our hypothesis.

5. CLUSTER FORMATION

We do not know the nature of the dark matter forming the potential well. We suppose that it is the same as the dark matter long known to be present in rich clusters. It can be shown that if our model potential well is formed by a stationary distribution of non-interacting particles of mass m, then this distribution must be the sum of two Boltzmann distributions of temperature $m\sigma_\infty^2$ and $\frac{m\sigma_\infty^2}{2}$. In particular, if these particles are identified with one species of neutrino and anti-neutrino ($g = 1$) or a single gravitino ($g = 0.5$), the quantum mechanical limit on their phase space density requires that (Tremaine and Gunn 1979; Bond et al. 1980; Wasserman 1981):

$$m > 24\, g^{-1/4} \left(\frac{a}{10\,\mathrm{kpc}}\right)^{-0.5} \left(\frac{\sigma_\infty}{1000\,\mathrm{km/s}}\right)^{-0.25} \mathrm{eV} \tag{7}$$

These particles contribute a fraction

$$\Omega \gtrsim\ 0.24 \left(\frac{a}{10\,\mathrm{kpc}}\right)^{-0.5} \left(\frac{\sigma_\infty}{1000\,\mathrm{km/s}}\right)^{-0.25} g^{0.75} \tag{8}$$

of the critical density to the mean density of the universe. It is perhaps of interest that if the pit extends out to a radius $r_{\max}$ then its total mass is:

$$m \approx 5 \times 10^{14}\, M \left(\frac{r_{\max}}{1\,\mathrm{Mpc}}\right) \left(\frac{\sigma_\infty}{1000\,\mathrm{km/s}}\right)^2 \mathrm{M}_\odot \tag{9}$$

which is comparable ($\sim$1/10) with the maximum Jeans' mass (e.g., Bisnovatyi-Kogan and Novikov 1979; Doroshkevich et al. 1979; Bond, Efstathiou, and Silk 1980) in neutrinos for the required particle mass of $m = 30$ eV.

We emphasize that our observational data seem to indicate that the dark matter is centrally concentrated in clusters. That is, our isolated db sample from the field shows no evidence for the density of dark matter to dominate bright matter on small scales outside of clusters. This seems consistent with the picture that the dark matter has fragmented into a highly inhomogeneous distribution with the highest density concentrations corresponding to our extreme black pits. Results of two-dimensional simulations of massive neutrino fragmentation (Doroshkevich et al. 1980; Melott 1982) indicate that a "draining" of dark matter into "knots" on supercluster scales occurs naturally. Full three-dimensional dynamical calculations of this fragmentation process show the same effect (Centrella and Melott 1983; cf. also Clypin and Shandarin 1981; Frenk et al. 1982). Indeed, from a mathematical analysis, Arnold et al. (1982) show that a collisionless system (e.g., massive neutrinos) moving in a three-dimensional conservative potential (gravity) must produce a number of cusps (catastrophes). This may be the underlying physical mechanism which creates the high-density black pits out of the cosmic dark matter.

Also seen in these computer simulations are the formation of "filaments" and "sheets." It is likely that these highly non-spherical concentrations of dark matter are unstable to further fragmentation. In that case, one may expect a series of density maxima, or "black pits," strung along the supercluster. Such a phenomenon may be occurring in the Hercules supercluster (Abell 1961; Burns

and Owen 1979; Chincarini et al. 1981), which includes Abell clusters (2052, 2063, 2147, 2151, 2152, 2162, 2197, and 2199) stretching across 35° of the celestial sphere. Of these clusters, five have cD galaxies (2052, 2063, 2147, 2162, 2199), with compact radio sources (Jaffe and Perola 1974; Jaffe and Perola 1975; Heckman 1981; Fanti et al. 1982; Burns et al. 1982) and X-ray distributions centered on most of them. As described in the previous section, this indicates that these five clusters have small core radius dark matter concentrations in their central regions. Evidence was also presented in Section 4.3 for a similar conclusion for A2151. High-resolution 3-D numerical simulations will be needed to see if such large-scale (∼40–100 Mpc) superclusters can fragment and whether the fragments can contract until their core radii are one thousand times smaller (∼10–50 kpc), corresponding to the formation of cluster black pits. In addition, detailed redshift surveys and large-scale integration of X-ray maps are needed to determine the observational substructures of these superclusters.

