PROPERTIES OF CD GALAXIES

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ABSTRACT. cD galaxies are the most luminous galaxies in the universe. They are characterized by a surface brightness profile that falls off more slowly with radius than most elliptical galaxies. In most respects D galaxies are a continuous extrapolation from other ellipticals: their M/L and their colors are comparable to other ellipticals, their inner parts are fitted by an $r^{1/4}$ law, and they follow the same relation between L and σ. On the other hand, their luminosity is too bright to be consistent with the luminosity function of other ellipticals and they are always found at the center of a cluster of other galaxies. Being at the center of a cluster of galaxies often endows D galaxies with a very faint, very extended halo of luminosity and multiple nuclei, but these are more properly associated with the cluster than the D galaxy itself. The connection between the formation of cD galaxies and the formation of clusters remains a mystery. It is still unresolved whether cDs are a byproduct of cluster evolution, whether they formed in parallel with clusters, or whether primeval D are galaxies the seed around which clusters accreted.

1. INTRODUCTION

cD galaxies are the largest galaxies in the universe. They are probably the sites of extensive galaxy evolution and they are also intimately linked to clusters of galaxies and the properties of clusters. There are many facts, conjectures, and myths relating to cD galaxies and it is not clear how these fit together. Two recent review articles that have touched on the subject of cD galaxies were written by Dressler (1984) and Sarazin (1986).

I will first discuss what is meant by a cD galaxy and what its defining characteristics are. Next I will describe some of the observations relating to the morphology and dynamics of cD galaxies. Finally I will discuss some theories relating to the origin and evolution of cD galaxies.

2. WHAT IS A CD GALAXY?

Figure 1 shows surface brightness data of a few selected galaxies. N1278 is a typical giant elliptical galaxy. AWM7 is a D galaxy at the center of a poor cluster of galaxies, and A2029 is the brightest cluster galaxy at the center of a rich cluster, as is A1413. The left-hand plots show log surface brightness in magnitudes versus log radius and the right-hand plots show surface brightness versus $r^{1/4}$ (coordinates such that a deVaucouleurs $r^{1/4}$ law fit is a straight line).

cD galaxies were originally defined by Matthews, Morgan, and Schmidt (1964) as being distended superluminous galaxies. "c" is the designation coined by Miss Maury (1897) for stars with unusually narrow H lines, which we now understand to be superluminous, and "D" originated with Morgan

