Mon. Not. R. Astron. Soc. **000**, 1–?? (2012) Printed 17 September 2012 (MN LaTeX style file v2.2)

On the Formation of cD Galaxies and their Parent Clusters

Hrant M. Tovmassian[1⋆] and Heinz Andernach[2⋆]
[1] *Instituto Nacional de Astrofísica Óptica y Electrónica, AP 51 y 216, 72000, Puebla, Pue, Mexico*
[2] *Departamento de Astronomía, Universidad de Guanajuato, Apartado Postal 144, 36000 Guanajuato, Gto, Mexico*

17 September 2012

ABSTRACT

In order to study the mechanism of formation of cD galaxies we search for possible dependencies between the K-band luminosity of cDs and the parameters of their host clusters which we select to have a dominant cD galaxy, corresponding to a cluster morphology of Bautz-Morgan (BM) type I. As a comparison sample we use cD galaxies in clusters where they are not dominant, which we define here as non-BM I (NBMI) type clusters. We find that for 70 BM I clusters the absolute K-band luminosity of cDs depends on the cluster richness, but less strongly on the cluster velocity dispersion. Meanwhile, for 37 NBMI clusters the correlation between cD luminosity and cluster richness is weaker, and is absent between cD luminosity and velocity dispersion. In addition, we find that the luminosity of the cD galaxy hosted in BM I clusters tends to increase with the cD's peculiar velocity with respect to the cluster mean velocity. In contrast, for NBMI clusters the cD luminosity decreases with increasing peculiar velocity. Also, the X-ray luminosity of BM I clusters depends on the cluster velocity dispersion, while in NBMI clusters such correlation is absent. These findings favor the cannibalism scenario for the formation of cD galaxies. We suggest that cDs in clusters of BM I type were formed and evolved preferentially in one and the same cluster. In contrast, cDs in NBMI type clusters were either originally formed in clusters that later merged with groups or clusters to form the current cluster, or are now in the process of merging.

Key words: galaxies: clusters – clusters: general – galaxies: formation – galaxies: cD galaxies

1 INTRODUCTION

The formation mechanism of the brightest cluster galaxies (BCGs) is an important problem of modern astronomy (e.g. Lin & Mohr 2004; von der Linden et al. 2007; Hansen et al. 2009; Garijo, Athanassoula, & Garcia-Gómez 1997; Tutukov, Dryumov, & Dryumova 2007; Jordán et al. 2004). Some of the BCGs are cD galaxies (Matthews, Morgan, & Schmidt 1964) which are characterized by an extended "envelope" or halo. The physical properties of these unique objects were reviewed e.g. by Tonry (1987), Kormendy & Djorgovski (1989), Schombert (1992) and Jordán et al. (2004).

According to one of the proposed scenarios, BCGs are formed in cluster cooling flows, when the gas density has grown enough to cool and condense, leading to star formation in the cluster core (Silk 1976; Cowie & Binney 1977; Fabian 1994). In this scenario there should be color gradients of the optical haloes in the sense that the latter should become redder with increasing radius. However, such gradients have not been found (Andreon et al. 1992). Also, the finding that the X-ray gas does not cool significantly below a threshold temperature of $kT \approx 1-2\,\mathrm{keV}$ (Kaastra et al. 2001; Peterson et al. 2001; Tamura et al. 2001) puts this possibility of cD formation in doubt.

The second hypothesis on the formation of cDs supposes a rapid merging of galaxies during cluster collapse (e.g., Merritt 1983). However, as Merritt (1985) argues, the truncation of galaxy haloes during cluster collapse would lead to time scales for dynamical friction longer than a Hubble time and thus "turn off" subsequent evolution in the cluster, i.e. the growth rates after the cluster's virialization are slowed down. Also, according to simulations made by Dubinski (1998), the central galaxy does not develop the extended envelope that is characteristic of cD galaxies.

cD galaxies which formed by the above-mentioned scenarios are expected to be located near to the centres of their host cluster and are expected to have a radial velocity close to the mean of the cluster galaxies. Meanwhile, some cDs are located at an appreciable projected distance from the geometric centre of the cluster and their median absolute peculiar velocity with respect to their host cluster's mean velocity is ∼27% of the host cluster's velocity dispersion

⋆ E-mail: hrant@inaoep.mx (HMT); heinz@astro.ugto.mx (HA)

(e.g. Oegerle & Hill 2001, Coziol et al. 2009, and references therein). This fact poses problems for the mentioned mechanisms of formation of BCGs.

The third hypothesis for the cD formation is *galactic cannibalism* (Ostriker & Hausman 1977; Searle, Sargent & Bagnuolo 1973; Ostriker, & Tremaine, 1975; Hausman & Ostriker 1978; White 1976; Dressler 1980; Barnes 1989; Baier & Schmidt 1992; Garijo et al. 1997). It appears to be the one that is most compatible with observational evidence. According to this mechanism, cDs are formed as a result of galaxies falling in along primordial filaments and their subsequent merging (e.g. West et al. 1995; Fuller et al. 1999; Garijo et al. 1997; Dubinski 1998; Knebe et al. 2004; Torlina et al. 2007). The weak trend of the optical major axis of the BCGs to be aligned with their parent clusters' major axes (Binggeli 1982; Struble 1987; Rhee & Katgert 1987; Lambas, Groth, & Peebles 1988) supports the hypothesis of the formation of the former as a result of hierarchical merging (Niederste-Ostholt et al. 2010). Mergers of red galaxies, apparently without significant merger-triggered star formation (dry mergers), have been observed at low redshift (e.g. van Dokkum 2005). According to Aragon-Salamanca et al. (1998), Gao et al. (2004), De Lucia & Blaizot (2007), the stellar mass of BCGs grows by a factor of between 3 and 4 via mergers since $z = 1$. On the other hand, it has been argued (e.g. Merritt 1985; Tremaine 1990) that the observed dominance of BCGs cannot be achieved via cannibalism of other cluster members, since the high velocity dispersion of clusters makes frequent merging of galaxies unlikely. By studying the surface brightness and color profiles of a few cD galaxies and analysis of their globular cluster systems Jordán et al. (2004) concluded that cDs appear to have formed rapidly (e.g., Dubinski 1998) at early times, via hierarchical merging prior to cluster virialization.

A related mechanism for formation of cDs involves tidal stripping by cluster galaxies which pass near the cluster centre. The stripped material falls to the centre of the potential well and may form the halo of the giant galaxy there (Gallagher & Ostriker 1972; Richstone 1975, 1976). Garijo et al. (1997) mention that this theory cannot explain, however, the difference between central dominant cluster galaxies with and without a prominent halo, and that the velocity dispersion of stars in cD haloes is three times smaller than the velocity dispersion of galaxies in the cluster. So this theory has a difficulty in explaining why the tidally stripped material is slowed down as it builds up a cD halo.

In this paper we present arguments in favor of the cannibalism model of the formation of cD galaxies. We look for correlations between the cD luminosity and its host cluster parameters, including the number of its members, which was not considered in other models. Our emphasis is on the formation of cD galaxies in clusters of Bautz-Morgan (BM) type I (Bautz & Morgan 1970), since the performed analysis is applicable only to clusters with a single dominant galaxy. For comparison we considered a sample of clusters containing cD galaxies as well as one or more other galaxies of comparable luminosity, and call the latter clusters "non-BM I type" (or NBMI in what follows). The observational data we used allows us to suggest that clusters of BM I and NBM I types have different evolution histories.

2 THE DATA

In the analysis presented here we looked for possible correlations between the K-band luminosity of cD galaxies on the one hand, and the cluster richness and the velocity dispersion on the other. For the selection of clusters we started out from the compilation of BCGs in Abell clusters (Abell et al. 1989) by Coziol et al. (2009), using clusters of any BM type containing a cD galaxy, but restricting ourselves to clusters with redshift $z < 0.15$. In compiling our list we excluded all supplementary S-clusters, and exluded most clusters that had more than one significant redshift components along the line of sight. We required that the mean redshift be based on at least five spectroscopic members. However, in the analysis involving the cluster velocity dispersion σ_v we only used those clusters with at least 10 cluster member redshifts. We took the cluster velocity dispersions σ_v from the most recent version of the Abell cluster redshift compilation maintained by one of us (see Andernach et al. 2005 for a description). A few velocity dispersions were taken from a recent analysis by Zhang et al. (2011).

