THE DYNAMICAL STATE OF BRIGHTEST CLUSTER GALAXIES AND THE FORMATION OF CLUSTERS

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ABSTRACT

A large sample of Abell clusters of galaxies, selected for the likely presence of a dominant galaxy, is used to study the dynamical properties of the brightest cluster members (BCMs). From visual inspection of Digitized Sky Survey images combined with redshift information we identify 1426 candidate BCMs located in 1221 different redshift components associated with 1169 different Abell clusters. This is the largest sample published so far of such galaxies. From our own morphological classification we find that ∼92% of the BCMs in our sample are early-type galaxies and 48% are of cD type. We confirm what was previously observed based on much smaller samples, namely, that a large fraction of BCMs have significant peculiar velocities. From a subsample of 452 clusters having at least 10 measured radial velocities, we estimate a median BCM peculiar velocity of 32% of their host clusters’ radial velocity dispersion. This suggests that most BCMs are not at rest in the potential well of their clusters. This phenomenon is common to galaxy clusters in our sample, and not a special trait of clusters hosting cD galaxies. We show that the peculiar velocity of the BCM is independent of cluster richness and only slightly dependent on the Bautz–Morgan type. We also find a weak trend for the peculiar velocity to rise with the cluster velocity dispersion. The strongest dependence is with the morphological type of the BCM: cD galaxies tend to have lower relative peculiar velocities than elliptical galaxies. This result points to a connection between the formation of the BCMs and that of their clusters. Our data are qualitatively consistent with the merging–groups scenario, where BCMs in clusters formed first in smaller subsystems comparable to compact groups of galaxies. In this scenario, clusters would have formed recently from the mergers of many such groups and would still be in a dynamically unrelaxed state.

Key words: galaxies: clusters: general – galaxies: formation – large-scale structure of universe

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Clusters of galaxies are dynamical systems formed by hundreds to thousands of galaxies and an even larger mass of intergalactic hot gas \((kT = 0.5–15 \text{ keV}; \text{Hartley et al. 2008})\). Unfortunately, understanding the formation of these structures turned out to be much more complicated than originally expected. In part, this is because we still do not know what is the nature of the main constituent of these systems. The present paradigm for clusters of galaxies states that both galaxies and gas are located in formidable potential wells formed by non-baryonic dark matter halos.

Observational evidence in favor of this paradigm is based on various mass estimates for clusters of galaxies (see Biviano et al. 2006, and references therein). Considering first the velocity dispersions of the galaxies in clusters, which range from a few hundred to over 1000 km s\(^{-1}\), and assuming clusters to be dynamically relaxed, the virial theorem suggests masses in the range of \(10^{13}–10^{15} \text{ M}_\odot\). This exceeds a few hundred times the mass deduced from the light of the galaxy members. We know now that part of this missing mass is associated with the hot gas component. In fact, X-ray observations suggest that the bulk of the baryon mass in clusters of galaxies is really in the form of gas, with an estimated gas-to-stellar mass ratio of the order of \(\sim 10:1\) (Mushotzky 2004). If one assumes hydrostatic equilibrium, the corresponding dynamical mass, once again, surpasses that of the directly observable mass, i.e., gas and stars. According to this interpretation, no more than 10%–20% of the mass in clusters is in the form of baryonic matter.

According to the cold dark matter (CDM) model, huge cluster halos form hierarchically by the merging of smaller mass halos (see Loeb 2008, and references therein). Numerous simulations (White & Rees 1978; Navarro et al. 1995b, 1997) have shown that the final dynamical state expected at \(z = 0\) is one of a dynamically relaxed system. But what about the galaxies that are observed within the cluster? If these objects participate in the formation of the cluster, then theoretical considerations and numerical simulations suggest that through dissipation and cooling they would follow the potential of the dark matter and settle into a dynamically relaxed distribution (White & Rees 1978; Navarro et al. 1995a, 1995b, 1997; Benson et al. 2001; Springel et al. 2005; Loeb 2008). According to this scenario, the brightest cluster members (BCMs) would thus be expected to be at rest at the bottom of the potential well of their clusters (Ostriker & Tremaine 1975; Hausman & Ostriker 1978; Merritt 1984; Malumuth 1992).

One way to test the above prediction is to determine how far the BCMs are located from the peak of the galaxy surface density in their clusters. This was done by Beers & Geller (1983). Using a sample of 55 rich clusters of galaxies, these authors found cD galaxies to lie at the bottom of local potential wells, rather than global ones as would have been expected. Consistent with this result, Malumuth et al. (1992), Zabludoff et al. (1993), Bird (1994), and Oegerle & Hill (2001) also found large fractions of D and cD galaxies with significant peculiar velocities with respect to the cluster mean. These results suggest that BCMs are not at rest at the bottom of the potential well of their clusters. However, the question remains if these observations reflect a general pattern in the formation of clusters or some special

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conditions connected only to the formation of D and cD galaxies at the epoch of cluster formation (Tonry 1985b).

Indeed, it is often assumed that BCMs are of D or cD type, i.e., huge elliptical galaxies with extended envelopes. The most probable scenario for their formation is that they grow in situ through the process of "cannibalism," which describes the accretion of smaller mass companion galaxies (Hausman & Ostriker 1978; Richstone & Malumuth 1983; Dubinski 1998). However, the accretion rates possible in clusters today seem too low to produce the luminosity of a D or cD galaxy in a reasonably short period of time (Hill et al. 1988; Lauer 1988; Merritt 1984; Tonry 1985b; Malumuth 1992; Nipoti et al. 2003). The difficulty is due mostly to the velocities of galaxies in clusters, which on average are too high for mergers to be efficient (Mihos 2004).

The formation of BCMs in clusters is a more complicated matter. The main question is how can we explain, at the same time, the formation of a high number of galaxies (especially very massive giant Es, Ds, and cDs), and the predominance of a very hot gas component? Indeed, the formation of a large number of galaxies in a system implies a high level of efficiency for the process of transformation of gas into stars (Gunn & Gott 1972). This, in particular, requires very short cooling times for the gas. Consequently, there should not be any intergalactic hot gas left in clusters (Gunn & Gott 1972; White & Rees 1978; Navarro et al. 1995a; Sugino & Ostriker 1998). To solve this very serious difficulty, intricate and contrived models were devised. Usually these include dynamical, thermal, and chemical inputs of star formation and active galactic nuclei (AGNs) on the intracluster medium to eliminate the extra cooling (e.g., Pearce et al. 2000; Kay et al. 2003; Romeo et al. 2006; Domainko et al. 2006). As ingenious as the models are, it seems difficult to understand how these sporadic events could have left over such huge amounts of gas after the formation of so many massive galaxies.

Considering the difficulties involved in explaining how BCMs appear in clusters, some authors suggested that they really formed in smaller mass subsystems, like compact groups of galaxies (Merritt 1985; Zabludoff & Mulchaey 1998). This hypothesis would easily solve the problem of the low merger rates: compact groups have lower velocity dispersions, favoring galaxy interactions and mergers (Merritt 1985; Tonry 1985b; Mihos 2004; Coziol & Plauchu-Frayn 2007), and generally, very low quantities of intergalactic hot gas to inhibit fast cooling (Ponman et al. 1996; Helsdon & Ponman 2000; Mulchaey et al. 2003; Jeltema et al. 2006).

Implicit in this scenario is that clusters must have formed from the combination of many such groups. Now, assuming that the BCMs retain part of the infall velocity of their original groups, and assuming that the clusters had not had enough time to relax dynamically since their formation, the BCMs in such clusters would not be expected to reside at the center of global potential wells, but only of local ones, i.e., the potential well of their original groups. This would explain their nonzero peculiar velocity (Malumuth 1992).

Consistent with the above scenario, the detection of substructures in a significant number of clusters (Dressler & Shectman 1988; Schuecker et al. 2001; Flin & Krywult 2006) suggests that they are not as relaxed as previously believed. Even the Coma cluster (A1656), once considered the "prototype of a rich, relaxed cluster," is now recognized as a relatively young, and still evolving dynamical system (Ledlow et al. 2003; Adami et al. 2005). Reinforcing this view, X-ray studies have recently revealed gas substructures, turbulence, and even cases of mergers between clusters (see Ledlow et al. 2003; Arnaud 2005, and references therein), which are impossible to explain if clusters are fully relaxed structures. All these observations seem to depict a process of formation for clusters of galaxies, which is more complex than what was previously assumed (West et al. 1994; Burns 1998; Forman et al. 2003). Within this new context, a more thorough study of BCM peculiar velocities seems warranted.