Some evidence that this scenario can happen is suggested by the observations that both cD galaxies and their rich clusters are usually elliptical in shape and are often co-aligned (Matthews et al. 1964; Sastry 1968; Dressler 1979; Carter and Metcalfe 1980; Dressler 1981; Binggeli 1982). This fact, in our view, simply reflects their common asymmetric potential well, rather than the conventional view that the cD envelope was deposited asymmetrically by cannibalizing cluster galaxies. Indeed, if the dark matter is collisionless (massive neutrinos, gravitinos, photinos, etc.), then this ellipticity of the cD and its cluster derives from the initial "pancake" anisotropy of the perturbation from which they were formed (see, e.g., Doroshkevich et al. 1981). Thus, the Rood-Sastry (1971) (RS) morphological classification scheme for Abell clusters may be categorizing the shape of the black pit potential. In particular, the F ("flat") type and the L ("line") type may be the "pancake" (extreme oblate) and "sausage" (extreme prolate) collapse forms favored in the collapse of collisionless matter.

There may even be several effectively invisible potential wells in the universe, whose presence can best be detected by lensing action on more distant quasars. This may be relevant in interpreting the second (Weymann et al. 1980) and third (Weymann et al. 1982) gravitational lens candidates and help explain why the observed spacing of multiple quasar images are ∼5 arcsec rather than ∼1 arcsec, which would be expected if galaxies were responsible.

6. CONCLUSION

Our work started with an old puzzle: why do some close galaxy pairs have very high velocity differences? In particular, why is the isolated field elliptical galaxy sample so different from the cluster core sample? Furthermore, how can galaxies be orbiting with speeds of ∼1000 km/s on scales just slightly larger than the size of the galaxies, inside of which stars have a velocity dispersion of only ∼300 km/s?

Our observation that the high ΔV compound galaxies occur in clusters with high velocity dispersion led us to propose a model in which the dark matter forms a scale-free gravitational potential from scales of $\gtrsim 1$ Mpc down to scales of $\lesssim 10$ kpc. Only at the very center of the cluster ($\lesssim 2$ kpc) does the bright matter finally become gravitationally dominant.

We have built a quantitative model for such black pits which makes definite observational predictions. Core radii of cD's must be smaller than previously thought (Schweizer 1979). Velocity dispersion in the cD envelope must rise outward (Dressler 1979; Carter 1979). Dynamical friction timescales are longer than in the conventional galactic cannibalism picture. This means fewer mergers will have taken place and that cannibalism may not be as large a cosmological effect as previously expected (Ostriker 1978). Because of the high velocities and small radii, phase space restrictions make it seem unlikely that the dark matter can be stripped galaxy halos (Gallagher and Ostriker 1972; Richstone 1975, 1976; Dressler 1979; Merritt 1983; Richstone and Malamuth 1983). Rather, we think the dark matter potential must have existed before the galaxies (cf. also White and Rees 1978). This reversal of the conventional picture implies that cD galaxy formation may still be occurring (Silk 1976; Valentijn 1982; Nulsen et al. 1982; Wirth, Kenyon and Hunter 1983; Fabian et al. 1982; Sarazin and O'Connell 1983).

A cursory glance at the observations is sufficient to show that rich clusters form a highly heterogeneous class of structures. In addition, they almost certainly violate the simplifying assumptions of spherical symmetry, stationarity, and isotropic velocity distributions on which our quantitative estimates have been based. Indeed, if clusters are gravitationally dominated by collisionless dark matter, then we expect them to be highly anisotropic in shape, which is exactly what is observed and classified (Rood and Sastry 1971; Struble and Rood 1982), and hence in velocity dispersion. Our model has two parameters even in the spherical case: the steepness of the potential and the cutoff radius of the logarithmic potential. This leads to a new theoretical classification of clusters which mirrors the observational classification

proposed by Jones and Forman (1983) based on X-ray surface distribution.

Some black pits will have large radii for the dark matter (e.g., Coma) and be indistinguishable from the classic "missing matter" proposed fifty years ago by Zwicky (1933). Nevertheless, we believe that there is substantial circumstantial evidence for the widespread incidence of deep potential wells. Our picture of these extreme black pits explains in a unified manner a number of disparate phenomena. The morphologies of D, cD, and db galaxies (Mathews et al. 1964; Wirth, Smarr and Gallagher 1982) emerge naturally as the different ways in which galactic cores and envelopes fill the pit. Because of the long dynamical friction time, cores "hang up" on the sides of the potential, producing the large percentage of multiple nuclei brightest cluster members observed (Rood and Leir 1979; Hoessel 1980; Schneider et al. 1983). Most galaxies are at large distances in the cluster potential, but a few get captured in the cusp at the bottom of the pit. This produces the bimodal distribution of brightest cluster members observed by Struble and Rood (1982). This background potential also allows for stable high multiplicity (Minkowski 1961; Schneider and Gunn 1982) central galaxies. The pit pins the central cD or db to the cluster center to high accuracy (Quintana and Lawrie 1982). Because of its great depth, radio jets may not be able to climb completely out of it supersonically, but may transform into subsonic plumes waving in the intergalactic breeze (e.g., Burns and Owen 1980; Burns 1981; Burns, Eilek and Owen 1982), appearing as wide-angle radio tails (Owen and Rudnick 1976).