We used the Abell number count, N_A, as an indicator of the cluster richness. N_A is the number of galaxies in the magnitude range between m_3 and $m_3 + 2$, where m_3 is the apparent photored magnitude of the third-brightest cluster member, located within one Abell radius, R_A, of the cluster centre, where $R_A = 1.7'/z$. The values of N_A were taken from Abell et al. (1989) and were mostly based on estimated redshifts used to determine the Abell radii. Thus we understand that N_A is not a precise measure of the cluster richness. Nevertheless, it is an appropriate parameter, since it gives the number of galaxies in the central region of a cluster where merging of galaxies preferentially takes place. For those clusters which had other significant components at different redshift along the line of sight, we corrected the Abell count N_A downwards, in proportion to the number of measured redshifts in the component containing the cD galaxy, as compared to the number of redshifts in all components along the line of sight (see values marked with an asterisk in column 6 of table 1 below).

2.1 Definition of main and control sample

In our study we considered separately the BM I type clusters with a dominant cD galaxy and NBMI clusters. According to Bautz & Morgan (1970) the BM I clusters are defined as *clusters containing a centrally located cD galaxy.* In BM II types the brightest galaxies *are intermediate in appearance between class cD and the Virgo-type giant ellipticals.* BM III types were defined as *clusters containing no dominant galaxies.* We introduced a quanitative criterion to differentiate between clusters. We assumed a cD galaxy as dominant and the cluster as of BM I type, if the cD's K-band magnitude was brighter than the second-brightest cluster member by $\Delta K \geqslant 1.00^m$. This corresponds to a luminosity of the brightest galaxy 2.5 times higher than that of the second-brightest galaxy. When this "luminosity gap" was less than a factor of 1.9, i.e. the K-band magnitude difference was less than 0.70^m, we assumed that the cluster was of NBMI type. To avoid the ambiguity of finding the second-brightest galaxy in a cluster we imposed a lower limit of 0.035 for the cluster redshift. Since the clusters with a luminosity gap between the first and second-brightest galaxy in the range $0.7^m < \Delta K < 1.0^m$ may belong to either of the BM I or NBMI classes, we omitted these intermediate clusters. We list the luminosity gap ΔK between the cD and 2nd-brightest cluster member in column 4 of table 1.

For the determination of the cD galaxy luminosity we used the $K_{s-total}$ apparent magnitude from the 2MASS Extended Source Catalogue (Jarrett et al. 2000). The 2MASS magnitudes have been widely used in galaxy studies (e.g. Temi, Brighenti, & Mathews 2008; Courteau et al. 2007; Masters, Springob, & Huchra, 2008, etc.). The K band is more appropriate for our study, since it encompasses the light of the predominantly red population in early-type galaxies. Note that Lauer et al. (2007) showed that 2MASS photometry is free from possible errors which may be caused by the sky background subtraction and crowding. The most important inconsistency may be produced by the extrapolation scheme to generate "total magnitudes" (Jarrett et al., 2000). Lin & Mohr (2004) used a correction scheme to extrapolate isophotal magnitudes to "total" magnitudes and showed that both schemes are consistent. Bell et al. (2003) mentioned that 2MASS magnitudes have problems in detecting the low surface brightness light, such as haloes of cD galaxies (e.g. Schombert 1988). In addition, Lauer et al. (2007) demonstrated that 2MASS photometry is likely to underestimate the total light from cDs. However, it is obvious that the errors in the 2MASS K-magnitudes may not create correlations of absolute magnitude M_K with the corresponding cluster parameters, N_A and σ_v, which also are determined with some errors. The errors may only increase the dispersion and thus dilute or even destroy the correlations we are seeking.

The absolute stellar magnitudes M_K of the cD galaxies were deduced using the mean redshift of their host cluster (Andernach et al. 2005), adopting a Hubble constant of $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. A correction for the Galactic extinction was introduced according to Schlegel, Finkbeiner & Davis (1998) as given in the NASA/IPAC Extragalactic Databae (NED, ned.ipac.caltech.edu), and the k-correction according to Kochanek et al. (2001).

2.2 Lists of BM I and NBMI type clusters

Based on the BCG compilation by Coziol et al. (2009), we inspected images of all clusters containing a BCG classified as a cD galaxy, and compared $K_{s-total}$ magnitudes of the brightest and second-brightest galaxies using NED's photometric data. During this inspection we found that a few clusters listed as of BM I type in Coziol et al. (2009) are in fact clusters of NBMI type according to our definition above. For example, in the supposed BM I type cluster A1839 the K magnitudes of the brightest (2MASX J14023276−0451249) and the second-brightest (2MASX J14023417−0449449) galaxies are about the same: 12.84^m and 12.81^m. We also found examples of the opposite case: the second-brightest galaxy (2MASX J14070976+0520132) in the supposed BM II type cluster A1864A is fainter than the cD (2MASX J14080526+0525030) by 1.15^m, so we consider the cluster as of BM I type.

In addition to the Coziol et al. (2009) sample of clusters we made use of an additional set of galaxies claimed to be cD galaxies in NED, kindly provided to one of us (H.A.) by

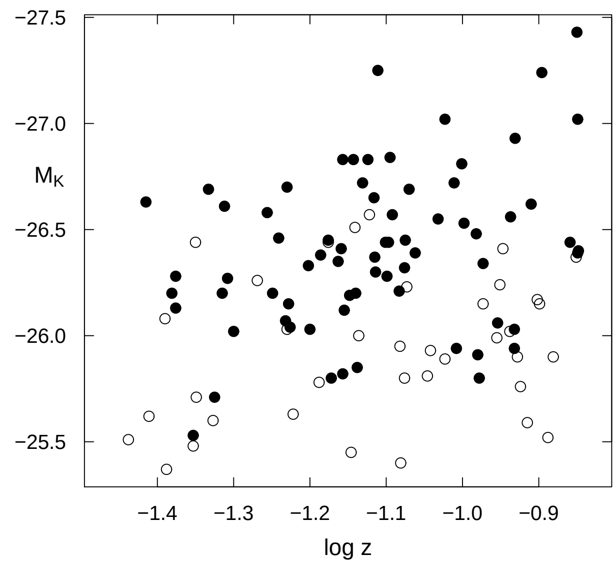

Figure 1. M_K absolute magnitude of cD galaxies versus redshift z in clusters of BM I type (filled circles) and NBMI type (open circles).

H.G. Corwin Jr. in 2006. We inspected Digitized Sky Survey images of those cDs that are located within Abell clusters of a sufficient number of measured redshifts. As a result we compiled a list of 70 cDs in clusters of BM I type and of 37 cDs in clusters of NBMI type, presented in Table 1. Twenty-one intermediate-type clusters out of 128 listed in Table 1 were omitted from the analysis.

3 RESULTS

In this section we discuss the correlations between six different pairs of parameters we collected for our cluster sample.

(a) The distribution of absolute K-magnitudes of cD galaxies is shown in Figure 1, separately for BM I and NBMI clusters, versus the redshift of their host clusters. The luminosity of the most luminous cDs increases gradually with increasing redshift z, forming an upper envelope of the $z - M_K$ distribution. Less luminous cD galaxies are observed almost equally all over the considered redshift range.

(b) In Figure 2 we present the graphs of $logN_A$ vs. $log\ z$ separately for clusters of type BM I and NBMI. Figure 2 shows that the Abell number count N_A of both BM I and NBMI clusters is weakly rising with redshift. This reflects the well-known effect that at higher redshifts the poor clusters are missed and the relative fraction of rich clusters increases (Scott 1957; Postman et al. 1985). Over the considered redshift range of 0.035 to 0.15 the average N_A in BM I clusters increases from from $N_A \approx 43$ to $N_A \approx 74$. In the case of NBMI clusters N_A increases from approximately 49 to 77.

(c) Whiley et al. (2008) found a weak dependence of the cD luminosity on the velocity dispersion σ_v of the cluster. We looked for a correlation between the luminosity of the

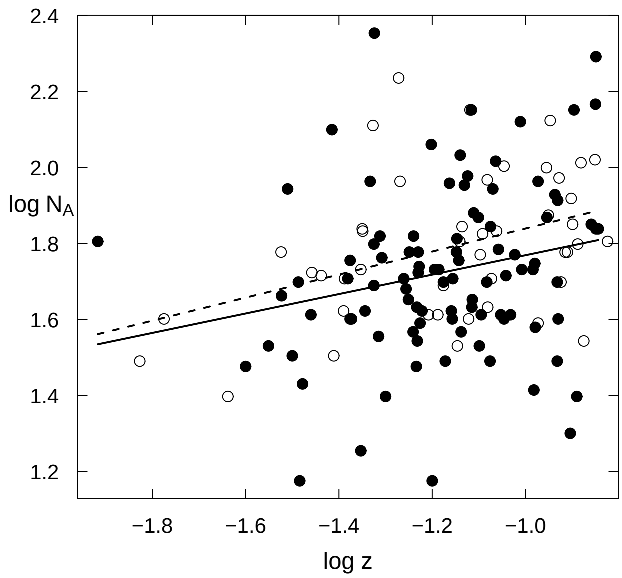

Figure 2. The Abell number count N_A of clusters of BM I and NBMI types that host the cD galaxy, versus the cluster redshift. Symbols are as in Fig. 1, and continuous and dashed regression lines correspond to BM I and NBMI clusters, respectively.