Most studies published so far on BCM peculiar velocities are based on samples of limited size (not more than 30) or on samples that are biased toward special types of galaxies, such as D or cDs. In order to alleviate these limitations we have built a new sample of BCMs, based on Bautz–Morgan and Rood–Sastry types, so as to select all the Abell clusters harboring a dominant galaxy. Our sample is sufficiently large and general to allow a statistically significant comparison of the BCM peculiar velocities and their morphological types with the global properties of their clusters and test the models of their formation.

This paper is organized as follows. In Section 2, we describe our selection method for BCM recognition and present our sample. In Section 3, we study the relation between the peculiar velocities of the BCMs and the global characteristics of their clusters, concentrating on different subsamples with well defined properties. In Section 4, we discuss the dynamical implications of our observations and introduce the merging-groups scenario for the BCMs formation in cluster. A brief summary and our conclusions are presented in Section 5.

2. SELECTION OF THE SAMPLE AND PROPERTIES OF THE BCM

2.1. Identification of the BCMs

From the Abell et al. (1989, ACO) catalog of clusters of galaxies, including supplementary (S) clusters, we selected clusters that have the highest probability to possess one dominant galaxy. To this end, we chose all clusters that have a Bautz–Morgan type I or I–II (Bautz & Morgan 1970; hereafter denoted as BM type). Note that the definition of BM types used by ACO is not based on the morphology, as was the original intention of Bautz & Morgan (1970). As a second criterion, we also selected clusters with a Rood–Sastry type cD (Rood & Sastry 1971; hereafter denoted as RS type). For the southern and supplementary samples, which do not have an RS classification, we selected the clusters based on the comments in Tables 7A–C of the ACO paper that suggest the presence of a galaxy of cD type or one with a “corona.” The application of these criteria resulted in an initial sample of 1207 clusters.

To identify the BCMs in our sample, we used R-band images of the Second-Epoch Digitized Sky Survey (DSS2; see, e.g., archive.stsci.edu/dss) centered on the cluster positions published by ACO, or occasionally, on more precise positions found in the literature. The sizes of the images were chosen according to the cluster redshifts (z) to cover a circle of typically, and at least, half an Abell radius (Abell 1958; \( R_A = 1.7/z = 1.5 h^{-1} \) Mpc, where \( H_0 = 100 \) km s\(^{-1}\) Mpc\(^{-1}\) is the Hubble constant). For example, we used images of 40' × 40' for clusters with \( z < 0.045, 30' \times 30' \) for 0.045 ≤ z ≤ 0.06, and 20' × 20' for \( z \geq 0.06 \). Cluster redshifts were taken from the most recent upgrade of the compilation by Andernach & Tago (see Andernach et al. 2005 for a description), with redshifts for ∼110,000 individual cluster members in ∼3700 ACO clusters (as of 2007 December). If a cluster had no spectroscopic redshift, we used photometric estimates based on the work of Peacock & West (1992), as kindly provided by M. West (2007, private communication).
Visual inspection of these images allowed the identification of usually one, sometimes two or three, and rarely four BCM candidates. We then used the “NASA/IPAC Extragalactic Database” (NED, nedwww.ipac.caltech.edu), HyperLEDA (leda.univ-lyon1.fr), or the compilation by Andernach and Tago to retrieve available redshifts and other basic parameters like names and magnitudes for these candidates. The list of these BCM candidates is given in Table 1.

In many clusters the first obvious candidate turned out to be a luminous foreground or background galaxy, as judged on its redshift compared to the cluster mean or photometric estimate. In general, any candidate whose radial velocity differed by more than 2500 km s⁻¹ from the cluster mean was rejected as a BCM. In a few cases, a somewhat smaller difference was applied after a detailed analysis of the cluster member velocity distribution. Note that we also excluded as BCM a few additional galaxies without redshift, like, for example, MCG+10-17-046, a 16° galaxy located to the north of A1351, which is obviously far too luminous to be the member of the assumed associated z = 0.32 cluster. As a reference for future work in the field, the list of the 238 rejected BCMs associated with 192 clusters is given in Table 2.

Whenever a BCM candidate for one cluster was found in the foreground or background of the cluster, the cluster image was reinspected for further possible candidates, until either a member galaxy was found and included in Table 1, or else the cluster itself was discarded as a whole from the sample, for its lack of a dominant galaxy. The latter occurred for 38 clusters, which we list in Table 3.

Frequently a cluster was found to be a superposition of different clusters along the line of sight, as judged from available redshifts in the cluster region. These “redshift components” of the same original Abell cluster are distinguished in Table 1 with capital letters appended to the cluster number (A through E, according to increasing redshift). Occasionally, we were able to identify a BCM in more than one such component of the same Abell cluster. We shall refer to these clusters as the “superposed clusters.”

In 165 cases, we accepted more than one candidate as BCMs in the same redshift component of a cluster. In Table 1, these are identified by small letters appended to their name (a, b, etc., in the order of decreasing brightness). This apparent multiplicity may have various reasons: either there are two real dominant galaxies, or the lack of dominance of the brightest galaxies motivated us to include more than one galaxy, or simply the difficulty to distinguish small magnitude differences between the candidates by eye. In 33 cases, we accepted a third candidate as BCM, marked as “c,” and in six cases a fourth one, marked as “d.”

The cases of foreground (background) galaxies and superposed clusters may have affected the BM types and possibly the richness class of the assumed associated clusters, since these classifications were performed mostly before the cluster and BCM redshifts were known (or in other cases this redshift information was simply not taken into account). As already discussed by Leir & van den Bergh (1977) this may also have affected other BCM studies in the past. Apart from repeating the original uncertainty flags on the BM type by ACO in Table 1 (“:” and “?“), we have put the BM types within parentheses whenever the cluster has a rejected BCM listed in Table 2. In our statistical analysis, we deliberately exclude these when necessary.

2.2. Description of Samples: Tables 1–3

Table 1 contains data and properties for 1426 BCMs in 1221 redshift components (see explanation above) of 1169 distinct Abell clusters. This is, by far, the largest compilation of BCMs associated with Abell clusters published up to now.

In Columns 2 and 3 of Table 1, we give the R.A. and decl. of the BCMs. The position was measured by fitting a bidimensional Gaussian on its image, using the NRAO program FITSview. Except for the very nearby BCMs that extend over several arcminutes, they have a typical uncertainty of 0.5 arcsec.

Note that since the general rms uncertainty of the cluster center positions published by ACO is known to be ~3″, and since good X-ray positions are available only for a small fraction of clusters in our sample, we refrained from calculating angular offsets of the BCM positions with respect to their cluster centers.

In Table 1, we also list the properties of the host clusters of the BCMs, as found in the upgraded compilation of Abell cluster redshifts by Andernach and Tago. These properties are: in Column 4, the Abell richness, in Column 5, the BM type of the cluster (converting roman numbers I, II, . . ., III, to 1, 2, . . ., 5), and in Column 6, its RS type from Struble & Rood (1987) and Struble & Ftaclas (1994). For southern clusters without RS type, we indicate whether the notes in Tables 7A, B, or C of the ACO paper suggest the presence of a galaxy of cD type (listed as “ncD”) or one with a “corona” (listed as “ncor”). The heliocentric cluster mean velocity, vcl, or a photometric estimate if appended with the letter “e,” follows in Column 7, as taken from the updated version of the ACO redshift compilation by Andernach and Tago. An appended letter “n” on this value means that these velocities were taken directly from NED or the literature; a colon marks an uncertain redshift and an asterisk indicates a value differing by more than a factor of 2 from the photometric redshift estimate. The number of galaxies, Ngal, used to determine the redshift of the cluster is given in Column 8, followed in Column 9 by the velocity dispersion of the galaxies in the cluster, σcl, determined using the method developed by Danese et al. (1980). In Column 10, we give the heliocentric velocity for 1032 (73%) of the BCMs, usually from NED. An asterisk appended to this last velocity indicates that it comes from Andernach and Tago’s cluster redshift compilation, or occasionally from HyperLEDA.

It is interesting to note that among the clusters without a radial velocity for the BCM in Table 1, there are 60 clusters with Ngal ≥ 5, of which 22 have Ngal ≥ 10. We have undertaken a spectroscopic observing program in both the northern and southern hemispheres to obtain velocities for most of these galaxies (these velocities are not included in the present paper).