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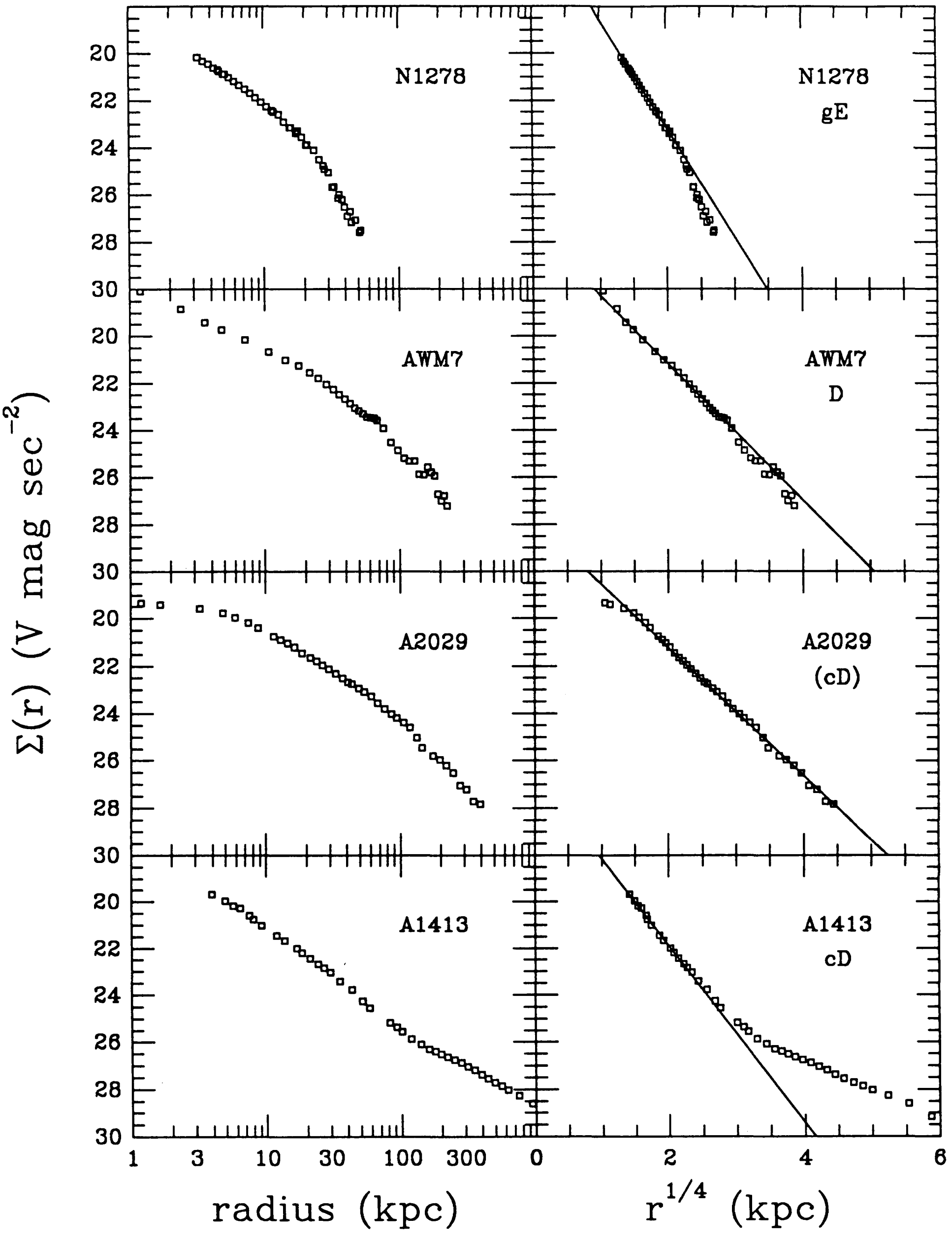

Figure 1. Surface brightness profiles are shown as a function of log radius and $r^{1/4}$ (H_0=50) for four galaxies. $r^{1/4}$ law fits are shown as straight lines. N1278 is a typical giant E galaxy in the Perseus cluster; AWM 7 is a D galaxy in a poor cluster; A2029 is a D galaxy in a very rich cluster; and A1413 is a cD galaxy in a rich cluster. A2029 is often called a cD galaxy although it lacks an extended cD halo. The data are from Schombert (1986).

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(1958), meaning "dustless", I believe. AWM7, A2029, and A1413 all satisfy this criterion, but there is a lot of inconsistency in what gets called a D and what gets called a cD. The characteristics that have been traditionally used to identify cD galaxies are luminosity and an apparent halo, very faint and extensive, appearing just at the limits of photographic plates. The primary authority for bona-fide cD galaxies has been Matthews, Morgan, and Schmidt and the extensive catalog of cD galaxies and cluster morphology compiled by Leir and Van den Bergh (1977).

It has been pointed out by Malumuth (1983) and Schombert (1984), among others, that what causes a galaxy to look distended is the logarithmic slope of the surface brightness profile at the plate limit. This governs whether the galaxy looks as though it has a halo. Notice A1413 actually does have a halo beyond the $r^{1/4}$ law fit to the interior, but that this halo doesn't appear until very faint surface brightnesses, fainter than would be visible to the eye on a plate. Oemler (1976) found that a number of classical cD galaxies have these halos, but by no means all.