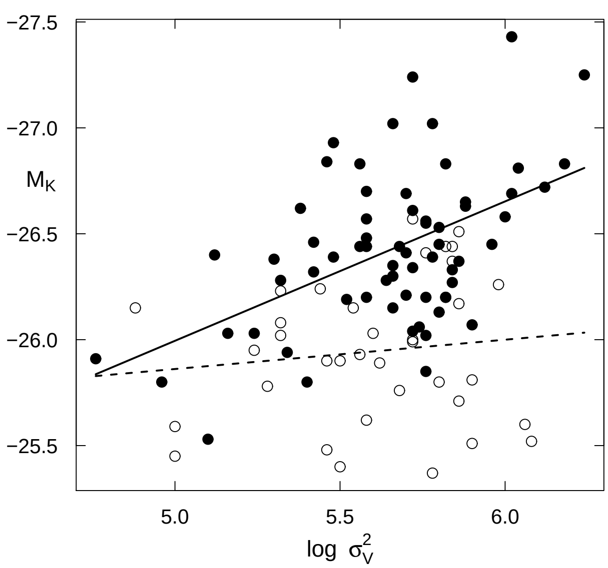

Figure 3. The absolute K-magnitude of cD galaxies versus the square of the velocity dispersion σ_v^2 of the parent clusters of BM I and NBMI types. Symbols are as in Fig. 1, and regression lines as in Fig. 2.

cD galaxy (expressed as M_K) and σ_v^2, since the mass M of a cluster depends on the square of the velocity dispersion of the parent cluster. Figure 3 shows that the M_K magnitude of cD galaxies in clusters of BM I type certainly correlates with σ_v^2, with a correlation coefficient of -0.50, and a regression slope of -0.65 ± 0.13. Meanwhile, the absolute magnitude M_K of the cD galaxies in NBMI clusters does not correlate with σ_v^2 of the cluster. The correlation coefficient is -0.12.

(d) A weak correlation between the BCG luminosity and

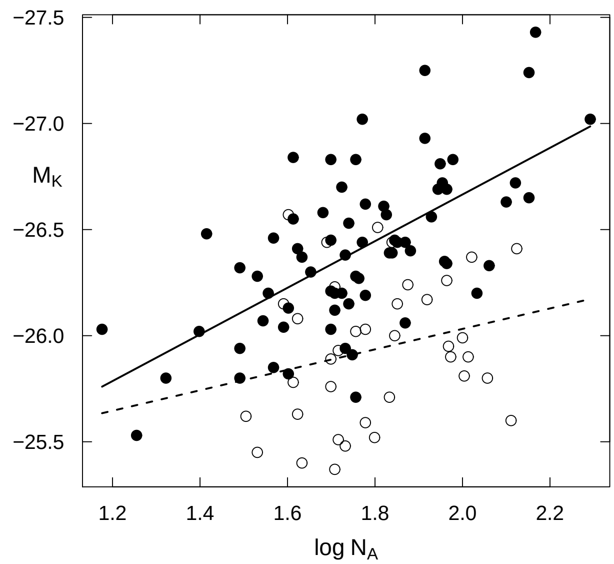

Figure 4. M_K absolute magnitude of cD galaxies versus the Abell number count, N_A, of clusters of BM I and NBMI types that host a cD galaxy. Symbols are as in Fig. 1, and regression lines as in Fig. 2.

cluster richness has been found previously (e.g. Schneider, Gunn, & Hoessel 1983; Schombert 1987). In Figure 4 we plot the absolute M_K-magnitude of cD galaxies versus the corresponding N_A of their host clusters separately for BM I and NBMI types. Figure 4 shows that the K-band luminosity of cDs in clusters of BM I type correlates with N_A. The correlation coefficient is -0.63, and the slope of the regression line is -1.10 ± 0.16. Meanwhile, the luminosity of cDs in NBMI clusters shows a weaker dependence on the cluster richness, with a correlation coefficient of -0.23 and a slope of -0.48 ± 0.34.

(e) One may expect that the velocity dispersion of a cluster would depend on its richness. In Figure 5 we present the graph $logN_A$ vs. $log\sigma_v$ separately for clusters of BM I and NBMI types. It shows that the velocity dispersion of both BM I and NBMI clusters increases with increassing cluster richness. The correlation coefficients are about the same, 0.43 and 0.46, respectively. The slopes are different: 0.28 ± 0.06 for clusters of BM I type and steeper, 0.41 ± 0.13 for NBMIs.

(f) It has been found that some cD galaxies have peculiar velocities, defined as the difference between the BCG and the cluster mean radial velocity: $v_{pec} = (v_{BCG} - cz_{cl})/(1 + z_{cl})$. In some clusters these peculiar velocities may reach significant fractions of the cluster velocity dispersion (Sharples, Ellis, & Gray 1988; Hill et al. 1988; Oegerle & Hill 1994; Pimbblet, Roseboom, & Doyle 2006; Coziol et al. 2009). We tried to find out whether the cD galaxy luminosity depends on its peculiar velocity. In Figure 6 we plot M_K vs. $log\,|v_{pec}|$ for cDs in clusters of BM I and NBMI types. Figure 6 shows that the K-band luminosity of cD galaxies in BM I clusters increases with v_{pec}, but shows the opposite trend in NBMI clusters. We omitted the cluster A2657 from this plot because for its very low $v_{pec} \approx 0$, placing it far from the bulk of the other clusters. The correlation coefficients for

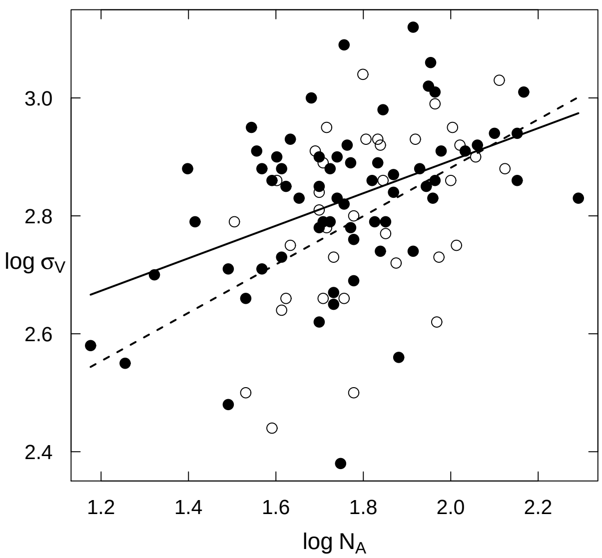

Figure 5. The cluster velocity dispersion, σ_V, versus the Abell number count N_A for clusters of BM I and NBMI types. Symbols are as in Fig. 1, and regression lines as in Fig. 2.

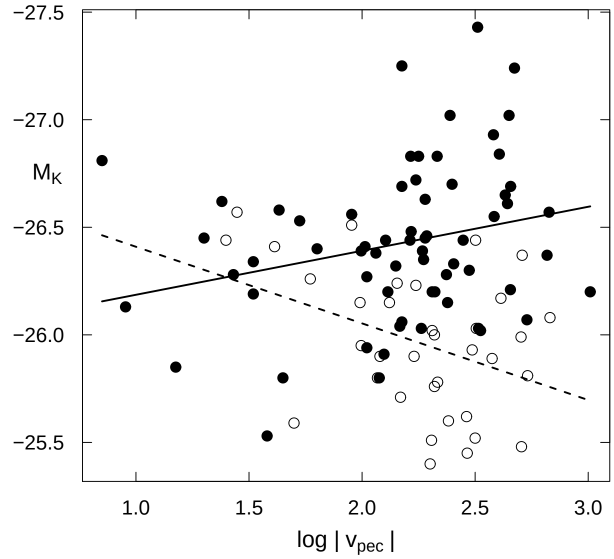

Figure 6. cD luminosity M_K vs. the peculiar velocity for cD galaxies in clusters of BM I and NBMI types. Symbols are as in Fig. 1, and regression lines as in Fig. 2.

both samples are low, -0.25 and 0.39 respectively, while the slopes of the regression lines, -0.21 ± 0.11 and 0.36 ± 0.15 respectively, differ significantly from each other.