We stress that a cluster of galaxies has two separate components: the dark matter potential and the gas, stars, and galaxies living in that potential. Depending on the ratio of luminous matter to dark matter, the same shaped potential may appear as a rich or a poor cluster. Depending on how many stars and galaxies have settled to the center of the potential, the cluster may be Bautz-Morgan class I or III. It seems that the spatial distribution of the X-ray gas is the most reliable tracer of the underlying gravitational potential. Even here, however, the likelihood of X-ray cooling makes determination of the core radius of the dark matter difficult. More detailed calculations of all these processes are required if observations are to make direct contact with the underlying physics.

We believe our model fits in well with the idea that the cosmos is held together by dark matter on scales from 10^7 kpc down to 10 kpc. Galaxies become test particles tracing out for us the underlying cluster potential. The great clusters are early condensations of the dark matter which only recently ($z \leq 10$) have become illuminated.

7. ACKNOWLEDGMENT

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Cluster	D.C.	B.M.	R.S.	NA	$\sigma_{\rm cl}$	ΔV	$r_\perp$ (kpc)	Refs ΔV	Refs $r_\perp$
102	3	3	F	37	435	295	22	(1)	(1),(3)
151	3	3	cDs	72	–	600	11	(2)	(3)
194*	1	3	L6a	37	435	200	8	(5),(1)	(4),(3)
400*	1	4	Ic	58	242	380	6	(4),(1)	(4),(3)
576	2	5	Ic	61	1211	1300	9	(6)	(3)
779	1	2	cDps	32	755	1800	9	(2),(7)	(3)
787*	4	3	F	106	–	800	24	(4)	(4),(3)
1185	2	3	C10	52	–	880	12	(1)	(1),(3)
1213	2	5	C10	51	549	390	18	(8)	(9),(3)
1413*	5	1	cD	196	–	25	17	(4)	(4),(3)
1775*	4	1	Bb	92	1522	1700	23	(4),(11)	(4),(11),(3)
2151	1	5	F	87	887	800	6	(12)	(13)
2199	1	1	cD	88	808	1500	6	(14)	(14)
2256	3	4	B	88	1257	1100	7	(16)	(15),(3)
2634*	1	3	cDs	52	899	1100	5	(1),(4),(17)	(1),(3),(4),(17)

Table 1: Abell Clusters Measured Redshift Differences (ΔV) and Projected Separations ($r_\perp$). These are the Abell clusters whose brightest cluster members have measured redshift differences (ΔV) and projected separations ($r_\perp$). The properties of the clusters—distance class (D.C.), Bautz-Morgan class (B.M.), Rood-Sastry class (R.S.), Abell number counts (N_A), and cluster velocity dispersion ($\sigma_{\rm cl}$)—are taken from Struble and Rood (1982). The references for ΔV and $r_\perp$ are given at the bottom of the table.

Note: * Included in Jenner's (1974) sample.
References for ΔV and $r_\perp$:
(1) Tifft 1982; (2) Humason et al. 1956; (3) Struble and Rood 1982; (4) Jenner 1974; (5) Zwicky and Humason 1964; (6) Melnick and Sargent; (7) Mitzen et al. 1978; (8) Burbidge and Strittmatter 1972; (9) Riley 1975; (10) van Breugel; (11) Chincarini et al. 1971; (12) Tarenghi et al. 1979; (13) Burbidge and Burbidge 1959; (14) Minkowski 1961; (15) Bridle and Fomalont 1976; (16) Faber and Dressler 1977; (17) Scott et al. 1977.

	Small $\sum$	Large $\sum$
High α	A2634, A2199	A1656 (Coma)
	High ΔV double nuclei	No double nuclei
	WAT likely	WAT unlikely
	X-ray Dominated	Non X-ray Dominated
Low α	A194, A400	A1367
	Low ΔV double nuclei	No double nuclei
	WAT likely	WAT unlikely
	X-ray Dominated	Non X-ray Dominated

Table 2: Black Pit Parameters and Representative Abell Clusters

Notes: The two parameters for the black pit model are defined as:
$\sum = \sigma/\sigma_0$ — measures the slope of the gravitational potential.
$\alpha = a/r_0$ — measures the degree of central condensation of dark matter.
We have selected a few Abell clusters to exemplify the four extremes of this two-parameter space. Tracers of the dark matter distribution are listed for each case.