Figure 2 is a schematic diagram of how surface brightness profiles vary as a function of galaxy luminosity. The four curves show the log surface brightness as a function of log radius for what are labelled an E galaxy, a giant E galaxy, a D galaxy, and a cD galaxy.

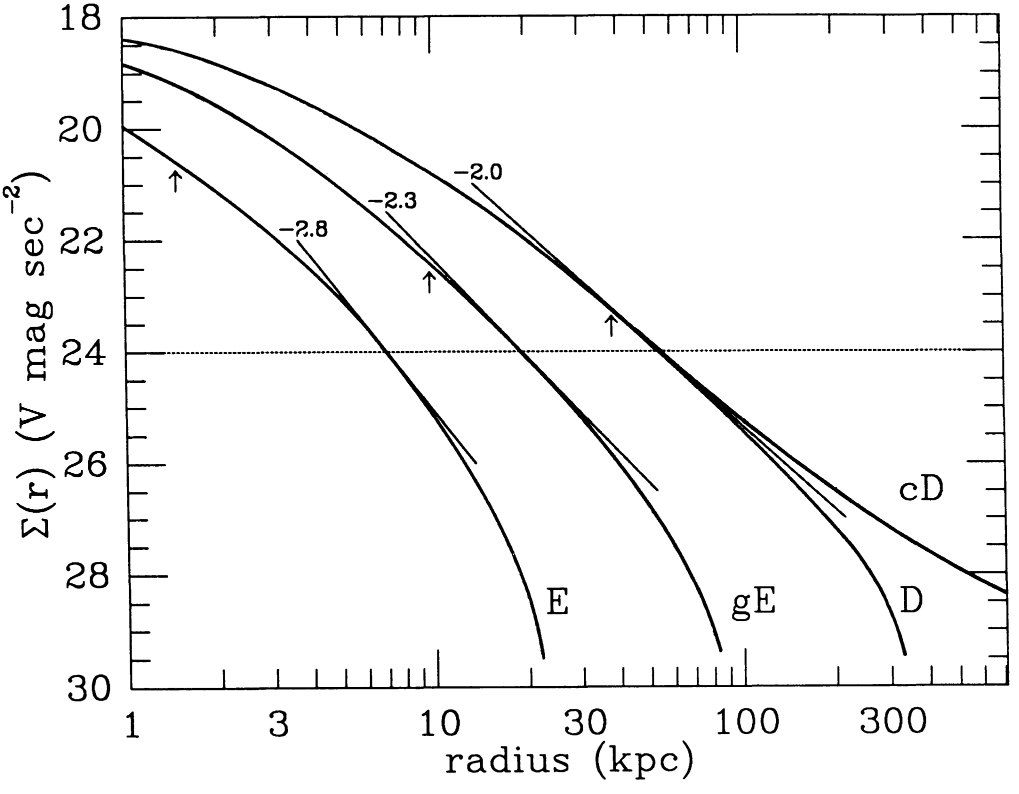

Figure 2. Schematic surface brightness profiles are shown for E, gE, D and cD galaxies as a function of log radius (H_0=50). The tangent line to the profiles at $V = 24$ mag sec^{-2} are drawn and labelled with their slope. The arrows point to the effective radius of each profile, determined by an $r^{1/4}$ law fit to the inner parts of each profile. The cD profile is identical to the D profile brighter than $V \approx 25$. The curves are from Schombert (1986) and are derived from mean galaxy profiles.

Notice how I am modifying the original nomenclature. What I call an E galaxy is an elliptical galaxy whose profile is falling steeply at the plate limit ($V \approx 24$ mag sec^{-2}). A gE galaxy is one whose profile is falling less steeply, a D galaxy even less steeply, and finally a cD galaxy is a D galaxy with an additional halo tacked on. This I think is as faithful as possible to the original definitions while making a quantitative classification possible. The requirement that cD galaxies be superluminous as well as having flat profiles is superfluous because there are very few galaxies that have the flat profiles of D galaxies that are not superluminous. Table 1 shows typical values for a number of parameters derived from $r^{1/4}$ law fits to the inner parts of the profiles shown in figure 2.