Note that the correlations found in the above items (a) to (f) are revealed in spite of possible errors in the used parameters of clusters. Obviously, the errors may only weaken any existing correlations.

We wish to note also that for Figs. 2–6 we used the "robust fitting of linear models" (`rlm` in the R software package), and in all cases the robust fit was indistinguishable from the standard linear model (`lm`), i.e. it differed much less than the errors of the fit parameters. In what follows we shall discuss seven aspects which we find to support our conclusions.

4 DISCUSSION AND CONCLUSIONS

As mentioned above, we define a BM I type cluster as one with a single dominant cD galaxy, and a NBMI type cluster as one that contains one or more galaxies with luminosities comparable to that of the cD galaxy. In this section we argue that the correlations we found between the parameters of cD galaxies and their parent clusters not only reveal differences in the formation histories between BM I and NBMI type clusters, but also favor the cannibalism model for the cD galaxy formation.

1. Different evolution histories of BM I and non-BM I clusters hosting a cD galaxy

According to hierarchical model, clusters evolve by merging with groups of galaxies and other clusters (e.g. Merritt, 1984; Zabludoff & Mulchaey, 1998). We found that clusters of BM I and NBMI types have different properties that give clues to their different evolution histories.

The dependence of the K-band luminosity of cD galaxies on the host cluster richness expressed by the Abell number count N_A is stronger in BM I clusters (cf. Fig. 4). The slope of the regression line of the correlation $N_A - M_K$ in BM I clusters is -1.10, while in NBMI clusters the slope is only -0.48. Also the cD galaxy luminosity hosted in BM I clusters depends on the cluster velocity dispersion, σ_v^2 (Fig. 3). The correlation coefficient is -0.50, and the slope of the regression line is -0.65. Meanwhile, the cD luminosity in NBMI clusters does not depend on the host cluster velocity dispersion.

The correlations of the cD luminosity with the parent cluster parameters for BM I clusters allow us to suggest that cD galaxies in these clusters were formed and evolved preferentially within one and the same cluster. The absence of the cD luminosity correlations with the parent cluster parameters for NBMI type clusters shows that the cD galaxy in them was formed in a cluster that is in the process of merging with another cluster, or has already merged with other groups or clusters. The parameters of the composite cluster will obviously differ from those of the *initial* cluster in which the cD galaxy was formed, and correlations observed in BM I clusters will be weakened or erased in composite NBMI clusters. Also, the velocity dispersion of the composite cluster will not be proportional to the cluster mass.

We suppose that the luminosity of the cD galaxy formed in the initial cluster would fit the correlations seen in Figures 3 an 4. Merging of other groups and clusters with the initial cluster will increase the richness and velocity dispersion of the resulting observed cluster, while the luminosity of the cD galaxy will remain the same. The richer and more massive the initial cluster is, (and consequently the brighter the formed cD galaxy), the more groups will merge with it, the larger will be the increase of richness and velocity dispersion, and the farther to the right from the regression line determined by BM I clusters in Figures 3 and 4 the corresponding point will be located. As a result, the slope of the regression line of M_K vs. N_A for NBMI clusters will decrease.

Since the correlation between M_K and σ_v^2 for BM I clusters is generally weaker, the correlation for NBMI clusters even disappears.

The steeper slope of the regression line for NBMI clusters in Figure 5 also favors the suggestion made on the different evolution histories of BM I and NBMI clusters. Merging of groups and clusters with the initial cluster will increase the richness and velocity dispersion of the observed cluster. If the mean velocity of member galaxies of merged groups differs significantly from that of the initial cluster, the increase of the velocity dispersion will obviously be stronger than the increase in richness. Therefore, the slope of the regression line for NBMI clusters in the graph $N_A - \sigma_v$ becomes steeper than for BM I type clusters.

The cluster(s) that merge with the initial cluster (forming the cD) are generally poorer, and their brightest galaxy will usually be fainter than the cD galaxy in the initial cluster. However, it is possible that the luminosity of the BCG in the cluster that merges with the initial one is comparable to, or even brighter than that of the cD galaxy. This may be the case for some NBMI clusters in our sample (A1736B, A2051, A2969) where the cD galaxy is even fainter than the brightest galaxy formed in the merged (currently seen) cluster.

If the clusters of BM I and NBMI types indeed have different evolution histories, and the velocity dispersion of NBMI clusters is not proportional to cluster mass, then one may expect that the X-ray properties of both types of clusters will be different. In order to check this conjecture we compared the dependence of X-ray luminosity on the cluster velocity dispersion for both types of clusters. In Figure 7 we plot the cluster X-ray luminosity, $log\, L_{X,500}$, versus σ_v for BM I and NBMI clusters. $L_{X,500}$ is the luminosity within r_{500}, the radius within which the mean overdensity of the cluster is 500 times the critical density of the Universe at the cluster redshift, as published by Piffaretti et al. (2011). Figure 7 shows that, as we expected, the X-ray luminosity of NBMI clusters does not depend on the velocity dispersion, while in BM I clusters it does. The correlation coefficient is 0.45, and the slope of the regression line, i.e. the power in the $L_{X,500} \propto \sigma_v^x$ is $x = 1.60 \pm 0.57$.

We conclude that clusters of BM I and NBMI types have different evolution histories.

2. Luminosity difference between cD galaxies in BM I and NBMI clusters

One may expect that cD galaxies formed and evolved in a single rich cluster may be brighter than those cDs that were formed in relatively poor clusters that later merged with other galaxy groups or clusters. Indeed, Figure 1 shows that cD galaxies in BM I clusters are more luminous than those formed in NBMI clusters: the mean M_K of cDs in clusters of BM I type is -26.40 ± 0.09 (95% confidence), while that of cDs in NBMI clusters, -25.94 ± 0.10 (95% confidence), is fainter. The Kolmogorov-Smirnov (KS) and Mann-Whitney U (MWU) two-tailed tests show that the two samples of M_K magnitudes are significantly different ($P_{KS} = 0.00001$ and $P_{MWU} < 0.0001$). If we restrict both samples to the most luminous cDs with $M_K < -26.0$, then the mean M_K of cDs in BM I clusters will be -26.49 ± 0.08, and in NBMIs -26.27 ± 0.10 (both 95% confidence), i.e.

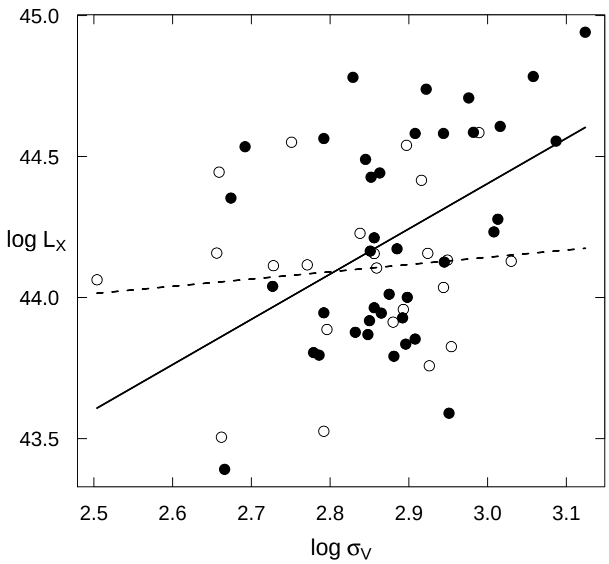

Figure 7. The cluster X-ray luminosity (within r_{500} and in units of erg s^{-1}) versus the velocity dispersion σ_v for clusters of BM I and NBMI types. Symbols are as in Fig. 1, and regression lines as in Fig. 2.

there is still a luminosity difference in this restricted sample. Hence, different luminosities of cD galaxies in BM I and NBMI clusters favor the suggestion of different evolution histories of the two types of clusters.

3. Dependence of the cD galaxy luminosity on its peculiar velocity

Figure 6 shows that the luminosity of the cD galaxy in clusters of BM I type increases with the peculiar velocity of the cD galaxy, while it shows the opposite trend in clusters of NBMI clusters. A different dependence of the cD luminosity on its peculiar velocity in clusters of BM I and NBMI clusters is explained in the assumed model of different evolution of BM I and NBMI clusters.

We suggest that the increase of the cD galaxy luminosity hosted in BM I clusters may be explained in the following way. The cD galaxy may be formed not at the exact gravitational centre of the corresponding cluster and will oscillate about it (Quintana & Lawrie, 1982). The higher the velocity of its movement, the more chances it will have to encounter with other members of the cluster and the larger will be the number of galaxy mergers. Therefore, cDs with higher peculiar velocity become more luminous. This fact favors the cannibalism model of the cD galaxy formation.