In the rightmost columns of Table 1, we give individual properties of the BCMs. Column 11 gives the peculiar velocity of the BCM with respect to the mean velocity of its host cluster. This value is calculated using the following relation:

\[ \nu_{pec} = \frac{\nu_{BCM} - \nu_{cl}}{(1 + z_{cl})}, \]

where \( \nu_{BCM} \) is the heliocentric velocity of the BCM, \( \nu_{cl} \) and \( z_{cl} \) are the heliocentric mean velocity and redshift of its host cluster. The term \( (1 + z_{cl})^{-1} \) is a cosmological correction (Danese et al. 1980). Note that we quote \( \nu_{pec} \) only if \( N_{gal} \geq 10 \), i.e., when \( \nu_{cl} \) is based on at least 10 cluster members with measured redshift.
Table 1
Identification and Properties of the BCMs and Their Host Cluster

| BCM-ID | R.A. (J2000) | Decl. (J2000) | R | BM   | RS/ACO89 | $v_{cl}$ (km s$^{-1}$) | $\sigma_{cl}$ (km s$^{-1}$) | $v_{BMC}$ (km s$^{-1}$) | $v_{pec}$ (km s$^{-1}$) | Morph. | 2MASX | Other Names |
|--------|--------------|---------------|---|------|----------|------------------------|--------------------------|-------------------------|------------------------|--------|-------|------------|
| A0002  | 00 08 16.87  | +19 39 41.6   | 1 | (1:) | B        | 36620                  | 2                        | 36720                   |                        | D      |       | J00081685−1939423 |
| A0005  | 00 10 09.09  | +33 07 16.4   | 1 | (1:) | cD       | 41000                  | 0.07                     |                         |                        | cD     |       | J00100909+3307162 |
| A0017  | 00 17 06.38  | +08 49 44.9   | 1 | (1:) | cD       | 26961                  | 2                        | 26440                   |                        | cD     |       | J00170632+0849445 |
| A0021  | 00 20 37.19  | +28 39 33.6   | 1 | (2)  | B        | 28401                  | 5                         | 28333                   | -62                    | -0.07  |       |            |
| A0022B | 00 20 43.11  | -25 42 28.4   | 3 | (2)  | B        | 42432                  | 77                       | 42725                   | 257                    | 0.32   | cD    | J00204314−2542284ID |
| A0034A | 00 27 33.30  | -08 53 11.4   | 2 | (2)  | I        | 39657                  | 2                        | 39333                   |                        | D/cD   |       | J00273334−0853112 |
| A0034B | 00 27 04.76  | -08 47 03.3   | 2 | (2)  | I        | 56535                  | 2                        | 56493                   |                        | D      |       | SDSS J002704.78−084703.4 |
| A0035  | 00 27 23.47  | -21 33 01.5   | 3 | (5)  | I        | 58000                  | D                        |                         |                        | D int  |       | J00272350−2133017 |
| A0038  | 00 28 19.80  | +13 54 59.8   | 1 | (3)  | cD       | 42330                  | 13                       | 42217                   | -99                    | -0.18  | cD     | J00281984+1354596 |
| A0049  | 00 31 26.81  | -11 24 41.8   | 1 | (3)  | cD:      | 47100                  | 1                        | 47100                   |                        | cD     |       | J00312683−1124418 |

Notes.

a BM types were converted from roman numbers I, I–II, . . . , III, to 1, 2, . . . , 5, and are given in parentheses if this cluster has a discarded BCM candidate in Table 2.
b Appended with (n) if taken from literature, (e) if photometric estimate, (:) if poor spectrum, (*) factor 2–4 different from photometric estimate.
c Taken from literature whenever $v_{cl}$ is taken from literature.
d Appended with (*) if taken from Andernach and Tago’s database, (n) if taken from literature, (:) if poor spectrum.
(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
### Table 2
Identification of Discarded BCMs and the Clusters on Which They are Projected

| Abell No. | R.A. (J2000) | Decl. (J2000) | $v_{cl}$ | $v_{BCM}$ | Other Names |
|-----------|--------------|--------------|---------|-----------|-------------|
| A0002     | 00 07 50.56  | −19 42 26.8  | 36755   | 19551     | 2MASX J00075059−1942265 |
| A0022     | 00 20 39.10  | −25 35 29.7  | 38548   | 19097     | 2dFGRS S138Z189 |
| A0034     | 00 27 19.40  | −08 48 21.0  | 39657   | 12193     | 2MASX J00271944−0848212 |
| A0099     | 00 45 11.38  | −17 16 10.1  | 28794n  | 8562      | 2MASX J00045114−1716107 |
| A0107     | 01 22 31.19  | −03 07 31.0  | 40368n  | 35961     | 2MASX J01223119+0307312 |
| A0327     | 02 12 43.64  | −26 09 49.9  | 50801   | 17628     | 2MASX J02124363−2609504 |
| A0403     | 02 58 10.24  | +03 21 42.4  | 30044   | 3126      | NGC 1153 |
| A0415     | 03 06 55.96  | −11 59 00.6  | 23756   | 3993      | MCG-02-08-052 |

**Notes.**

*a* Only one radial velocity for a representative cluster component is given for clusters with known superposition; we made sure that $v_{BCM}$ is incompatible with all redshift components known to us; appended with “n” if taken from literature, “:” if uncertain, and “e” if photometric estimate; an asterisk indicates a value that is a factor of 2–4 lower than the photometric estimate.

*b* Appended with an asterisk if taken from Andernach’s database, with “b” if in the background to the cluster, and with “e” if photometric estimate.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 3
List of Discarded Clusters

| Abell No. | Reason |
|-----------|--------|
| A0319     | DSS plate defect |
| A0812     | BCM is bg |
| A1329     | BCM is fg |
| A1727     | No dominant galaxy; faint |
| A2023     | BCM is fg |
| A2724     | No dominant galaxy; faint |
| A2725     | Too faint |
| A2896     | BCM is fg |
| A2942     | BCM is fg |
| A2944     | BCM is fg |
| A3052     | Complex field; cluster not BM1 |
| A3056     | BCM is fg |
| A3087     | BCMs are fg/bg |
| A3307     | BCM is fg |
| A3428     | BCM is fg; very sparse |
| A3459     | BCM is fg |
| A3462     | BCM is fg |
| A3542     | BCM is fg |
| A3599     | BCM is fg |
| A3602     | BCM is fg; low gal. latitude |
| A3607     | BCM in between two subcl. along line of sight |
| A3778     | Same as A3832 |
| A3832     | Same as A3832 |
| S0294     | BCMs are fg/bg |
| S0329     | BCM is fg |
| S0372     | BCM is fg |
| S0376     | No dominant galaxy |
| S0379     | BCM is fg |
| S0571     | BCM is fg |
| S0596     | Too faint |
| S0631     | BCM is fg |
| S0675     | BCM is bg |
| S0698     | BCM is fg |
| S0715     | BCM is bg |
| S0790     | Too faint, low galact. lat. |
| S0812     | BCM probably fg |
| S0852     | BCM is fg |
| S0933     | No dominant galaxy |

### Table 4
Relative Peculiar Velocities of the BCMs as Function of their Morphological Type

| Samples | All | cD | E | S |
|---------|-----|----|---|---|
| Number of BCMs | 452 | 234 | 180 | 27 |
| Percentile 25 | 0.15 | 0.15 | 0.20 | 0.14 |
| Median $|v_{pec}|/\sigma_{cl}$ | 0.32 | 0.27 | 0.45 | 0.38 |
| Percentile 75 | 0.63 | 0.46 | 0.76 | 0.66 |
| Mean $|v_{pec}|/\sigma_{cl}$ | 0.44 | 0.35 | 0.52 | 0.43 |
| Std. error on mean | 0.02 | 0.02 | 0.03 | 0.07 |

### Table 5
Relative Peculiar Velocities of the BCMs Versus Cluster Richness and BM Type

| Samples | R0 | R1 | R2+ | BM1 | BM2 |
|---------|----|----|-----|-----|-----|
| Number of BCMs | 140 | 84 | 52 | 84 | 105 |
| Percentile 25 | 0.16 | 0.18 | 0.09 | 0.09 | 0.21 |
| Median $|v_{pec}|/\sigma_{cl}$ | 0.33 | 0.32 | 0.25 | 0.26 | 0.40 |
| Percentile 75 | 0.58 | 0.52 | 0.48 | 0.48 | 0.64 |
| Mean $|v_{pec}|/\sigma_{cl}$ | 0.43 | 0.40 | 0.33 | 0.31 | 0.48 |
| Std. error on mean | 0.03 | 0.04 | 0.04 | 0.03 | 0.04 |

### Table 6
Cluster Velocity Dispersion Versus Cluster Richness and BCM Morphological Type

| Samples | Cluster | BCM type |
|---------|---------|----------|
| Number of BCMs | 362 | 167 | 94 | 299 | 261 | 41 |
| Percentile 25 | 362 | 453 | 532 | 456 | 368 | 348 |
| Median $\sigma_{cl}$ (km s$^{-1}$) | 515 | 659 | 744 | 632 | 536 | 520 |
| Percentile 75 | 678 | 809 | 902 | 793 | 753 | 653 |
| Mean $\sigma_{cl}$ (km s$^{-1}$) | 539 | 651 | 744 | 647 | 566 | 514 |
| Std. error on mean (km s$^{-1}$) | 12 | 18 | 30 | 15 | 15 | 33 |

For comparison purposes, we also give in Column 12 the relative peculiar velocity of the BCM, which is the peculiar velocity in units of the cluster velocity dispersion, $\sigma_{cl}$. For two clusters with $N_z \geq 10$ (A0136 and A3088B) no $\sigma_{cl}$ is available,
since neither $\sigma_d$ nor individual galaxy redshifts were published. Column 13 gives the BCM morphological type, as determined by us (see the explanations below), followed in Column 14 by the galaxy identification from Two Micron All Sky Survey (2MASS), and other names as found in the literature in Column 15. The latter two columns entries were both retrieved from NED.