Table 1.

Galaxy	dlogΣ/dlog$r$	α	Σ_e	r_e	L/L^*
E	−2.8	0.05	20.5	1.7	0.3
gE	−2.3	0.35	22.5	10.0	1.5
D	−2.0	0.70	23.5	40.0	9.0

Column 1 is the galaxy type, column 2 is the log slope of the profile at V=24 mag sec^{-2}, column 3 is the structure parameter α=dlog$L$/dlog$r$ (see e.g. Hoessel 1980), column 4 is the V surface brightness at the effective radius, column 5 is the effective radius in kpc (H_0=50), and column 6 is the $r^{1/4}$ luminosity in units of L^* (the luminosity of the break in the luminosity function).

E, gE and D galaxies can equally well be characterized by surface brightness at the effective radius as by profile slope at a fixed surface brightness, since the two are equivalent for an $r^{1/4}$ law. This classification is fairly artificial, however, because this is a continuous sequence of galaxy shape and luminosity. The $r^{1/4}$ profiles that Hoessel and Schneider (1986) fitted to their sample of first ranked cluster galaxies show an rms scatter of about 25 percent in r_e at fixed profile slope (or fixed Σ_e). The effective radius of these galaxies increases exponentially with decreasing profile slope, growing by a factor of roughly 30 per unit change in profile slope.

It is important to note that E, gE, D, and cD galaxies are all fitted nicely by $r^{1/4}$ laws for surface brightnesses greater than $V \approx 25$ mag sec^{-2}, and this is the primary means of differentiating Ds and cDs: cDs have an additional halo component above an $r^{1/4}$ law fit to their interiors. This halo starts at about $V \approx 25$ mag sec^{-2} and it has a log slope of about −1.5. According to this scheme A2029 and AWM7 would be D galaxies and only A1413 a cD. This classification will be used for the rest of the article.

Figure 2 also shows the effective radius of these profiles; notice that the surface brightness at the effective radius drops as luminosity increases. This fact, along with a few examples of D galaxies with large core radii and low central surface brightness, has led to the belief that D galaxies have low surface brightness. This is not correct. The surface brightness at r_e drops with increasing L because r_e increases faster than $L^{1/2}$. At any physical radius greater than about 1 kpc, however, D galaxies have higher surface brightness than lower luminosity galaxies. This fact has been stressed by Schombert (1986), and it is also apparent in the data of Hoessel and Schneider (1986). In both data sets there is a clear trend of more luminous galaxies and galaxies with flatter profiles having higher average surface brightness in small central apertures. This does not necessarily imply that the surface brightness at the very center of the galaxy also increases with luminosity; but the luminosity in any aperture of fixed size that includes a significant fraction of the light will increase with luminosity.

3. OBSERVATIONS OF CD GALAXIES

Not suprisingly, all galaxies with cD halos have the shallow profiles of D galaxies; conversely 25 percent of Ds have cD halos (Schombert 1986). D galaxies only occur in the center of galaxy clusters, never in the field, according to Geller and Beers (1983). There are three cases known of cD galaxies that are not at the overall center of a cluster, but they are found centered on subclumps of their own. Beers and Tonry (1986) have found that D galaxies are surrounded by a cusp of cluster galaxies with a projected density distribution which falls off as r^{-1}.