We found that the cD luminosity hosted in BM I clusters depends on the cluster richness (cf. Fig. 4). Obviously the same must be the case in the initial cluster that later became of NBMI type after its merging with other groups or clusters. The poorer the initial cluster, the fainter will be the formed cD galaxy. At the same time, the richer the merged cluster, the higher will be the peculiar velocity of the cD galaxy, since the mean redshift of the merged cluster will differ more from the redshift of the initial cluster. Therefore, the fainter the cD luminosity, the higher may be its peculiar velocity, which is consistent with Fig. 6. This supports the conclusion we made on the different evolution histories of clusters of BM I and NBMI types. WE note also that cD galaxies in NBMI clusters may be located far from the bottom of the gravitational well of the cluster. The projected separation of the BCG from the X-ray peak of the corresponding cluster was measured by Hudson et al. (2010). Among the brightest galaxies with a large separation there are clusters common to our list: A0754, A1736 and A3376 with separations of 714, 642 and 939 kpc, respectively. The first two are of NBMI type, and the third one, A3376, by its $\Delta K = 0.73$ value is close to an NBMI cluster, but for the sake of reliability, we excluded this cluster from our analysis. Hence, this fact also supports the suggested hypothesis on different evolution of BM I and NBMI clusters.

4. The difference of merging efficiency on cluster richness and velocity dispersion

According to all models of cD galaxy formation, the cD luminosity depends on the parent cluster mass. This is the case when the cD was formed in the cluster cooling flow or by a rapid merging of galaxies during cluster collapse. According to the cannibalism model, the higher the cluster mass, the stronger will be the gravitational force towards the cluster center, and consequently more member galaxies will be attracted to the central area and may be cannibalized.

The mass of a cluster may be estimated from its velocity dispersion. The cluster mass may be estimated also from the number of its member galaxies, characterized by the Abell number count N_A. Both parameters, σ_v and N_A, are correlated (cf. Fig. 5). In the following paragraph we show that the cluster richness is more decisive for the formation of a cD galaxy.

The luminosity of the cD galaxy depends on the richness N_A of the host cluster. According to the regression line in Figure 4, an increase of M_K by one magnitude from -25.8 to -26.8 in BM I clusters corresponds to an increase of N_A from 16 to 138. According to the regression line in Figure 5, an increase of N_A from 16 to 138 corresponds to an increase of σ_v from 468 km s^{-1} to 840 km s^{-1}, i.e. by 1.8 times. If the effectiveness of the cluster richness and the velocity dispersion for the formation of the cD galaxy are about the same, we may expect that for an increase of the luminosity from -25.8 to -26.8 the velocity dispersion must increase by about 1.8 times. However, the regression line in Figure 3 shows that for such an increase of M_K the velocity dispersion increases in fact from 190 km s^{-1} to 1340 km s^{-1}, i.e. by 7.1 times. This means that the cluster richness is by $7.1/1.8 \approx 4$ times more effective for the cD formation than the velocity dispersion which is commonly used to estimate the cluster mass.

This finding strongly favors the cannibalism model of the cD galaxy formation. The higher the BM I cluster richness, the more of its members may be cannibalized, and the more luminous will be the resulting cD galaxy. Hence, the cluster richness, i.e. the number of member galaxies, plays a more decisive role in the cD formation than the cluster mass determined by velocity dispersion. Models for cD formation other than the cannibalism scenario do not differentiate between the mass of the cluster and the number of its members.

It is evident that in NBMI clusters the luminosity of the cD galaxy formed in the initial cluster may not depend on the parameters of the (presently) observed cluster formed as a result of merging of the initial cluster with other galaxy groups or clusters.

5. Rough estimate of the number of galaxies merged to form the cD

Suggesting that cD galaxies were assembled through the so-called dissipationless "dry" mergers of gas-poor, bulge-dominated systems (Tran et al. 2005; van Dokkum 2005; Bell et al. 2006; De Lucia et al. 2006; Bernardi et al. 2007) we roughly estimate the number N_m of merged galaxies required to form the observed cD. Dry mergers are consistent with the high central densities of ellipticals and their old stellar populations. If mergers are responsible for the formation of BCGs, then, as has been shown by several authors (Malumuth & Richstone 1984 and references therein), the luminosity growth will be at the expense of fainter members. Assuming that the merged galaxies are ordinary faint galaxies, with an absolute magnitude $M_{K(isol)} = -22.7$ (see Tovmassian, Plionis & Andernach 2004) for isolated E/S0 galaxies, we estimate that the faintest cD with $M_K \approx -25.5$ are formed by the assembly of only about 13 galaxies with a mean luminosity of an isolated E/S0 galaxy. The most luminous cDs with $M_K \approx -27.5$ are formed by merging of about 80 ordinary E/S0 galaxies.

6. The rate of galaxy merging in poor and rich clusters

Merritt (1985) and Tremaine (1990) showed that the efficiency of merging depends on the cluster velocity dispersion σ_v in the sense that a high velocity dispersion will prevent frequent merging. In agreement with this, Forman & Jones (1982), and Schombert (1987) mentioned that a cluster with a lower velocity dispersion would have a higher rate of mergers.

We compared the velocity dispersion σ_v of clusters of BM I type located near to the lower and upper envelopes of the $M_K - z$ distribution in Figure 1. The mean σ_v for 7 clusters with the least luminous cDs and known σ_v (A0912A, A1076, A1227A, A2110, A2170B, A2544, A3104) is 504 ± 176 km s^{-1}. These clusters are poor. Their mean N_A is 41 ± 18. The mean σ_v for 12 clusters with the most luminous cDs in Figure 1 (A0085A, A0399, A0655, A0690A, A1146, A1644, A1738, A2420, A2457, A3112B, A3571, A4059) is 819 ± 215 km s^{-1}. The mean N_A of these clusters is 86 ± 35. The MWU two-tailed tests show that the difference of the velocity dispersion σ_v of these two subsamples is highly significant $P_{MWU} = 0.0128$). Hence, the process of merging is fast in poor clusters of BM I type with small velocity dispersion. The situation is different in clusters of NBMI type, where no difference of σ_v of clusters with the most and least luminous cD galaxies is observed. The mean σ_v of the 12 NBMI clusters hosting most luminous cD galaxies (median $M_K = -26.3$) is 706 ± 195 km s^{-1} and that of the 9 clusters with the least luminous cD galaxies (median $M_K = -25.5$) is 688 ± 276 km s^{-1}.

7. The evolution of cD galaxies in rich and poor clusters

The evolution of cD galaxies in BM I clusters may be followed in the frames of the adopted cannibalism model in Figure 1. Our Figure 2 suggests that clusters at low redshift are poorer on average. However, part if this can be explained by the fact that rich clusters are rare and the local volume is small. Since the velocity dispersion of poor clusters is small, the process of merging in them is fast. At the same time, the reservoir of galaxies for merging is also small. Therefore, the process of luminosity increase in cD galaxies in poor clusters terminates in a relatively short time, and it may reach only a modest luminosity. The final stage of poor clusters may be a fossil group (Tovmassian 2010). Thus, cD galaxies in nearby poor clusters almost reached their possible maximum, rather low luminosity.

The mean N_A of the five poorest BM I clusters with $z < 0.05$ (A0912A, A1308A, A2271, A0376, A1890) is $30{\pm}8$, and that of the five poorest clusters in our highest distance range ($0.11 < z < 0.15$; A0038, A1023, A1068, A1076, A3854A) is 56 ± 15. Thus, the distant poor clusters are relatively rich, the process of cannibalism in them probably still continues, and cDs in these clusters did not yet reach their possible maximum luminosity.

The situation is different in rich clusters. The velocity dispersion of rich clusters is high. Therefore, the rate of merging in rich clusters is low and lasts longer also due to the larger reservoir of candidate galaxies for merging. The cD galaxies in rich clusters slowly move up in Figure 1, occupying almost uniformly the space from the smallest to the highest luminosities in each redshift range. Thus, the upper envelope of this distribution may be explained without invoking the Malmquist bias, but simply by the fact that cDs are observed in clusters of different richness and assuming cannibalism for their formation

Hence, the observational data favor the cannibalism model of the cD galaxy formation. We conclude that cD galaxies in clusters of BM I type were formed and evolved in one and the same cluster. We suggest also that cDs in NBMI clusters were originally formed in poorer cluster and are observed now in clusters that were formed by merging with other galaxy groups and clusters.