The morphological types of the BCMs in Column 13 of Table 1 were determined from visual inspection of the DSS images. Following Morgan (1958), we define a D galaxy as an elliptical galaxy (E) with an extended, low-surface-brightness envelope, where the envelope is at least two times larger than the high-surface-brightness central region of the galaxy. Further to this first definition, we define a cD galaxy as a giant D galaxy (Matthews et al. 1964). By “giant” we mean the galaxy is apparently the largest or most extended galaxy of the cluster. When it is not possible to distinguish clearly between these cases using these definitions, we classify the galaxy as E/D (i.e., a possible D galaxy) or D/cD (i.e., a possible cD galaxy).

The only further classification we used is the spiral type (S). Again, the class E/S (possibly a spiral) was used when it was not possible to distinguish between the two. Except for very few cases, it was impossible to be more explicit on our classification of the spirals in our sample. Consequently, the type S is used in Table 1 to describe either an S0, Sa, or Sb galaxy.

In many cases, the above morphological types seemed insufficient to describe the galaxies. This is particularly true for cD galaxies. For example, in Table 1 we classified the few cases of possible “dumbbell” cD galaxies as “cD db.” Frequently we were also able to distinguish some structures within the envelope of the cD. While these structures could be mere superpositions, they suggest possible evidence for mergers, explaining our label as “cD m” in Table 1. Finally, we found many systems formed by two or more, apparently elliptical galaxies. Without prejudice on the nature of these objects, we marked them as possibly interacting (“int”) in Table 1. A high level of uncertainty on our classification is indicated by an interrogation sign. Note that only five galaxies (~0.3%) in our sample could not be classified at all.

In Table 2, Columns 2 and 3 give the positions (also measured by us) of the discarded BCMs, followed in Columns 4 and 5 by the heliocentric mean velocities of the presumed associated clusters and actual redshifts of the discarded BCMs. We also give in Column 6 the names of these galaxies as found in NED.

### Table 7

Relative Peculiar Velocities of the BCMs Versus Cluster Richness

| Number of BCMs | cD Subsample | E Subsample |
|----------------|--------------|--------------|
|                | R0 | R1 | R2+ | R0 | R1 | R2+ |
| 107            | 78 | 49 | 132 | 50 | 25 |
| Percentile 25  | 0.15 | 0.15 | 0.11 | 0.16 | 0.19 | 0.22 |
| Median $|v_{pec}|/\sigma_d$ | 0.28 | 0.30 | 0.22 | 0.44 | 0.35 | 0.44 |
| Percentile 75  | 0.47 | 0.45 | 0.34 | 0.76 | 0.77 | 0.73 |
| Mean $|v_{pec}|/\sigma_d$ | 0.37 | 0.36 | 0.31 | 0.51 | 0.50 | 0.51 |
| Std. error on mean | 0.03 | 0.03 | 0.04 | 0.04 | 0.06 | 0.08 |

The distribution of morphological types of the galaxies in the two subsamples is shown in Figure 1. The dominant morphological type in the primary sample is cD (35% of the sample). Together with the BCMs classified as D/cD they represent 48% of the whole sample. The second most frequent type is E (19%). Adding to these the D and E/D types, they form 44% of the whole sample. In the primary sample, therefore, very few BCMs (8%) are spiral-like (i.e., of type E/S or S).

In the secondary sample, we see a shift toward later morphological types compared to the primary sample. The dominant morphology in this group is E (44%), followed by the E/D and D which added together form 73% of the whole sample. Even the S type (10%), which together with the E/S forms 22% (there is no D/cD in the statistical group S), is more abundant than the cD (5%).

The distribution of the morphologies in the primary sample is consistent with what we expect for BCMs: galaxy clusters are systems dominated by early-type galaxies, many of which (the D and cDs) are unique to clusters. The shift toward later morphological types in the secondary sample is consistent with the expectation that second-, third-, and fourth-brightest galaxies in clusters are less “evolved” morphologically as compared to the dominant BCM.

Taked at face value, this result seems to support our choice of BCMs. For our statistical analysis, the BCMs in the primary sample will form our main sample.

Before looking into the relation between morphology and peculiar velocity, we note one further interesting characteristic of their morphological distribution: not all BCMs are cDs. This is somewhat surprising considering the bias introduced by our selection criteria. Indeed, we would have expected clusters with a dominant galaxy to host mostly cDs. Considering the size of our sample one can interpret this result in two ways: (1) assuming cDs are part of the normal evolution of E galaxies, then most clusters in our sample did not reach a stage of evolution sufficient to produce them; (2) assuming cDs are a special phenomenon, then not all the clusters in our sample possess the conditions required to form them.

### 3. ANALYSIS

#### 3.1. Peculiar Velocities of the BCMs

The main concern of our study is the peculiar velocity, $v_{pec}$, of BCMs in clusters. As mentioned previously, the peculiar velocities in our sample were calculated only when the number of galaxies with redshifts measured to determine the dynamical characteristics of the cluster, $N_z$, is greater or equal to 10. This reduces our main sample to 452 BCMs. The distribution of relative peculiar velocities is presented in Figure 2. The mean, median, and percentile values for $|v_{pec}|/\sigma_d$ for the whole sample, as well as for the different morphological types of BCMs, are reported in Table 4. Based on these statistics, we conclude that 50% of the BCMs in our sample have a peculiar velocity higher than 32% the velocity dispersion of their cluster.

Our analysis confirms the findings obtained by different authors: an important number of BCMs in clusters have significant peculiar velocities. In previous studies, these findings were based on rather small and incomplete samples, which were prone
to statistical fluctuations: 22 clusters in Malumuth et al. (1992), 31 in Zabludoff et al. (1993), 25 in Bird (1994), and 25 in Oegerle & Hill (2001). The generality of our result (452 clusters) clearly establishes this phenomenon as a common trait of clusters of galaxies harboring a dominant galaxy, and not a special feature of clusters with D- or cD-like BCMs.

3.2. Robustness and Errors of Peculiar Velocity

To test the robustness of our definition of peculiar velocity, we look for a possible dependence on the number of galaxies used to calculate the cluster velocity dispersion. To do so, we separate our sample into four different statistical groups: N10 (452 BCMs) contains clusters with \( N_z \geq 10 \) measured redshifts, N30 (243 BCMs) contains clusters with \( N_z \geq 30 \), N50 (151 BCMs) those with \( N_z \geq 50 \), and N100 those with \( N_z \geq 100 \) (64 BCMs). The box–whisker plots for the distribution of BCM peculiar velocities in the different subsamples are presented in Figure 3. Note that we use the absolute peculiar velocity instead of the relative one to avoid the obvious problem of the increase of velocity dispersion with richness (clusters with more than 100 galaxies measured are among the richest and have consequently higher velocity dispersions, which reduces, somewhat artificially, the relative peculiar velocities of their BCMs). The median or mean peculiar velocities do not decrease significantly with increasing number of redshifts, i.e., when going from subsamples N10 to N100.

In order to establish the statistical significance of this result, we perform a nonparametric Kruskal–Wallis (K–W) test on these subsamples. A nonparametric test is used because the distributions are not Gaussian (as verified using three different tests: Kolmogorov–Smirnov, D’Agostino and Pearson, and Shapiro–Wilk normality tests). The probability, \( P \), calculated by the K–W test is the probability that random sampling from populations with similar distributions produces a sum of ranks as far apart as observed. All the nonparametric tests used in our analysis are done at a level of significance of 95%, which is standard for such tests. A small probability (\( P < 0.05 \)) suggests that the samples are unlikely to be drawn from the same population.

The K–W test applied to our subsamples detects no significant difference between the distributions (\( P = 0.9126 \)). We conclude that our finding of a high fraction of high peculiar velocity BCMs is independent of the number of galaxies used to calculate the cluster velocity dispersion.