It has long been known that the brightest galaxies in clusters of galaxies are usually exceptionally luminous. A large fraction of these first-ranked cluster galaxies, or brightest cluster galaxies (BCGs), have D galaxy profiles. A classic observation of BCGs is that they vary little in luminosity within a fixed metric aperture (Sandage 1973); this fact has been extensively exploited in attempts to use BCGs as standard candles to measure q_0. This standard luminosity has small positive correlations with galaxy structure parameter α, cluster richness, and cluster morphology (Schneider, Gunn and Hoessel 1983a). BCGs are extremely luminous, too luminous to be consistent with a Schechter function fitted to other elliptical galaxies. It is a non-trivial fact that D galaxies (as a subset of BCGs) are very luminous and span a small range in luminosity (rms of about 0.3 magnitudes).

There have been reports by Hoessel (1980), among others, that D galaxies have larger core radii than gEs. While there are a number of D galaxies with flagrantly large core radii and low central surface brightness, it is not clear whether there is a correlation at fixed luminosity between flatness of surface brightness profile and core radius. There undoubtedly is a correlation between luminosity and core radius, but that does not directly address the question of whether D galaxies have different core structure than gE galaxies of the same luminosity.

D galaxies have the same color (and so presumably stellar population) as gEs and do not appear to have significant color gradients (Lugger 1984). There have been interesting reports by Sastry (1968), Binggeli (1982), and others that D galaxies are slightly more flattened on average than gEs, and that the direction of flattening is weakly aligned with the overall shape of the cluster in which the D galaxy resides.

The galaxy AWM7 in figure 1 is an enormous galaxy in a very sparse cluster. It certainly is a D galaxy but does not have the deviation from an $r^{1/4}$ law characteristic of a cD halo. This appears to be true in general for poor clusters. According to Thuan and Ravanishin (1981), D galaxies in poor clusters never have cD halos although they may be extremely luminous and have extremely flat profiles.

Another property of D galaxies is that they often have "multiple nuclei" which are other, smaller galaxies seen projected on top of the luminosity profile of the D galaxy (within 10 or 20 kpc of the center). Hoessel and Schneider (1986) find that 50% of BCGs have "multiple nuclei." This is not true of the second brightest galaxy, nor does the fraction vary with cluster richness or morphology. These "multiple nuclei" are not deficient in luminosity; they are roughly consistent with being drawn from the overall luminosity function of the cluster.

D galaxies are not only spatially projected at the center of clusters. Quintana and Lawrie (1982) find that they have a much lower rms velocity with respect to the cluster mean than do the rest of the galaxies in the cluster. Thus D galaxies are apparently stationary at the bottom of the cluster potential well.

Observations of the stellar velocities within D galaxies reveal a number of facts. The stellar velocity dispersion never exceeds roughly 400 km/s and is usually between 300 and 350 km/s. D galaxies agree nicely with the $L \propto \sigma^{3.3}$ relation when any excess halo luminosity above an $r^{1/4}$ law fit to the interior is excluded (Tonry 1986). The stellar velocity dispersion never seems to fall with radius, nor do the galaxies ever show any rotation, in contrast with lower luminosity ellipticals which do both. There have been some very intriguing reports by Dressler (1978) and Carter *et al.* (1985) that indicate that in some D galaxies the stellar velocity dispersion actually starts to rise at about 50 kpc (or a surface brightness of $V \approx 23$ mag sec^{-2}). This needs further observation, and more important, needs to be tested as a function of cluster richness, because cluster richness seems to have major effects on the outer parts of D galaxies.

The mass to luminosity ratio of D galaxies is comparable to E galaxies; they are not supermassive. Malumuth and Kirshner (1981) observed a number of Ds and found that their M/Ls were 50% larger than Es. They were limited to a small sample of galaxies, and they used only central velocity dispersions and uncertain core radii, so this result is not beyond question. Tonry (1984) observed the velocity dispersion of two D galaxies as a function of radius and found a mass to luminosity ratio consistent with that of other E galaxies.