ACKNOWLEDGEMENTS

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propolsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The figures were created within the "R" software package (cran.r-project.org) and we thank R. A. Ortega Minakata for advice in producing these. We thank the anonymous referee whose comments helped us to substantially improve the paper.

REFERENCES

Abell G.O., Corwin Jr., H.G., Olowin R.P. 1989, ApJS, 70, 1
Andernach H., Tago E., Einasto M., Einasto J., Jaaniste J., 2005, Nearby Large-Scale Structures and the Zone of Avoidance, eds. A.P. Fairall & P. Woudt, ASP Conf. Series 329, 283
Andreon S., Garilli B., Maccagni D., Gregorini L., Vettolani G., 1992, A&A, 266, 127
Aragon-Salamanca A., Baugh C.M., Kauffmann G., 1998, MNRAS, 297, 427
Baier F.W., Schmidt K.-H., AN, 1992, 313, 275
Barnes J.E., 1989, Nature 338, 123
Bautz L., Morgan W.W., 1970, ApJ, 162, L149
Bell E.F., McIntosh D.H., Katz N., Weinberg M.D. 2003, ApJS, 149, 289
Bell E.F., et al. 2006, ApJ, 640, 241
Bernardi M., Hyde J.B., Sheth R.K., Miller C.J., Nichol R.C. 2007, AJ, 133, 1741
Binggeli B., 1982, A&A, 107, 338
Courteau S., Dutton A.A., van den Bosch F.C., MacArthur L.A., Dekel A., McIntosh D.H., Dale D.A. 2007, ApJ, 671, 203
Cowie L.L., Binney J., 1977, ApJ, 215, 723
Coziol R., Andernach H., Caretta C.A., Alamo Martínez K.A., Tago E., 2009, AJ, 137, 4795
De Lucia G., Springel V., White S.D.M., Croton D., Kauffmann G., 2006, MNRAS, 366, 499
De Lucia G., Blaizot J., 2007, MNRAS, 375, 2
Dressler A., 1980, ApJ, 236, 351
Dubinski J., 1998, ApJ, 502, 141
Fabian A.C., 1994, ARA&A, 32, 277
Forman W, Jones C. 1982, ARA&A, 20, 547
Fuller T.M., West M.J., Bridges T.J., 1999, ApJ, 519, 22
Gallagher J.S., Ostriker J.P., 1972, AJ, 77, 288
Gao L., Loeb A., Peebles P.J.E., White S.D.M., Jenkins A., 2004, ApJ, 614, 17
Garijo A., Athanassoula E., Garcia-Gómez C., 1997, A&A, 327, 930
Hansen S.M., Sheldon E.S., Wechsler R.H., Koester B.P., 2009, ApJ, 699, 1333
Hausman M.A., Ostriker J.P., 1978, ApJ, 224, 320
Hill J.M., Hintzen P., Oegerle W.R., Romanishin W., Lesser M.P., Eisenhamer J.D., Batuski D.J. 1988, ApJ, 332, L23
Hudson D.S., Mittal R., Reiprich T.H., Nulsen P.E.J., Andernach H., Sarazin C.L., 2010, A&A 513, A37
Jarrett T.H., Chester T., Cutri R, Schneider S., Skrutskie M., Huchra J.P., 2000, AJ, 119, 2498
Jordán A., Côté P., West M.J., Marzke R.O., Minniti D., Rejkuba M. 2004, AJ, 127 24
Kaastra J.S., Ferrigno C., Tamura T., Paerels F.B.S., Peterson J.R., Mittaz J.P.D. 2001, A&A, 365, L99
Knebe A., Gill S.P.D., Gibson B.K., Lewis G.F., Ibata R.A., Dopita M.A., 2004, ApJ, 603, 7
Kochanek C.S., Pahre M.A., Falco E.E. et al., 2001, ApJ, 560, 566
Kormendy J., Djorgovski S., 1989, ARA&A, 27, 235
Lambas D., Groth E.J., Peebles P.J.E., 1988, AJ, 95, 996
Lauer T.R., Faber S.M., Richstone D. et al., 2007, ApJ, 662, 808
Lin Y.-T., Mohr J.J., 2004, ApJ, 617, 879
Malumuth E.M., Richstone D.O., 1984, ApJ, 276, 413
Masters K.L., Springob C.M., Huchra J.P., 2008, AJ, 135, 1738
Matthews T.A., Morgan W.W., Schmidt M. 1964, ApJ, 140, 35
Merritt D., 1983, ApJ, 264, 24
Merritt D., 1984, ApJ, 276, 26

Merritt D., 1985, ApJ, 289, 18
Niederste-Ostholt M., Strauss M.A., Dong F., Koester B.P., McKay T.A., 2010, MNRAS, 405, 2023
Oegerle W.R., Hill J.M. 1994, AJ, 107, 857
Oegerle W.R., Hill J.M. 2001, AJ, 122, 2858
Ostriker J.P., Tremaine S.D., 1975, ApJ, 202, L113
Ostriker J.P., Hausman M.A. 1977, ApJ, 217, L125
Peterson J.R., Paerels F.B.S., Kaastra J.S. et al. 2001, A&A, 365, L104
Piffaretti R., Arnaud M., Pratt G.W., Pointecouteau E., Melin J.-B., 2011, A&A, 534, A109
Pimbblet K.A., Roseboom I.G., Doyle M.T., 2006, MNRAS, 368, 651
Postman M., Huchra J.P., Geller M.J., 1985, AJ, 90, 1400
Quintana H., Lawrie D.C., 1982, 97, 1
Rhee G., Katgert P., 1987, A&A, 183, 217
Richstone D.O., 1975, ApJ, 200, 535
Richstone D.O., 1976, ApJ, 204, 642
Searle L., Sargent W.L.W., Bagnuolo W.G., 1973, ApJ, 179, 427
Schlegel D.J., Finkbeiner D.P., Davis M., 1998, ApJ, 500, 525
Schneider D., Gunn J.E., Hoessel J.G., 1983, ApJ, 268, 476
Schombert J.M., 1987, ApJS, 64, 643
Schombert J.M., 1988, ApJ, 328, 475
Schombert J.M., 1992, in *Morphological and Physical Classification of Galaxies*, Dordrecht: Kluwer Academic Publishers, eds. G. Longo, M. Capaccioli, G. Busarello, Astrophysics and Space Science Library, 178, p. 53 (cf. also `ned.ipac.caltech.edu/level5/March07/Schombert/frames.html`)
Scott E.L., 1957, AJ 62, 248
Sharples R.M., Ellis R.S., Gray P.M., 1988, MNRAS, 231, 479
Silk J., 1976, ApJ, 208, 646
Struble M.F., 1987, ApJ, 317, 688
Tamura T., Kaastra J.S., Peterson J.R. et al. 2001, A&A, 365, L87
Temi P., Brighenti F., Mathews W.G., 2008, ApJ, 672, 244
Tonry J.L. 1987, Structure and Dynamics of Elliptical Galaxies, ed. T. de Zeeuw, IAU Symp. 127, 89, Reidel, Dordrecht
Torlina L., De Propris R.D., West M.J., 2007, ApJ, 660, L97
Tovmassian H.M., 2010, RMxA&A, 46, 61
Tovmassian H.M., Plionis M., Andernach H., 2004, ApJ, 617, L111
Tran K.-V. H., van Dokkum P., Illingworth G.D., Kelson D., Gonzalez A., Franx M., 2005, ApJ, 619, 134
Tremaine S., 1990, Dynamics and Interactions of Galaxies, ed. R. Wielen, p. 394, Springer Verlag, Berlin
Tutukov A.V., Dryumov V.V., Dryumova G.N., 2007, Astronomy Reports 51, 435
van Dokkum P.G., 2005, AJ, 130, 2647
von der Linden A., Best P.N., Kauffmann G., White S.D.M., 2007, MNRAS, 379, 867
West M.J., Jones C., Forman W., 1995, ApJ, 451, L5
Whiley I.M., Aragon-Salamanca A, De Lucia G. et al. 2008, MNRAS, 387, 1253
White S.D.M., 1976, MNRAS, 174, 19
Zabludoff A.L., Mulchaey J.S. 1998, ApJ, 496, 39
Zhang Y.-Y., Andernach H., Caretta C., Reiprich T.H., Böhringer H., Puchwein E., Sijacki D., Girardi M., 2011, A&A, 526, A105

Table 1. Data on the 70 clusters of type BM I, 21 of intermediate type, and 37 of type NBMI and corresponding cD galaxies as well as second-brightest galaxies. Table columns are as follows: (1) Abell cluster designation, appended by a letter indicating the cluster's component along the line of sight; (2) mean redshift of the cluster; (3) number of galaxies which were used to determine the mean cluster redshift; (4) difference in K-band magnitude between cD and 2nd-brightest galaxy; (5) absolute K-band magnitude, M_K, of the cD galaxy; (6) Abell number count N_A; "*" indicates a downward correction for an overlap of two or more redshift components of a cluster; (7) cluster velocity dispersion σ_v; (8) peculiar velocity of cD galaxy; (9) NED name of cD galaxy; (10) NED name of 2nd-brightest galaxy.