It is easy to show that our result neither depends on the errors in the BCM radial velocity nor on those of the cluster mean, nor on those of the cluster velocity dispersion. A typical value for the error on the radial velocity of the BCMs is \( \Delta v_{BCM} = 60 \text{ km s}^{-1} \). For the error of the cluster mean velocity, we use the standard deviation of the mean, which is \( \Delta v_{cl} = \sigma_{cl}/\sqrt{N_z} \). The error of the absolute BCM peculiar velocity is then \( \Delta v_{pec} = \sqrt{\sigma_{cl}^2/N_z + (\Delta v_{BCM})^2} \). For our sample of 452 BCMs, we find that 41% have peculiar velocities of more than twice this error, and 25% of them with more than three times their error. Assuming a very conservative value of \( \Delta v_{BCM} = 100 \text{ km s}^{-1} \), we obtain 33% of BCMs with \( v_{pec} \geq 2\Delta v_{pec} \) and 19% with \( v_{pec} \geq 3\Delta v_{pec} \). To estimate the error in the relative peculiar velocity we assumed an error in the cluster velocity dispersion of \( \Delta v_{cl} = 100 \text{ km s}^{-1} \). This is a reasonable estimate as this error depends more on the median error of the individual galaxy velocities than on the total number of cluster members (see Danese et al. 1980; Adami et al. 1998; Fadda et al. 1996; De Propris et al. 2002). The error of the relative peculiar velocity is then \( \Delta (v_{pec}/\sigma_{cl}) = \sqrt{(\Delta v_{pec})^2 + (v_{pec}\Delta \sigma_{cl}/\sigma_{cl})^2}/\sigma_{cl} \). For the very conservative value of \( \Delta v_{BCM} = 100 \text{ km s}^{-1} \) we find that of our 452 BCM candidates 31% have \( v_{pec}/\sigma_{cl} \geq 2\Delta (v_{pec}/\sigma_{cl}) \) and 13% have \( v_{pec}/\sigma_{cl} \geq 3\Delta (v_{pec}/\sigma_{cl}) \). We conclude, therefore, that the uncertainties in BCM and cluster mean radial velocities, as well as those in the cluster velocity dispersion, are not the cause for a significant fraction of high peculiar velocity BCMs.

3.3. Relations Between Peculiar Velocity, BCM Morphology, Cluster Richness, and BM Type

Our large sample allows us to go further in our analysis by searching for a possible relation of the peculiar velocity with the BCM morphology, the cluster richness, and the BM type.

To check for a relation between BCM relative peculiar velocity and BCM morphology, we separate our sample into three subsamples: the cD sample is obtained by merging the D/cD galaxies with the cD, the D, E/D, and E are grouped into the E sample, and all the other galaxies (E/S and S type) are grouped into the S sample. The distributions for the three subsamples are shown in Figure 4. The E galaxies trace a more homogeneous distribution than the cDs, who seem to aggregate at lower relative peculiar velocities.
Our statistics for the three subsamples are reported in the rightmost columns of Table 4. We clearly distinguish a tendency for galaxies in the cD subsample to have lower relative peculiar velocities: the median $|v_{pec}|/\sigma_{cl}$ is 0.27 for the cD subsample, compared to 0.45 for the E sample. Curiously, the median decreases again to 0.38 in the S sample. However, this last sample is quite small and prone to larger statistical uncertainties (as suggested in Table 4 by the relatively large standard error on the mean).

In order to verify the statistical significance of the differences, we perform a K–W test on these subsamples, since, once again, the distributions are not Gaussian. The probability for our three subsamples to be drawn from the same population is only $P = 0.0002$, which is extremely significant. A post-test (Dunn's multiple comparison test) allocates the difference between the cD and E subsamples. No significant differences are encountered between the E and S samples, or between the cD and S samples. Application of a different nonparametric test, the Mann--Whitney (M–W) test, which compares only two samples, is only in question if the distributions are not Gaussian. The probability for our three subsamples to be drawn from the same population is again, the distributions are not Gaussian. The probability for our three subsamples to be drawn from the same population is $P = 0.0017$ from an M–W test implies that the difference is very significant. This suggests that the dominant nature of a BCM in its cluster favors lower relative peculiar velocities.

We conclude that the relative peculiar velocity of a BCM depends very strongly on its morphological type. In general, therefore, cD-type BCMs have lower relative peculiar velocities than D, E/D, or E together.

To investigate the effect of cluster richness we separate our sample into three subsamples. The subsamples identified as R0 and R1 contain clusters with respective Abell richness classes $R = 0$ and $R = 1$. Those with a richness class 2 or more were grouped into the subsample R2+. Since the richness class of the superposed clusters (i.e., those with component letters A, B,...) is questionable, we excluded them from our statistics. That leaves us with 276 BCMs. The distributions for the three subsamples are shown in Figure 5(a). The medians, percentiles, and means for $|v_{pec}|/\sigma_{cl}$, for BCMs in clusters of different richness and BM types, are reported in Table 5.

Comparing the distributions in Figure 5(a), and the medians in Table 5, we do not see any significant changes in the BCM relative peculiar velocity distribution when passing from the richness samples R0 through R1 to R2+. This is not only confirmed by the high $P$ value of a K–W test: $P = 0.2026$, but also by individual M–W tests. We conclude that, in general, the relative peculiar velocity of a BCM does not depend on the richness of its host cluster.

To check for a relation between BCM relative peculiar velocity and its host cluster BM type, we divide our sample into two subsamples: clusters with BM type I form the subsample BM1 and those with a BM type I–II form the subsample BM2. Clusters with a BM type II or later were included in our main sample only because they contain a cD, or were suspected to contain one. They are thus not fully represented in our sample and are not considered in the present comparison. The superposed clusters are also excluded, since their BM types must be considered as uncertain. This leaves us with 189 BCMs. The distributions for the two subsamples are shown in Figure 5(b) and the statistical results are also reported in Table 5.

We observe a significant variation in the relative peculiar velocities of the BCMs, passing from the BM1 clusters to the BM2 clusters: the median increases from 0.26 to 0.40. A value of $P = 0.0017$ from an M–W test implies that the difference is very significant. This suggests that the dominant nature of a BCM in its cluster favors lower relative peculiar velocities.

Note that this last result is consistent with the relation with morphology, since we expect cD galaxies to be the dominant galaxies in their host clusters. We suspect, therefore, that the strong relation encountered between the relative peculiar velocity and morphology is the main cause of the relation found with the BM type. This interpretation will be checked in the following section.

### 3.4. Relations between BCM Morphology, Cluster Richness, and BM Types

To better understand the nature of the relations (or the absence thereof) found in the previous section, it is important to establish the connections which exist between the different parameters studied.

As judged from Figure 6(a), there is a definite increase in the fraction of cD-type BCMs in clusters of earlier BM type: 46% in BM1 clusters compared to 22% in BM2 clusters. There are also many more BCMs of types E/D and E in clusters of later BM type: 48% in BM2 clusters compared to 27% in BM1 clusters. This result is expected, considering the definition of cDs as dominant galaxies.
We extracted the cD-type galaxies in clusters with BM types I and I–II and performed an M–W test on the medians of their relative peculiar velocity. No significant difference ($P = 0.1239$) was found. In other words, cD galaxies have similarly low relative peculiar velocities, independent of the BM type of their host cluster. This supports our interpretation that the relation between the BCM relative peculiar velocity and its host cluster BM type is due to the fact that BCMs in BM I clusters are mostly cDs.

In Figure 6(b), we compare the distributions of the morphologies of the BCMs in the three richness subsamples, as defined before. There is a definite rise in the fraction of the cD morphology for the BCM in richer clusters. The fraction of cDs increases from 25% in R0 clusters to 48% and 57% in R1 and R2+ clusters, respectively. Consequently, there are slightly more BCMs of later types (later than D) in low-richness clusters: 55% in R0 clusters compared to 33% in R1 and 23% in R2+ clusters.

Therefore, although we find no direct relation between the relative peculiar velocity of the BCM and the host cluster’s richness we do find a trend for richer clusters to harbor cDs, which have lower relative peculiar velocities.

### 3.5. Relation with Cluster Velocity Dispersion and Mass

The cluster velocity dispersion is usually taken as a proxy for the total mass of the system. This interpretation is founded on the assumption that clusters are dynamically relaxed and follow the virial theorem. If the distribution of the luminous mass follows that of the total mass, then more massive clusters must also be richer in galaxies. Consequently, we expect the richness of a cluster to increase with the velocity dispersion. But what about the peculiar velocity? We have just seen that there is no relation between richness and the relative peculiar velocity, and this is despite the fact that the frequency of cDs is higher in richer clusters.

To explore this point we examine how the velocity dispersion varies as a function of the other parameters in our study. Box–whisker plots for the velocity dispersion of galaxies in cluster subsamples separated by Abell richness and BCM morphological types (using the same regroupment as before) are presented in Figure 7.