Key to Symbols:

- Y = Yes
- ? = Unknown

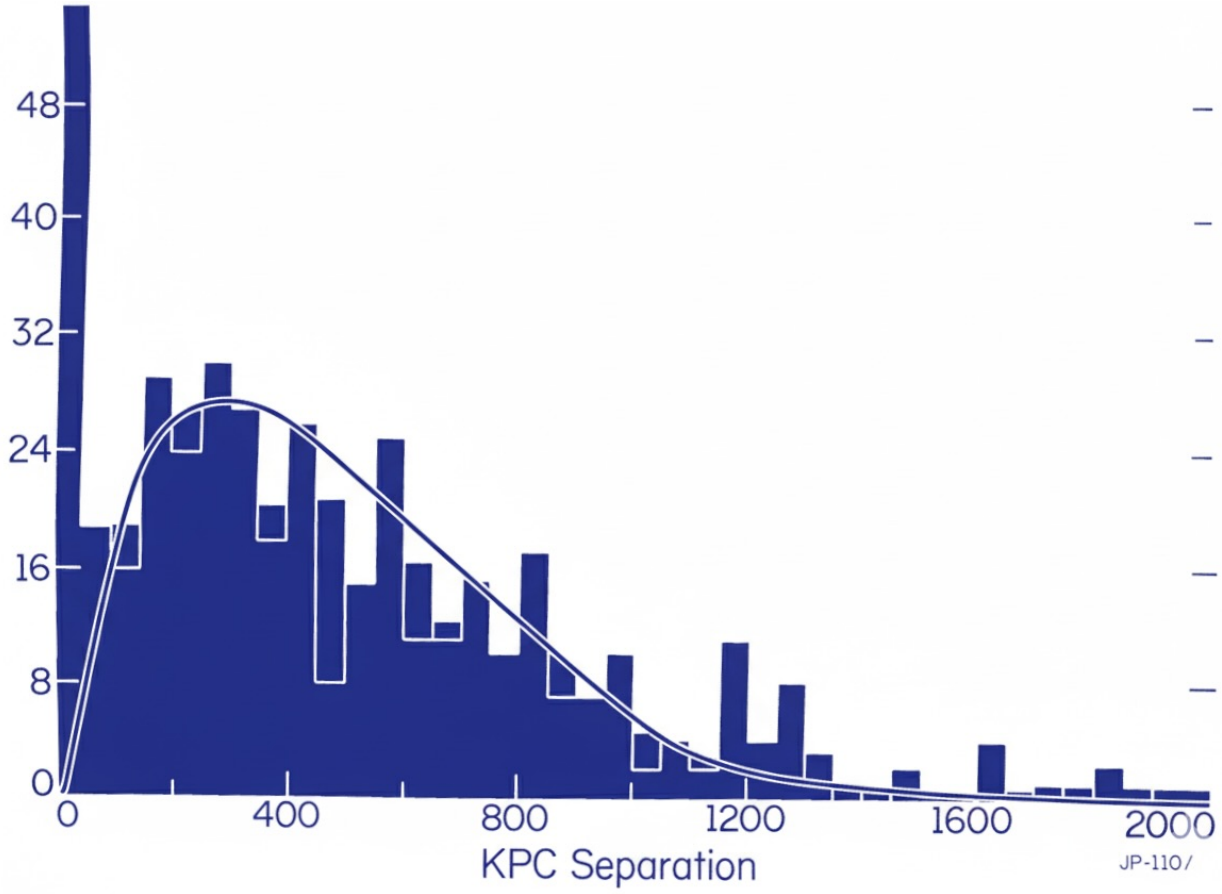
Table 3: Cluster Properties

Cluster	cD	MN	XD	Radio
Virgo	?	-	Y	cd(1)
85	Y	?	Y	?
102	-	Y	?	UL
119	Y	?	?	UL
133	Y	?	?	?
147	-	Y	?	UL
151	Y	Y	?	UL
154	Y	Y	Y	UR
193	Y	Y	?	UR
194	-	Y	Y	EX
240	-	Y	?	UL
262	D?	?	Y	UR
399	Y	?	Y	UL
400	-	Y	Y	WAT
401	Y	?	Y	UL
407	?	Y	?	EX
426	?	?	Y	cd(6)
496	Y	?	Y	?
505	Y	?	?	UL
576	-	Y	Y	UL
592	Y	?	Y	?
595	-	Y	?	cd(40)
644	Y	?	?	UL
671	Y	Y	Y	?
754	Y	Y	?	UL
779	Y	?	?	UL
957	-	?	Y	UL
978	Y	?	?	UL
1060	-	?	?	UL
1139	-	Y	?	UL
1142	-	Y	?	UR
1185	-	Y	?	UR
1213	-	Y	?	cd(20)
1291	-	Y	Y	UR
1436	-	Y	?	UR