Abell Cluster (1)	z (2)	N_z (3)	ΔK mag (4)	M_K mag (5)	N_A (6)	σ_v km s^{-1} (7)	v_{pec} km s^{-1} (8)	cD galaxy ID (9)	2nd-brighest galaxy ID (10)
Clusters of BM I type ($\Delta K \geqslant 1.00$ m):									
A0038	.1416	15	1.15	−26.39	69	544	−99	2MASX J00281984+1354596	2MASX J00280539+1347225
A0085A	.0554	355	1.61	−26.58	48*	1010	43	MCG −02−02−086	GIN 009
A0133A	.0563	137	1.69	−26.20	53*	760	204	ESO 541−G013	2MASX J01013597−2203488
A0150	.0591	17	1.50	−26.15	55	674	239	UGC 00716	2MASX J01085285+1320137
A0152A	.0594	88	1.67	−26.04	39*	724	−147	2MASX J01100320+1358417	2MASX J01100926+1407237
A0193	.0492	99	1.03	−26.27	58	840	−105	CGCG 411−049	CGCG 411−049
A0208A	.0796	66	1.12	−26.28	34*	456	−27	PGC 1169115	2MASX J01303645+0027305
A0225	.0701	8	1.46	−26.12	51			2MASX J01384892+1849311	2MASX J01384054+1848111
A0261A	.0473	9	1.69	−25.71	57*			2MASX J01512719−0215317	2MASX J01520129−0210478
A0279A	.0800	101	1.33	−26.44	59*	599	−280	MCG +00−06−002	2MASX J01570000+0103172
A0376	.0484	150	1.06	−26.20	36	810	210	UGC 02232	GIN 138
A0399	.0720	101	1.92	−26.83	57	1223	−164	UGC 02438	2MASX J02580300+1251138
A0401	.0739	116	1.04	−26.72	90	1144	173	UGC 02450	2MASX J02581064+1340419
A0415	.0810	14	1.89	−26.57	67	617	−671	2MASX J03065268−1206234	2MASX J03072144−1201357
A0644	.0693	44	1.13	−26.41	42	700	103	2MASX J08172559−0730455	2MASX J08172714−0736025
A0655	.1272	61	1.58	−27.24	142	729	472	2MASX J08252902+4707598	2MASX J08260055+4702348
A0690A	.0803	93	1.69	−26.84	41*	540	−405	2MASX J08391582+2850389	2MASX J08385000+2855172
A0705A	.1042	33	1.53	−26.48	26*	615	165	2MASX J08474520+3001335	2MASX J08482745+2952036
A0912A	.0444	18	1.65	−25.53	18*	356	38	CGCG 008−008	2MASX J09590714+0000385
A0941	.1048	13	1.12	−25.91	56	238	−125	2MASX J10094349+0337229	2MASX J10094422+0337499
A0971A	.0929	48	1.28	−26.55	41*	760	−384	2MASX J10195207+4059179	2MASX J10194571+4059389
A1004	.1418	13	1.30	−26.40	76	365	64	2MASX J10253527+5105541	2MASX J10254126+5106166
A1023	.1169	6	1.50	−25.94	31			LCRS B102528.0−063237	LCRS B102529.5−063045
A1068	.1382	13	1.12	−26.44	71	619	127	2MASX J10404446+3957117	2MASX J10403391+4003497
A1076	.1170	21	1.06	−26.03	50	420	183	2MASX J10451352+5808334	2MASX J10453036+5812322
A1146	.1412	72	1.48	−27.43	147	1019	−324	2MASX J11011449−2243525	2MASX J11013225−2247390
A1227A	.1113	45	1.18	−26.06	74*	733	150	2MASX J11213588+4802522	2MASX J11220532+4806152
A1302	.1156	58	1.70	−26.56	85	767	−90	2MASX J11331462+6622454	2MASX J11305335+6630438
A1308A	.0501	56	1.09	−26.02	25*	754	334	PGC 035654	2MASX J11325072−0347274
A1413	.1417	47	1.30	−27.02	196	674	245	2MASX J11551798+2324177	2MASX J11551747+2323287
A1516A	.0769	72	1.09	−26.30	45*	680	−298	2MASX J12185235+0514443	2MASX J12185824+0515163
A1644	.0465	307	1.23	−26.69	92	1030	150	2MASX J12571157−1724344	2MASX J12574919−1732431
A1651	.0841	222	1.28	−26.45	70	960	190	2MASX J12592251−0411460	2MASX J12593749−0406597
A1654	.0840	25	1.23	−26.32	31	512	141	2MASX J12592001+3001300	2MASX J12581976+2950557
A1663A	.0826	101	1.21	−26.21	50*	705	453	2MASX J13025254−0230590	2MASX J13025000−0226380
A1738	.1173	59	1.50	−26.93	82	546	−381	MCG +10−19−068	2MASX J13240096+5739160
A1795	.0628	179	1.04	−26.33	115	835	254	CGCG 162−010	2MASX J13482545+2624383
A1809A	.0793	132	1.01	−26.44	74*	690	−163	2MASX J13530637+0508586	2MASX J13523104+0456048
A1837	.0694	50	2.24	−26.83	50	601	−179	2MASX J14013635−1107431	2MASX J14012568−1109151
A1864A	.0867	61	1.15	−26.39	68*	771	185	2MASX J14080526+0525030	2MASX J14070976+0520132
A1890	.0574	94	1.60	−26.46	37	514	193	NGC 5539	NGC 5535
A1925	.1064	55	1.18	−26.34	92	718	33	2MASX J14283842+5651381	2MASX J14275634+5643558
A2029	.0775	202	1.85	−27.25	82	1330	150	IC 1101	2MASX J15110004+0546578
A2067A	.0767	171	1.41	−26.37	43*	850	−658	CGCG 165−049	2MASX J15234742+3111432
A2107	.0416	170	1.10	−26.20	51	611	130	UGC 09958	CGCG 136−050
A2110	.0981	53	1.24	−25.94	54	472	−105	2MASX J15395079+3043037	2MASX J15401322+3046338
A2124	.0667	118	2.00	−26.45	50	787	−20	UGC 10012	2MASX J15444687+3557004
A2170B	.1052	33	1.09	−25.80	21*	498	−45	2MASX J16165982+2311109	2MASX J16165866+2307549
A2228	.1005	30	1.66	−26.53	55	794	53	2MASX J16474406+2956314	2MASX J16480084+2956575
A2244	.0997	106	1.81	−26.81	89	1037	7	2MASX J17024247+3403363	2MASX J17021662+3358503
A2271	.0586	20	2.03	−26.07	35	894	−536	CGCG 355−030	2MASX J17182094+7802142
A2420	.0852	10	1.11	−26.69	88	712	−454	2MASX J22101878−1210141	2MASX J22100145−1219291
A2457	.0589	113	1.00	−26.70	53	620	−250	2MASX J22354078+0129053	2MASX J22352797+0128153
A2480	.0725	12	1.34	−26.20	108	806	−1020	2MASX J22455898−1737320	2MASX J22460031−1741210
A2544	.0673	11	1.57	−25.80	31	299	−119	2MASX J23101507−1047540	2MASX J23095939−1102380