In Figure 7(a), we distinguish a very strong increment of the velocity dispersion with the richness of the cluster, which is also confirmed by the statistics in Table 6, where we report the median, percentiles, and mean cluster velocity dispersion for clusters of different richness. The K–W test detects extremely significant differences ($P < 0.0001$). The post-test allocates the most significant differences between the R0 and R1 and between the R0 and R2+ subsamples. No significant difference is detected between the R1 and R2+ subsamples by the post-test. However, the result of an M–W test between the R1 and R2+ subsamples finds a significant difference ($P = 0.0129$).

If we take the velocity dispersion as a proxy for the cluster mass, then massive clusters are richer in galaxies.
In Figure 7(b), we distinguish a definite increase of the host cluster velocity dispersion when passing from the BCM type S through E and cD subsamples. The statistics reported in Table 6 confirm this observation, where the rightmost three columns give the mean, percentiles, and median velocity dispersion of clusters with different morphological types of BCMs. The K–W test detects extremely significant differences ($P < 0.0001$). The post-test identifies extremely significant differences between the cD and E and very significant difference between the cD and S samples. The K–W test does not detect a difference between the E and S samples. The high $P$ value ($P = 0.2524$) for an M–W test between the E and S subsamples confirms this last result.

Looking at Figure 7, and considering the statistical tests, we have to conclude that the relation between cluster richness and cD galaxies is consistent with the following interpretation: cDs are more common in rich clusters probably because rich clusters are generally more massive.

In Figure 8, we compare the velocity dispersion and the absolute value of the BCM peculiar velocity, $|v_{pec}|$. For this test we consider only the cD subsample and the E subsample. In Figure 8(a), we see a very weak trend in the cD subsample, suggesting that the peculiar velocity increases with the velocity dispersion. The trend is more obvious in the E subsample (Figure 8(b)). Comparable trends were previously observed by Malumuth et al. (1992) and Bird (1994). Contrary to these authors, however, we do not confirm a similar correlation with the richness of the clusters. In both graphs, we distinguish between the different richness classes. We see no particular difference in these trends for the different richness classes.

To verify if the trends we observe are statistically significant, we perform two Spearman correlation tests. The tests yield a correlation coefficient $r = 0.27$ for the cD subsample, and $r = 0.41$ for the E subsample, both with a probability $P < 0.0001$, consistent with extremely significant positive correlations. This implies that, in general, the BCM peculiar velocity rises as the cluster velocity dispersion increases.

In Figure 9, we show the box–whiskers plots for the peculiar velocities as found in the cD and E subsamples separated by richness classes. We find no differences in the peculiar velocity between the richness classes. The statistics for these two subsamples are reported in Table 7. The K–W tests detect no differences ($P = 0.3265$ for the cD subsample and $P = 0.9680$ in the E subsample) for the medians in the subsamples separated by richness classes. This result confirms that the cluster richness plays no role in the correlations found in Figure 8 and in the general frequency distribution shown in Figure 4.

4. DISCUSSION

Our analysis confirms the findings of previous authors working in the field (Beers & Geller 1983; Tonry 1985b; Malumuth et al. 1992; Zabludoff et al. 1993; Bird 1994; Oegerle & Hill 2001; Pimbblet et al. 2006): most BCMs are not at rest at the center of their host cluster’s potential well. The large size and


velocity dispersions, which reduce the efficiency of mergers. However, richer clusters also have higher mass in the clusters. Therefore, richer clusters are more frequent in richer clusters, which is consistent with our analysis. This is because the number of mergers, or the completeness of our sample, eliminates any doubts on the physical reality and generality of this phenomenon. Our analysis also shows that this is a common trait of clusters of galaxies harboring a dominant galaxy and not a special feature related to particular systems, like clusters hosting a D or cD galaxy.

There is no easy way out of this situation. Assuming, for example, that the BCMs are really at rest at the dynamical center of their clusters would raise the peculiar velocity of the other galaxies, putting them at higher energy levels in the potential well of their clusters. To explain the observations assuming dynamical equilibrium would increase the amount of dark matter to possibly unacceptably large values (for instance, in terms of $M/L$; see Tonry 1985a for an explanation).

The fact, also, that the peculiar velocity, a dynamical parameter related to the cluster, is strongly correlated with the morphology of the BCMs, seems to suggest a strong connection between the formation of a cluster and its BCM. For example, assuming that BCMs form by the mergers of smaller mass elements, we would naturally expect massive galaxies (D and cDs) to be more frequent in richer clusters, which is consistent with our analysis. This is because the number of mergers, or the masses of the merging components, is expected to grow with the mass in the clusters. However, richer clusters also have higher velocity dispersions, which reduce the efficiency of mergers (Tonry 1985a; Mihos 2004). Unfortunately, the current status of simulations of large-scale structures formed by CDM is not of much help. These models do not include the physics of galaxy formation and the best simulations to date place, more or less artificially, the BCMs at the center of the halos (e.g., Taylor & Babul 2004; Springel et al. 2005, or De Lucia & Blaizot 2007), predicting zero peculiar velocities.

### 4.1. Explaining the BCM Peculiar Velocities

Let us re-examine the present paradigm of structure formation to see how it may be adapted to fit our observation. According to the model, 90% of the mass of a cluster is in the form of nonbaryonic dark matter. This follows directly from the standard cosmological scenario, in which dark matter perturbations are free to grow as soon as they enter the particle horizon, while baryonic matter can do so only after it decouples from radiation. In fact, this is the strongest argument in favor of the existence of dark matter, since structures dominated by nonbaryonic dark matter could grow to significant masses without producing anisotropies in the microwave background in excess of what is observed. For CDM cosmology the first structures to form after recombination ($z = 1000$) have typical masses of the order of $10^5 M_\odot$ (e.g., Coles & Lucchin 1997, or any good book on cosmology and structure formation).

After decoupling the physics becomes nonlinear and numerical simulations are necessary (see Davis et al. 1985, and references therein). Reviews of this subject can be found in Primack (1999), Arnaud (2005), or Loeb (2008). To summarize, within the CDM paradigm, structure formation follows a bottom–up scenario, where high-mass halos gradually form from the mergers of smaller mass ones. The question is how to include consistently the formation of the BCMs and their peculiar velocities into this model?

Numerous simulations show that in any self-gravitating system, the most massive galaxies are expected to lose energy through dynamical friction to the less massive bodies and to spiral toward the bottom of the potential well (White 1976; Merritt 1983; Tonry 1985a; Malumuth 1992). Following Tonry (1985a), the dynamical friction decay of velocity of a galaxy with path length $x$ is given by

$$\frac{dv}{dx} = -C \frac{M \rho}{v^3} g(v),$$

where $M$ is the mass of the galaxy, $v$ is its velocity, $\rho$ is the density of the background medium, and $g(v)$ is a function that depends on the distribution of velocities of the background particles. For an isothermal distribution of velocities with dispersion $\sigma$ the equation takes the form

$$\frac{dv}{dx} = -C \frac{M \rho}{\sigma^3} \frac{1}{\alpha + (v/\sigma)^3},$$

where $\alpha$ is a geometric constant. Dynamical friction increases with the mass of the galaxy and the density of the background particles, while it decreases with the velocity dispersion of the background particles. This seems consistent with our observations (assuming cDs are more massive than D galaxies).

On the other hand, what seems difficult to understand is why after a Hubble time, most BCMs are not at rest at the bottom of the potential well of their clusters. Indeed, slightly less than a third (29%) of the BCMs in our sample may be consistent with zero peculiar velocities. According to Malumuth et al. (1992), this phenomenon should be viewed as evidence of a relatively recent formation. This is because, in hierarchical structure formation models, the richest, most massive systems must have undergone the most recent merger events. Based on this interpretation, Malumuth et al. (1992) proposed that high peculiar velocity BCMs must occur only in rich, high velocity dispersion clusters.

Figure 9. Box–whisker plots for the relative peculiar velocity for (a) the cD subsample and (b) the E subsample. The layout is the same as in Figure 3.
This is not confirmed by our analysis. Although we do observe a positive correlation between the peculiar velocity and velocity dispersion of the clusters, we do not distinguish the trend expected with the richness. Neither can we find, according to this interpretation, a natural explanation why the correlation is stronger in the E subsample than in the cD subsample. In general, we do not observe any specific dynamical characteristic that allows to distinguish the clusters with low peculiar velocity BCMs from those hosting BCMs with high peculiar velocities.