Cluster	cD	MN	XD	Radio
1631	Y	?	?	UR
1691	Y	?	?	UL
1775	Y	Y	Y	WAT?
1795	Y	?	?	WAT
1800	Y	?	?	UL
1890	Y	?	?	UR
1904	Y	?	?	UL
1927	Y	?	?	UR
1983	?	?	Y	UR
1991	Y	Y	Y	UR
2029	Y	?	?	UR
2040	-	Y	Y	UL
2052	Y	?	?	UR
2063	Y	Y	Y	UR
2065	Y	Y	?	UK
2067	?	?	?	UL
2079	Y	Y	Y	cd(10)
2092	-	Y	?	UL
2107	Y?	?	Y	UL
2124	?	?	?	UL
2147	Y	?	?	UL
2151	-	?	?	EX
2162	Y	?	?	UR
2199	Y	Y	Y	cd(7)
2271	Y	?	Y	UL
2312	?	?	Y	UL
2319	Y	Y	N	UR
2382	?	Y	?	?
2415	?	?	Y	EX
2589	Y	?	?	UL
2626	Y	?	Y	UR
2634	Y	Y	?	WAT(9)
2657	Y	?	Y	UL
2666	Y	?	?	UL
2670	Y	Y	Y	UL

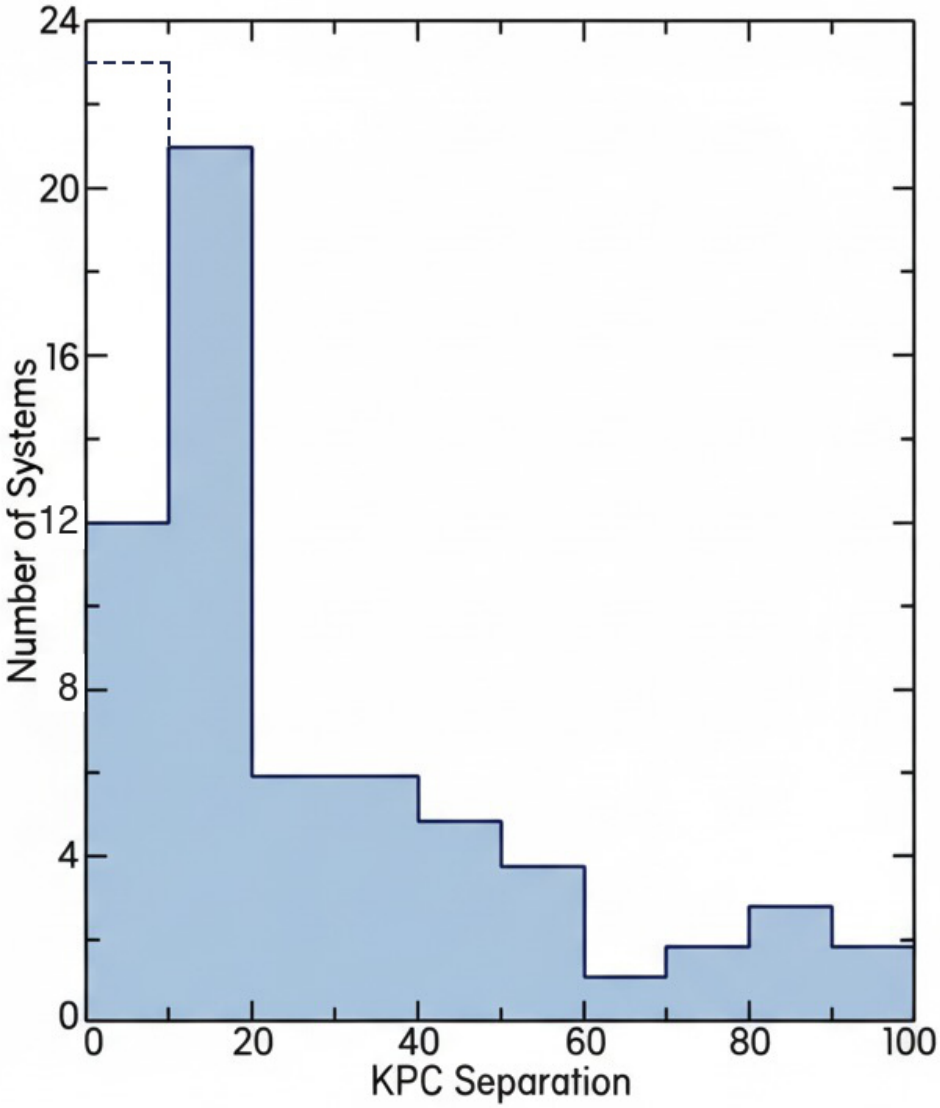
NOTE—MN = Multiple Nuclei. Radio codes: UL = unresolved, UR = unresolved radio source, EX = extended, WAT = wide-angle tail, cd(n) = core-dominated with reference number n, UK = unknown.