A complete sample of multiple nuclei were observed by Tonry (1986), and the rms velocity of these galaxies was found to be 800 km/s. This is so much in excess of the 300 km/s velocity dispersion of the stars in the D galaxies that few if any of these multiple nuclei are bound to the D galaxy. The term "multiple nucleus" is a misnomer: these multiple nuclei are merely sharing the bottom of the cluster potential with the D galaxy. Roughly a quarter of multiple nuclei are moving at less than 300 km/s projected velocity and could be interacting with the D galaxy, but it is surprising that such slow multiple nuclei are only found around low luminosity BCGs. When a BCG is brighter than 2 L^* the multiple nuclei around it all have projected velocities of at least 500 km/s, hinting that it is indeed the slow multiple nuclei that are consumed to make a bright D galaxy.

D galaxies occasionally have significant X-ray fluxes (Forman and Jones 1982). This emission is apparently from a halo of hot gas, but it is not clear whether this gas is bound to the D galaxy or to the cluster in which it resides. The X-ray spectral observations suggest that some of the gas is cool enough to cool further and accrete onto the central D galaxy (Canizares 1981). There have been observations of patchy dust and filaments of gas emission in D galaxies that may corroborate this. Alternatively this gas and dust may be the product of stellar evolution within the D galaxy itself. There has been speculation that if such cooling flows exist, the gas could be converted into low mass stars which could be a significant, high M/L contribution to D galaxies (Fabian *et al.* 1982).

4. ORIGIN AND EVOLUTION OF CD GALAXIES

Despite the fact that there is continuity of many properties between E and D galaxies, it appears that D galaxies have undergone an extra measure of evolution beyond ordinary elliptical galaxies. D galaxies are too bright to be a statistical fluctuation in accord with a continuous extrapolation of the luminosity function of other galaxies and they are relatively constant in luminosity. They are found only at the center of an r^{-1} cluster of other galaxies. These adjacent galaxies frequently appear as multiple nucleus companions, and D galaxies often have an extended cD halo. They are more flattened than elliptical galaxies, and appear to align with their clusters. It is a puzzle whether the process that makes D galaxies surrounds them with a cluster, or whether any galaxy that sits at the center of a cluster would acquire the same properties.

There has been a extensive work by Villumsen (1982), Farouki *et al.* (1983), Duncan *et al.* (1983), May and Van Albada (1984), and Aguilar and White (1986) on N-body simulations of galaxy mergers and accretion which indicate that $r^{1/4}$ laws are a natural formation product. Further, it appears that profiles become more and more flattened as they evolve and one can even get extensive halos. These halos are not very luminous and they are transient, but perhaps the environment of a rich cluster is sufficiently hospitable for them to survive and grow.

The most natural explanation of the origin of D galaxies is that they have formed from galaxy interactions: merging, accretion, and stripping. The question is when? One possibility is that mergers and accretion form D galaxies throughout the history of the cluster right up until the present. This scenario, discussed by Gunn and Tinsley (1976), Ostriker and Hausman (1977) and Hausman and Ostriker (1978), has the largest galaxies in the center of a cluster merge to form a D galaxy and then this galaxy continuing to accrete cluster galaxies, until it eventually grows to its present large size. cD halos are expected as the tidal debris from the galaxy interactions and the high velocity stars that are sprayed off in mergers. This is the "galactic cannibalism" model of cD formation. Richstone and Malumuth (1983) and Malumuth and Richstone (1984) have made detailed calculations indicating that this may be the case.

Several observational points seemed to be explained by this theory. The constancy of BCG luminosity was thought to be the result of homologous growth of the central galaxy, i.e., the galaxy maintains the same shape with rescaled radius and mass. Within a fixed aperture the luminosity could stay constant with growth if the surface brighness of the galaxy decreased as its scale size grew. The multiple nuclei were viewed as the stripped cores of cluster galaxies, drifting about within the halo of the cD. Sandage and Hardy (1973) found an anticorrelation between the luminosity of the second brightest galaxy in a cluster and the luminosity of the brightest. This was taken as evidence that there had been brighter galaxies in the cluster which had merged to become the cD, and present second brightest galaxy was originally much less highly ranked. The current observational evidence shows no indication that surface brightness decreases with luminosity, however. Multiple nuclei are not in the process of merging with the BCG. Schneider, Gunn and Hoessel (1983b) and Schombert (1984) find no anticorrelation between the first and second brightest galaxies in clusters. Thus much of the support for the cannibalism and homologous growth theory has disappeared.