Can we explain the peculiar velocities using a special form of dark matter halo? In his article Tonry (1985a) explains that the matter density, \( \rho \), of the background matter must play a major role. For example, when a cluster has a radial density profile that is cuspy, like for an isothermal sphere (with density as function of radius: \( \rho(r) \propto r^{-2} \)), the dynamical friction in the center of the cluster is stronger than when the density falls less rapidly with radius. Consequently, if the global halos of clusters have such a shallow central density profile the orbits of massive galaxies may take longer to decay. The Navarro, Frenk and White (NFW) halo model (density: \( \rho(r) \propto (r/r_s)^{-1}(1 + r/r_s)^{-2} \), where \( r_s \) is a scale radius) seems to show such a property. Therefore, if dark matter in clusters follows originally such a distribution, even after a Hubble time BCMs may not have had sufficient time to relax dynamically, explaining their nonzero peculiar velocities. However, it may be that the free parameters in the NFW model would need to vary significantly from one cluster to another to accommodate all our observations.

Even if we consider nonzero peculiar velocities possible within the NFW model (as an oscillation of the BCM around the center of the potential well) there would still be one more important difficulty. Because the intracluster gas producing the X-rays is 10 times more massive than the luminous matter in galaxies, we should not expect this gas to follow the oscillating BCMs. However, most observations seem to suggest just that: the large majority of BCMs are located at the peak of the X-ray emission (Jones & Forman 1984; Rhee & Latour 1991; Bahcall et al. 1995; Bahcall 1999; Mulchaey et al. 2003).

As a preliminary verification, we cross-correlate the X-ray peak positions of X-ray clusters as published by Magliocchetti & Brüggen (2007) with the positions of BCMs in a sample of Abell clusters, even larger than the present one (article in preparation), and found 76 clusters in common (with 46 BCMs in our present sample). The consistency between the positions of the X-ray peaks with the positions of the BCMs is impressive: only eight out of 76 BCMs show a positional offset larger than 20". Of the 46 clusters in common with Magliocchetti & Brüggen (2007) and our present sample, 41 BCMs have an offset of less than 20" from the cluster’s X-ray emission peak. All these clusters have a unique BCM in our Table 1, and 36 have a value for \( v_{pec}/\sigma_{cl} \). Their median \( |v_{pec}/\sigma_{cl}| \) is 0.28, and there are eight clusters with \( |v_{pec}/\sigma_{cl}| > 0.6 \). We classified 29 of these 36 BCMs as “cD” in Table 1, and these have a median \( |v_{pec}/\sigma_{cl}| \) of 0.26. Thus, a significant fraction of high peculiar velocity BCMs persists in subsamples where the positional coincidence between the BCMs and their X-ray peak is very good.

In conclusion, it seems difficult to explain the peculiar velocities of the BCMs as an oscillation component around the center of a global potential well formed by a spherical halo of dark matter, which is already dynamically relaxed. And this is true even if the halo has a shallow central density, like in the NFW model. Also, based on X-ray observations, the local potential well formed by the BCM must also be that of the dark matter halo of the cluster. In other words, it seems impossible to separate the dark matter halo of the clusters from that of their BCMs (Bahcall 1999).

Another intriguing result of our analysis is the correlation between the peculiar velocity and morphology of the BCM. In principle, the dissipative processes involved in galaxy formation are unrelated to the process that pulls the BCMs toward the center of the cluster. Consequently, we would not expect the peculiar velocity of a BCM, which depends on the latter, to be related to the morphology of the galaxy, which depends on the former. Therefore, the fact that we do observe a trend for cD galaxies to have smaller relative peculiar velocities can only be explained if the dissipative processes related to the formation of the BCMs are somehow connected to the force that is pulling them toward the center of the potential well of their clusters. This suggests that the peculiar velocities of the BCM must reflect not only the formation of the BCMs within the clusters but also the process by which the clusters are formed. The two phenomena cannot be separated.

More exotic explanations of peculiar velocities, like the effect of gravitational redshifts (Cappi 1995; Broadhurst & Scannapieco 2000; Kim & Croft 2004), can also be readily eliminated. Among the parameters that contribute to the velocity difference between a BCM and its cluster, the gravitational redshift component is always positive (Kim & Croft 2004). The effect of gravitational redshifts would therefore skew the distribution of peculiar velocities toward positive values, while the observed peculiar velocity distribution is very symmetrical about zero. Thus, we agree with Kim & Croft (2004) that there is currently no detectable evidence for gravitational redshifts in clusters of galaxies.

4.2. The Merging-Groups Scenario

As mentioned in the introduction, one alternative scenario proposed to explain BCMs like D and cD galaxies is that they actually formed in smaller systems like compact groups of galaxies (Merritt 1985; Bird 1994; Zabludoff & Mulchaey 1998; Pimbblet et al. 2006). Indeed, the low velocity dispersion of galaxies in compact groups render tidal interactions and mergers of galaxies much more efficient (Merritt 1985; Tonry 1985b; Mihos 2004; Coziol & Plauchu-Frayn 2007). Assuming that the compact groups that formed the BCMs were more massive than today’s compact groups, then giant elliptical D galaxies and even cDs are possible consequences.

Implicit in this hypothesis, clusters must then build by the fusion of many such groups (Ellington 2003; Mihos 2004; Andernach & Coziol 2007). What would then be the main condition to observe peculiar velocities for the BCMs in clusters? It seems that the only way to reproduce this phenomenon according to this hypothesis is to assume that the clusters are still in an unrelaxed dynamical state. That is, the BCMs still possess some of the dynamical properties of the groups in which they are formed, which translates into nonzero peculiar velocities (Malumuth 1992). Consequently, the BCMs are not at the centers of the global potential wells of their clusters, but rather at the bottom of local potential wells (Beers & Geller 1983; Oegerle & Hill 2001), which would be the potential wells of their groups.

Taken at face value, the merging-groups hypothesis seems capable of explaining the peculiar velocity of the BCMs, although we still have to verify if this hypothesis is consistent with our observations. This may be difficult to check because the dynamical behavior of an unrelaxed transient system, implied by this scenario, is more complex to describe and to follow up than that of a relaxed structure. One cannot apply the virial
We have found, for example, that the relative peculiar velocity is smaller for BCMs of type cD, compared to any other morphological type. This seems reasonably easy to understand. The fact that cDs are the dominant galaxies in their clusters suggests that they formed in the most massive groups. These groups would necessarily constitute an important fraction of the mass of their clusters, explaining the trend toward lower relative peculiar velocities. However, of the 29% BCMs with a peculiar velocity consistent with zero (within the observational errors), only 36% are cDs. Obviously, cDs are not restricted to these cases, because it also depends on the merger history of the cluster: cDs would be less dominant in clusters that formed from a large number of groups. This would be consistent with the lack of correlation of the peculiar velocity with richness and its increase with cluster velocity dispersion.

On the other hand, we have found that a higher richness favors the formation of cDs. As we stated earlier, the facts that cDs are the dominant galaxies in their clusters and have lower relative peculiar velocities suggest that these galaxies are formed in the most massive groups that merged to form clusters. Massive groups most probably attract other groups more easily, which would produce the trend with richness.

If one thinks in terms of the density perturbation spectrum, this last interpretation may also explain why cDs are not ubiquitous in clusters. Being more massive, groups which formed a cD were necessarily located in highest density peaks. Because high-density peaks are less frequent than lower density ones, not all clusters will be expected to possess a cD, consistent with our observations.

The higher the number of groups that coalesce to form a cluster, the richer this cluster must finally be. Assuming that the system is not in equilibrium, then statistically one would expect richer clusters to also have higher velocity dispersions. The difference here is that we do not have relaxation, and one cannot apply the virial theorem to deduce the mass. That is, the velocity dispersion is not a proxy for mass. On the other hand, the increase of luminous mass with richness and its increase with cluster velocity dispersion.

An early preheating phase for the intergalactic medium would obviously help in such a scenario. Indeed, hot gas would fall even less easily into shallow potential wells, explaining why such a huge quantity of gas did not form galaxies. The source of energy of this preheated gas could be related to the evolution of the first stars, the formation of the first black holes (AGNs), or to shocks produced by the formation of structure (Lloyd-Davies et al. 2000; Davé et al. 2001; Valageas et al. 2003; Dwarkaonath & Nath 2006).

This alternative scenario for the origin of the intracluster gas may also offer a simple alternative to the problem of the contamination of the gas by metals. Two of the mechanisms considered for this process are ram pressure stripping of late-type spirals falling into the clusters (Gunn & Gott 1972), and starburst winds produced by mergers (Schindler et al. 2005; Domainko et al. 2006; Kapferer et al. 2006). In the merging-groups scenario, the intense phase of starburst activity (and possibly AGNs) is directly related to the formation of galaxies in groups (Coziol et al. 1998; Coziol & Plauchu-Frayn 2007). This process may also have allowed a higher level of metals to reach the intergalactic medium. This is because the metals are more loosely bound to galaxies in a group environment (Renzini et al. 1993; Metzler & Evrard 1994; Ponman et al. 1996). Contrary to groups, however, these metals would not be lost, but swept up by the ram pressure of the intergalactic gas falling into the newly formed clusters for the first time.