- UL = Upper limit
- UR = Detected but unresolved
- EX = Extended but not well resolved
- cd = Close double
- WAT = Wide-angle-tail
- For cd and WAT, numbers in parentheses → Distance from nucleus to hot spot in kiloparsecs (kpc)



(a)

Figure 1


24
20
16
12
8
4
0
Number of Systems
0
20
40
60
80
100
KPC Separation

(b)

Figure 1

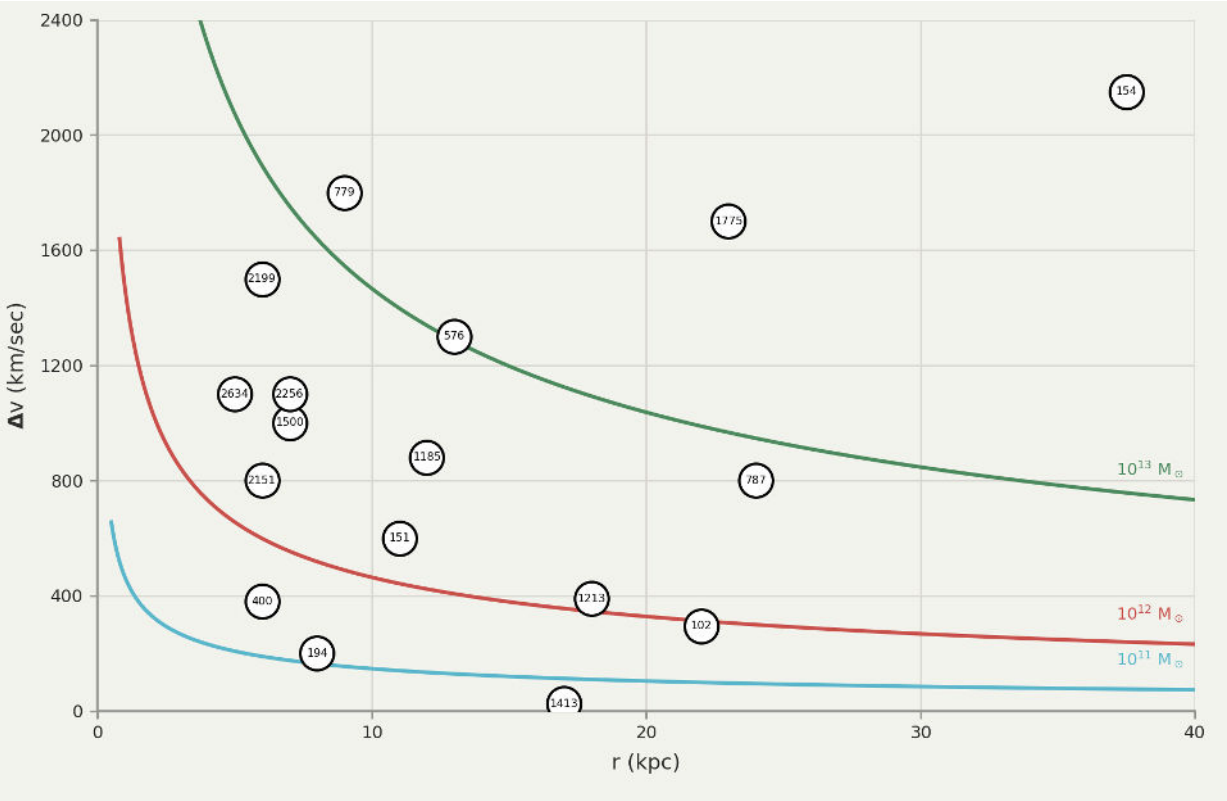

2400
2000
1600
1200
800
400
0
Δv (km/sec)
0
10
20
30
40
r (kpc)
154
779
1775
2199
576
2634
2256
1500
1185
2151
787
151
1213
400
102
194
1413
10^13 M⊙
10^12 M⊙
10^11 M⊙