Recent calculations by Miller (1983) and especially Merritt (1985) indicate that there is no present evolution because galaxies have become stripped of their halos and have high velocities, making them relatively immune to dynamical friction. These authors find that the accretion rates of Hausman and Ostriker (1978) and Malumuth and Richstone (1984) to be much too high. They argue that D galaxies formed in the early stages of formation of the cluster before it had virialized, and that the cluster is presently quiescent. There does not seem to be a simple reconciliation of the calculations by Malumuth and Richstone and Merritt because the differences arise mainly as a result of the values assumed for a number of poorly known quantities, such as the mass and extent of halos around cluster galaxies, the density and core radius of the dark matter that gives clusters such high velocity dispersions, and the extent to which clusters are subclustered.

Multiple nuclei and the cusps in galaxy density around D galaxies give ambiguous evidence. On the one hand, the majority of multiple nuclei are not merging with their D galaxies and will not in the near future. Lauer (1986) has extracted the luminosity profiles of some multiple nuclei and finds that they look like ordinary cluster galaxies showing little evidence of strong interaction. On the other hand, low luminosity BCGs apparently do have low velocity companions whereas high luminosity BCGs do not, suggesting that D galaxies evolve until they have consumed all their slow moving neighbors and then stop, and that low luminosity BCGs are currently in the process of growing.

There has also been some work on the possibilty that D galaxies have grown from a rain of gas falling into the center of the cluster and forming stars. This seems implausible to me because of the normal colors of D galaxies and the enormous inflows required by this theory (hundreds of solar masses per year averaged over a Hubble time).

5. SUMMARY

To a large extent D galaxies are a continuous extension from giant elliptical galaxies, characterized by flat surface brightness profiles, high luminosity, and high surface brightness. They have similar colors and *M/L* to elliptical galaxies. They do not vary much in metric luminosity: the rms scatter is about 30 percent. They do not rotate and they have flat or rising stellar velocity dispersion profiles.

In contrast to giant elliptical galaxies, D galaxies are inextricably linked with cluster centers. They only appear at rest at the center of a cluster, surrounded by an r^{-1} entourage of companion galaxies. D galaxies appear to be slightly more flattened than ellipticals and their flattening aligns weakly with the cluster. D galaxies often have cD halos and are surrounded by multiple nuclei. These are probably more intrinsic to the cluster in which the galaxy resides than the D galaxy itself; most of the multiple nuclei would not be bound by the D galaxy alone. Curiously, although cD halos only appear in rich clusters, the size and structure of D galaxies and the frequency of multiple nuclei does not appear to depend on cluster richness.

A number of questions remain unanswered. The constancy of the luminosity of BCGs is real, it is not an artifact of a particular aperture and compensating scale size and surface brightness. It therefore represents a maximum size that galaxies can attain (neglecting cD halos), and the discrepancy between this size and the luminosity function of other galaxies suggests that this cutoff is not caused by statistics, but rather by physics. The causality of the relation between D galaxies and clusters is obscure. Much of the evidence that D galaxies are cannibalism byproducts is not consistent with new observations. It is an open question whether D galaxies were formed at early epochs when the cluster itself was coalescing, and either acted as seeds for the nascent cluster, or grew out of the merging clumps of matter.

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DISCUSSION

White: I was a little confused by your conclusions. My impression is that the continuity from gE's to D's in profile shape and in relations between metallicity, and velocity dispersion and luminosity, would argue strongly for similar formation mechanisms. One argument against Brightest Cluster Members being drawn from a universal luminosity function has traditionally been based on the small scatter in their absolute magnitudes. How does this argument hold up for the D and cD galaxies you discussed?