It is important to note that according to our scenario, the ram pressure is exerted when the gas runs over the galaxies, and not the other way around. As an analogy, one may think of falling rain cleaning the air of its pollutants. On average, therefore, we expect the amount of metal in the intracluster medium to be equal to the amount encountered in all the galaxies forming the cluster (Schindler 2003). This is because the gas must have passed through all the galaxies on its way down the potential wells. In other words, we expect the mixture time to be short, and possibly shorter than in other models.

5. SUMMARY AND CONCLUSION

Based on our analysis of existing BCM velocity data, we have shown that the peculiar velocities of BCMs in clusters of galaxies cannot be ignored. This is a general phenomenon, affecting the majority of clusters with a dominant galaxy. We
have shown that such a phenomenon is difficult to explain within a model where the BCMs form independently from the dark matter halo of their clusters. The existence of a strong relation between the BCM peculiar velocity and its morphology also points toward an intrinsic relation between the formation of the BCM and that of its cluster.

Based on our analysis, we have found our observations to be qualitatively consistent with a scenario where BCMs in clusters form first in smaller mass systems comparable to compact groups (Merritt 1985; Bird 1994; Zabludoff & Mulchaey 1998; Pimbblet et al. 2006). Implicit in this hypothesis, the formation of clusters would have followed the merging of many such groups (Malumuth 1992; Ellingson 2003; Mihos 2004; Adami et al. 2005; Andernach & Coziol 2007; Coziol & Plauchu-Frayn 2007). This has one immediate consequence, which is that most clusters of galaxies harboring a dominant galaxy are not dynamically relaxed.

Although our observation of many BCMs with large peculiar velocities also seems in good agreement with the presence of substructures in clusters (Bird 1994; Dressler & Shectman 1988; Schuecker et al. 2001; Finl & Krywult 2006), we are not sure whether the two phenomena are equivalent. In particular, the explanation for each of these observations may be different. The usual interpretation of substructures in clusters of galaxies is that they are evidence that these systems formed recently. This seems somewhat in contradiction with the advanced morphological stage of galaxies in clusters. These are among the most massive and oldest (in terms of stellar populations) galaxies in the universe. In part, the merging–groups scenario solves this apparent contradiction. A group environment allows galaxies to evolve rapidly through tidal interactions and mergers (Coziol & Plauchu-Frayn 2007). However, one also has to consider that the relaxation time of a cluster formed by many groups, that is the time it takes for the energy to be redistributed equally throughout the cluster, is probably much longer than the typical dynamical friction time for one galaxy falling into an isotropic potential well. In fact, the relaxation time for the former could be much longer than the Hubble time. Consequently, it would be possible to observe peculiar velocities, even if the merging of groups forming the clusters started at a very early epoch ($z \sim 3–4$). On the other hand, the substructures observed in clusters today could be traces of more recent events, related to continuous accretion of mass by the clusters, namely, loose groups or smaller groups of galaxies falling in from the field. Another interesting consequence of the scenario is that the huge amount of hot intracluster gas found today in clusters may have been accreted only after the formation of the clusters by the merging of many groups and the formation of most of the galaxies in it. This is a direct consequence of the shallower potential wells of groups. This scenario greatly alleviates the problem of extra cooling for the formation of galaxies in clusters and may better explain the process of metal enrichment of the intracluster gas.

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ERRATUM: “THE DYNAMICAL STATE OF BRIGHTEST CLUSTER MEMBERS
AND THE FORMATION OF CLUSTERS” (2009, AJ, 137, 4795)

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Online-only material: machine-readable and VO tables

Due to an error that occurred during the preparation of the online version of Table 1 of the published article, the radial velocity of the brightest cluster member of cluster AS1063 was incorrectly published as “04176n” while it should actually read “104176,” the trailing “n” meaning that it was taken from the literature. Due to our own error, in Table 2 the name of the galaxy in the brightest cluster member of cluster AS1063 was incorrectly published as “04176n” while it should actually read “104176n,” appended with (n) if taken from literature, (:) if uncertain, and “e” if photometric estimate.

Table 1

| BCM-ID (J2000) | R.A. (J2000) | Decl. (J2000) | R | BM types | RS/ACO89 | vcl | Nc | σcl | vpec | vpec/σcl | 2MASX | Other Names |
|----------------|-------------|-------------|---|-----------|----------|-----|-----|-----|------|----------|------|------------|
| (1)            | (2)         | (3)         | (4) | (5)       | (6)      | (7) | (8) | (9) | (10) | (11)     | (12) | (13)       |
| A0002          | 0010 16.87  | −19 39 41.6 | 1  | (1)       | B        | 36620 | 2  | 36720 | D    | J00081685−1939423 |
| A0005          | 0010 09.09  | +33 07 16.4 | 1  | cD        | 41000e   | 25840| 2  | 25840| cD   | J00100909+3307162 |
| A0017          | 0017 06.38  | +08 49 44.9 | 1  | cD        | 26961n   | 26440| 2  | 26440| cD   | J00170632+0849444 |
| A0021          | 0021 20 37  | +28 39 33.6 | 1  | B b       | 28401    | 855 | 2  | 855  | 0.07  | D        | J00204314−2542284ID |
| A0022B         | 0022B 20 43  | −25 42 28.4 | 3  | B        | 42432    | 77  | 2  | 77   | 0.32  | cD       | J00204314−2542284ID |
| A0034A         | 0034A 27 33  | −08 53 11.4 | 2  | I c      | 39657    | 2   | 39333| 13   | 0.18  | D cD     | J00273334+0853112 |
| A0034B         | 0034B 27 04  | −08 47 03.3 | 2  | I c      | 56555    | 2   | 56493| 2    | 0.18  | D        | J00273334+0853112 |
| A0035          | 0035 27 23  | +23 33 01.5 | 3  | I c      | 58000e   | 2   | 58000| D    | J00273334+0853112 |
| A0038          | 0038 28 19 30 | +13 54 59.8 | 1  | cD       | 42330    | 13  | 538 | 42217| −0.18 | cD       | J00281984+1354596 |
| A0049          | 0049 31 26.81 | −11 24 41.8 | 1  | cD       | 47100    | 1   | 47100| 1    | 0.18  | D cD     | J00312683−1124418 |

Notes.
1 BM types were converted from roman numbers I, I–II, III, to 1, 2, . . . , 5, and are given in parentheses if this cluster has a discarded BCM candidate in Table 2.
2 Appended with (n) if taken from literature, (e) if photometric estimate, (;) if uncertain, and (‘) if photometric estimate; an asterisk indicates a value that is 2–4 lower than the photometric estimate.
3 Taken from literature whenever vcl is taken from literature.
4 Appended with (+) if taken from Andernach’s database, (n) if in the background to the cluster, and (e) if photometric estimate.

Table 2

| Abell No. | R.A. (J2000) | Decl. (J2000) | vcl | vBCM | Other Names |
|-----------|-------------|-------------|-----|------|------------|
| (1)       | (2)         | (3)         | (4) | (5)  | (6)        |
| A0002     | 0007 50.56  | −19 42 26.8 | 36575| 19551| 2MASX J00075059−1942265 |
| A0022     | 0020 39.10  | −25 35 29.7 | 38548| 19097| 2MASX J00203910−2535297 |
| A0034     | 0027 19.40  | −08 48 21  | 39657| 12193| 2MASX J00271940−0848212 |
| A0099     | 0045 11.38  | −17 16 10.4 | 28794| 8562  | 2MASX J00451138−1716104 |
| A0107     | 0050 15.33  | −19 14 43.0 | 17952a| 25809| 2MASX J00501533−1914431 |
| A0180     | 0122 31.19  | +03 07 31.0 | 40368a| 35961| 2MASX J01223119+0307312 |
| A0327     | 0212 43.64  | −26 09 49.9 | 50801| 17628| 2MASX J02124363−2609504 |
| A0403     | 0258 10.24  | +03 21 42.4 | 30044| 3126  | NGC 1153 |
| A0403     | 0258 41.48  | +03 26 05.1 | 30044| 7089  | UGC 02446 |
| A0415     | 0306 55.96  | −11 59 00.6 | 23756| 3993  | MCG-02-08-052 |

Notes.
1 Only one radial velocity for a representative cluster component is given for clusters with known superposition; we made sure that vBCM is incompatible with all redshift components known to us; appended with “n” if taken from literature, “;” if uncertain, and “e” if photometric estimate; an asterisk indicates a value that is a factor of 2–4 lower than the photometric estimate.
2 Appended with an asterisk if taken from Andernach’s database, with “b” if in the background to the cluster, and with “e” if photometric estimate.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)