Figure 2

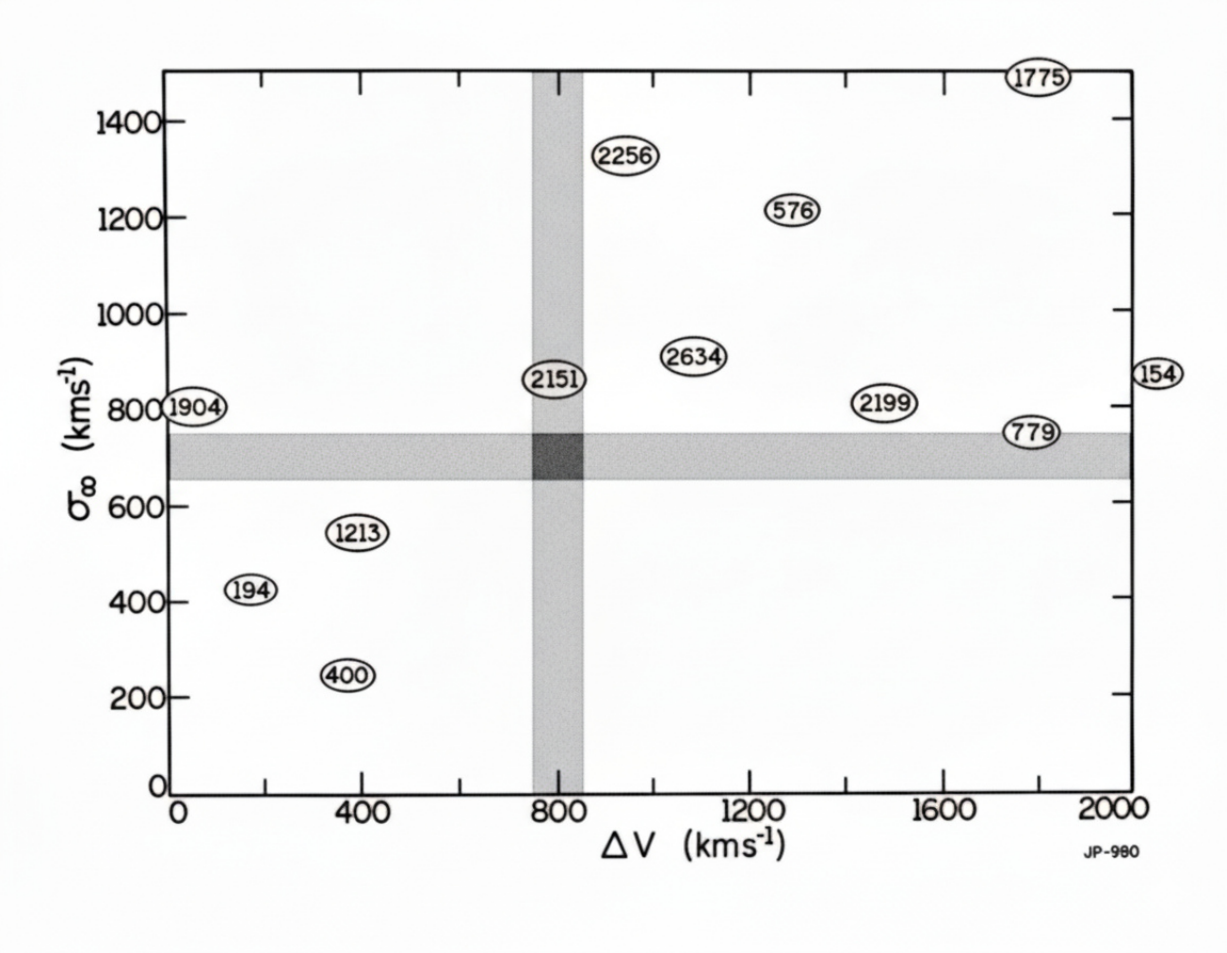

1775
2256
576
2634
2151
154
1904
2199
779
1213
194
400
1400
1200
1000
800
600
400
200
0
0
400
800
1200
1600
2000
σ∞ (kms⁻¹)
ΔV (kms⁻¹)
JP-980