Tonry: As I tried to stress, there does seem to be some contradiction in these observations, although I suspect that there is actually something faulty in our understanding of the formation of elliptical galaxies. D and cD galaxies do appear to form a continuous sequence with other elliptical galaxies, but enjoy some special properties such as flat profiles, constant metric luminosities, location of the center of clusters of galaxies and occasional cD halos. Whatever scenario we cook up to explain these properties of D galaxies must also extend in a continuous fashion to other elliptical galaxies—at least to around $1/2\ L^*$ where there may be a discontinuity in the properties of elliptical galaxies.

Spergel: I would like to offer a speculative theory for the formation of cDs. One of the currently fashionable theories of galaxy formation is accretion around cosmic strings. These strings provide the seeds for galaxy formation. Clusters form around the more massive string loops. The more massive loops would thus accrete both other galaxies and stars to form both the cluster and an anomolous galaxy in its center. The large loops could be the source of cD galaxies. One of the remnants of these large loops might be a nucleus with high velocity dispersion and unusual velocity field. My questions are: In what fraction of the cD's do the high velocity nuclei occur? What are the velocity fields of these nuclei?

Tonry: High velocity nuclei ($|v| > 300$ km/s) occur in 2/3 of BCG's with multiple nuclei. There is no hint, however, that there is anything anomalous in the potential there. The stellar velocity dispersion is low (~ 300 km/s) and shows no disturbance in the BCG. The high velocity nuclei appear to be independent galaxies seen in projection.

Gunn: Is the histogram of velocities of the "multiple nuclei" gaussian, or can the large dispersion be due to a bound population and a few interlopers which are accidentally superposed?

Tonry: To within the meager statistics (20 or so velocities) the distribution is a continuous gaussian. There is a hint of bimodality in the distribution, but all velocities are well represented in the distribution from 0 to 1000 km/s.

Kormendy: The classification of D galaxies has been disturbingly ambiguous for many years. I'd like to call attention to this, and to suggest that we return to a "purer" definition of cD galaxies.
When you look at Morgan's original form classification catalogue you find that most D galaxies are S0s. This is consistent with Morgan's description of the D type, which refers to "extra light" in some sort of halo around the galaxy. Morgan

was therefore consistent in his identification of cD galaxies, although their cluster–sized halos are physically very different from S0 disks. Today the term "D galaxy" is not very useful; "S0" or "lenticular"' more clearly isolate the physically distinct kind of structure that we want to name, i.e., essentially an elliptical plus a disk. Morgan's term cD galaxy remains useful, because it names an important physical phenomenon, namely an elliptical surrounded by a cluster–sized halo.
Now you are changing the definition of D galaxies to mean "very large elliptical". This also makes me uncomfortable. Elliptical galaxies have a range of luminosities, and many properties that correlate with luminosity. These include the radial surface brightness gradient, which is shallower in brighter galaxies. You are attaching a special name to some portion of the bright end of the sequence of normal galaxies. This seems to me to be unnecessary, like calling people over 6 feet tall not "people" but something else. I would prefer to attach new names only to new phenomena. So I would advocate not using the term "D galaxy" at all, and going back to Morgan's original, "pure" definition of a cD as a supergiant elliptical–like galaxy with an extra, cluster–sized halo.

Tonry: I agree with your distaste for the sloppiness with which people are applying the terms "D" and "cD", but I feel that this is partly the result of the vagueness of the original definition. I feel that the terms "D" and "cD halo" can be usefully applied as descriptions of galaxies as long as one is relatively precise about what one means.

Kochhar: M87 has many properties of D galaxies without being an E galaxy.

Tonry: According to the classification I am using here, M87 *is* a D galaxy: it has a flat profile (and even a bit of cD halo).