Table 1. – continued

Abell Cluster (1)	z (2)	N_z (3)	ΔK mag (4)	M_K mag (5)	N_A (6)	σ_v km s^{-1} (7)	v_{pec} km s^{-1} (8)	cD galaxy ID (9)	2nd-brighest galaxy ID (10)
A2589	.0421	94	1.47	−26.13	40	790	−9	NGC 7647	2MASX J23235357+1652479
A2637	.0712	11	1.22	−26.19	60	579	33	2MASX J23385333+2127528	2MASX J23384222+2130038
A2670	.0766	256	1.08	−26.65	142	881	430	2MASX J23541371−1025084	2MASX J23534052−1024201
A2694	.0974	8	2.37	−26.72	132			2MASX J00022410+0823541	2MASX J00014206+0818145
A2700A	.0949	11	1.43	−27.02	41*	780	450	2MASX J00034964+0203594	2MASX J00032769+0207014
A3009	.0652	23	1.87	−26.38	54	447	115	2MASX J02220707−4833495	FAIRALL 0379
A3104	.0727	89	1.15	−25.85	37	750	−15	LCRS B031238.4−453620	LCRS B031257.9−453607
A3109A	.0631	10	1.05	−26.03	15*	378	−327	2MASX J03163934−4351169	2MASX J03160986−4333339
A3112B	.0751	112	1.39	−26.83	95*	810	215	ESO 248−G006	LCRS B031515.1−442704
A3120	.0697	6	1.30	−25.82	40			2MASX J03215645−5119357	2MASX J03223357−5127128
A3407	.0421	53	1.02	−26.28	57	658	−236	ESO 207−G019	2MASX J07035803−4904502
A3490	.0687	88	1.52	−26.35	91	680	−187	2MASX J11452010−3425596	2MASX J11453744−3420143
A3571	.0385	172	1.00	−26.63	126	880	−190	ESO 383−G076	2MASX J13485033−3309071
A3854A	.1231	23	1.25	−26.62	60*	492	−24	2MASX J22174585−3543293	2MASX J22182696−3526418
A4059	.0488	188	1.29	−26.61	66	718	440	ESO 349−G010	MCG −06−01−006
Clusters of intermediate type ($0.70\,m < \Delta K < 1.00\,m$):									
A0126	.0548	11	0.71	−25.79	51	530	−490	6dF J0059591−135943	2MASX J00595379−1414403
A0478	.0862	13	0.81	−26.45	104	944	−86	2MASX J04132526+1027551	2MASX J04125893+1035156
A0715	.1432	17	0.97	−26.27	69	994	−73	2MASX J08545745+3524513	2MASX J08543921+3522043
A1406B	.1175	15	0.92	−25.97	40*	332	143	2MASX J11530531+6753513	2MASX J11530926+6748103
A1668	.0638	95	0.83	−25.86	54	759	−113	IC 4130	IC 4139
A1749A	.0561	80	0.94	−26.06	45*	451	−28	IC 4269	IC 4271 NED01
A1767	.0713	159	0.79	−26.60	65	863	70	MCG +10−19−096	2MASX J13342636+5922256
A2128A	.0583	5	0.91	−26.06	30*			2MASX J15484313−0259344	2MASX J15484608−0309254
A2148	.0885	47	0.75	−26.01	41	489	425	GIN 478	GIN 484
A2401	.0576	35	0.91	−26.07	66	438	142	2MASX J21582246−2006145	PKS 2156−203
A2593A	.0424	121	0.83	−26.07	40*	644	110	NGC 7649	CGCG 431−056
A2622	.0620	57	0.99	−25.95	41	942	−171	PGC 071807	2MASX J23352311+2719220
A2626A	.0585	96	0.96	−26.36	43*	1057	−802	IC 5338	IC 5337
A2734	.0612	189	0.71	−26.14	58	879	200	ESO 409−G025	SARS 002.29825−29.21075
A2961A	.1246	24	0.99	−25.99	20*	539	−33	2MASX J02000056−3114133	2MASX J02000195−3119133
A2984	.1038	33	0.86	−26.05	54	571	318	ESO 298−G017	2MASX J02105846−4011169
A3301	.0534	38	0.82	−26.11	172	686	34	NGC 1759	2MASX J05013224−3844105
A3376	.0453	165	0.73	−25.90	42	831	−14	ESO 307−G013	2MASX J06020973−3956597
A3556	.0473	209	0.80	−26.28	49	698	22	ESO 444−G025	2MASX J13235763−3138453
A3558	.0474	509	0.88	−26.88	226	940	−302	ESO 444−G046	2MASX J13272961−3123237
A3998	.0899	17	0.72	−26.02	40	574	90	ESO 347−G009	LCRS B231932.9−421633
Clusters of NBMI type ($\Delta K \leqslant 0.70\,m$):									
A0076	.0407	13	0.34	−26.08	42	459	−677	IC 1565	IC 1568
A0119	.0447	339	0.53	−26.44	69	840	25	UGC 00579	UGC 583
A0367	.0899	33	0.38	−25.81	101	900	539	2MASX J02363713−1922168	2MASX J02362667−1915078
A0389	.1131	55	0.15	−26.41	133	759	41	2MASX J02512479−2456393	2MASX J02513267−2504233
A0754	.0538	470	0.57	−26.26	92	976	59	2MASX J09083238−0937470	2MASX J09101737−0937068
A1149	.0714	49	0.56	−25.45	34	313	−292	2MASX J11025750+0736136	2MASX J11031132+0741093
A1168	.0908	46	0.34	−25.93	52	597	307	2MASX J11071768+1551475	2MASX J11080366+1554133
A1222	.1120	45	0.43	−26.24	75	523	−143	2MASX J11201257+4711323	MCG +08−21−017
A1361	.1154	20	0.70	−26.02	57	456	204	2MASX J11433959+4621202	2MASX J11424122+4624363
A1630A	.0649	37	0.44	−25.78	41*	440	−216	CGCG 043−047 NED01	CGCG 043−044
A1650	.0836	220	0.40	−25.80	114	789	117	2MASX J12584149−0145410	2MASX J12583829−0134290
A1691	.0722	111	0.55	−26.51	64	843	90	MCG +07−27−039	2MASX J13100997+3909235
A1736B	.0448	148	−0.69	−25.71	68*	860	−148	ESO 509−G009	IC 4252
A1800	.0755	91	0.67	−26.57	40	723	28	UGC 08738	2MASX J13493157+2800016
A1814	.1262	39	0.67	−26.15	71	590	98	2MASX J13540294+1454409	2MASX J13534984+1445380
A1839	.1295	49	0.56	−25.52	63	1104	316	2MASX J14023276−0451249	2MASX J14025270−0445249
A1918B	.1408	23	0.48	−26.37	105*	825	−511	2MASX J14252238+6311524	2MASX J14252117+6309214
A1920	.1314	39	0.31	−25.90	103	562	−120	2MASX J14272450+5545009	2MASX J14270303+5553259
A1927	.0949	50	0.58	−25.89	50	650	376	2MASX J14310681+2538013	2MASX J14303458+2538495
A1991	.0589	135	0.69	−26.03	60	625	320	NGC 5778	CGCG 105−068
A2050	.1190	37	0.70	−25.76	50	688	−209	2MASX J15161794+0005203	2MASX J15160950+0014541

Table 1. – continued

Abell Cluster (1)	z (2)	N_z (3)	ΔK mag (4)	M_K mag (5)	N_A (6)	σ_v km s^{-1} (7)	v_{pec} km s^{-1} (8)	cD galaxy ID (9)	2nd-brighest galaxy ID (10)
A2051	.1180	54	−0.31	−25.90	94	535	170	2MASX J15164416−0058096	2MASX J15165808−0106394
A2079A	.0667	151	0.20	−26.44	49*	816	−318	UGC 09861 NED02	UGC 09861 NED01
A2089	.0731	105	0.69	−26.00	70	722	209	2MASX J15324982+2802224	2MASX J15325912+2753405
A2147	.0365	397	0.20	−25.51	52	890	−203	UGC 10143	UGC 10143 NOTES02
A2372	.0600	7	0.46	−25.63	42			2MASX J21451552−1959406	ESO 600− G 010
A2428	.0845	51	0.47	−26.23	51	453	173	2MASX J22161561−0919590	2MASX J22164131−0914138
A2554	.1109	89	0.42	−25.99	100	717	−505	2MASX J23121995−2130098	2MASX J23121357−2130018
A2572	.0388	107	0.66	−25.62	32	620	−290	NGC 7571	NGC 7598
A2597	.0830	45	0.47	−25.40	43	564	−200	PGC 071390	2MASX J23245745−1212001
A2657	.0409	64	0.24	−25.37	51	782	0	CGCG 407−053 NED02	CGCG 407−050
A2871B	.1215	53	0.65	−25.59	60*	319	−50	2MASX J01075037−3643217	SARS 016.47866−37.05960
A2969	.1252	20	−0.15	−26.17	83	850	411	2MASX J02033533−4106002	LCRS B020108.7−412348
A3093	.0828	26	0.64	−25.95	93	419	−99	AM 0309−473 NED02	AM 0309−473 NED04
A3144	.0444	31	0.44	−25.48	54	532	−507	2MASX J03370557−5501186	IC 1987 NED02
A3546	.1065	14	0.36	−26.15	39	275	−132	2MASX J13130596−2958432	2MASX J13140646−3011328
A3562	.0471	265	0.33	−25.60	129	1070	241	ESO 444−G072	2MASX J13350306−3139187