Figure 3

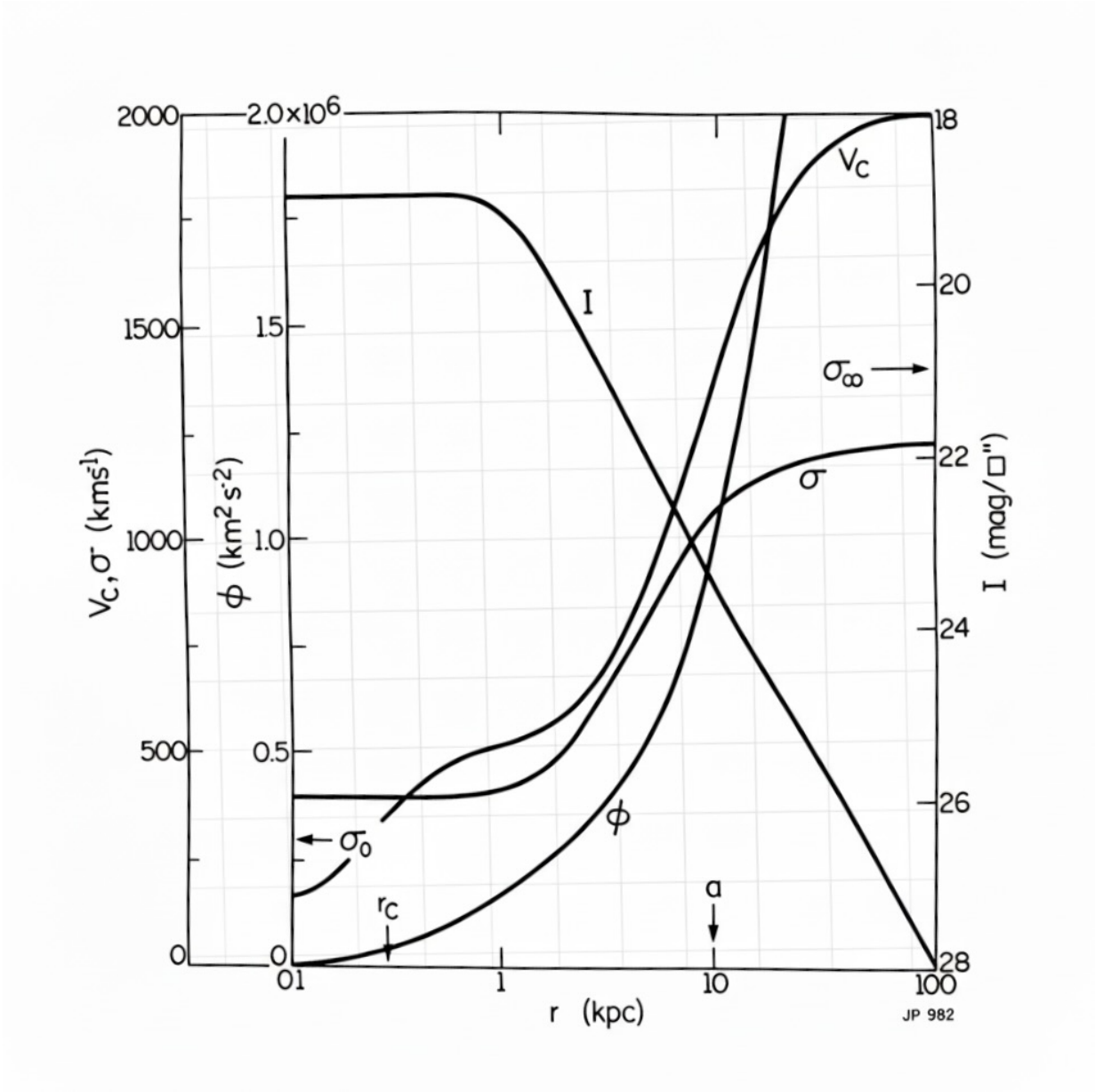

2000
1500
1000
500
0
V_c, σ (kms^{-1})
2.0×10^6
1.5
1.0
0.5
0
ϕ (km^2 s^{-2})
18
20
22
24
26
28
I (mag/□")
V_c
I
σ_∞
σ
ϕ
σ_0
r_c
a
0.1
1
10
100
r (kpc)
JP 982

Figure 4

FIGURE CAPTIONS

Figure 1: Projected separations of the three brightest galaxies in Abell clusters. The measurements are taken from the compilation of Struble and Rood (1982) and are normalized to a Hubble constant $H_0 = 100$ km s^{-1} Mpc^{-1}. In (a) the histogram of separations has a bin size of 50 kpc. The solid line is a curve similar to that found by Hickson (1977). Separations less than 100 kpc are sorted into bins of width 10 kpc in (b) in order to exhibit the excess of small separations. The dashed line in the first bin represents an estimate based on the finding of Hoessel (1980) that 25% of brightest-cluster members were multiple within 10 kpc. Note that the expected incidence of chance superpositions within a core of radius ~ 100 kpc should increase quadratically with the separation as indicated by the dotted line in Fig. 1(a).

Figure 2: Velocity difference ΔV plotted against projected radial separation r_1 (assuming $H_0 = 100$ km s^{-1} Mpc^{-1}) for compound galaxies in Abell cluster cores as labeled by Abell cluster number. Details of the sample used in this Figure are contained in Table 2.

Figure 3: The velocity difference ΔV of cluster core compound galaxies plotted versus the observed radial velocity dispersion σ_v of the cluster. The data are for all pairs for which σ_v is known (Struble and Rood 1982). The median value of both velocities is 700 km s^{-1}, even though the length scales involved differ by ~ 100.

Figure 4: Model of a spherically symmetric, isotropic cD in a rich cluster. There is a central elliptical galaxy of core radius $r_c = 300$ pc, bolometric mass-to-light ratio of 10 solar units and local central velocity dispersion $\sigma_0 = 300$ km s^{-1}. The dark matter potential ϕ well has a scale radius $a = 10$ kpc ($a = 33$) and a velocity dispersion at large radius of 1,400 km s^{-1} ($\Sigma = 4.7$). The combined light from the galaxy and the envelope has been convolved with a seeing disk of radius 2 kpc to give a B surface brightness profile I(r) and an observed velocity dispersion variation $\sigma(r)$. [Compare Dressler (1979) who uses a conventional cluster dark matter component with scale radius > 100 kpc.] If there were a second galaxy in circular orbit in the potential well, then its orbital speed would be $V_c(r)$.