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Observations of High Dispersion Clusters of Galaxies: Constraints on Cold Dark Matter

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ABSTRACT

We have studied the dynamics of several Abell clusters of galaxies, which were previously reported to have large velocity dispersions, and hence very large masses. In particular, we have investigated the assertion of Frenk *et al.* (1990) that clusters with intrinsic velocity dispersions $\gtrsim 1200$ km s^{-1} are extremely rare in the universe, and that large observed dispersions are due to projection effects. We report redshifts for 303 galaxies in the fields of A1775, A2029, A2142, and A2319, obtained with the Nessie multifiber spectrograph at the Mayall 4m telescope. A1775 appears to be two poor, interacting clusters, separated in velocity space by ~ 3075 km s^{-1} (in the cluster rest frame). A2029 has a velocity dispersion of 1436 km s^{-1}, based on 85 cluster member redshifts. There is evidence that a group or poor cluster of galaxies of slightly different redshift is projected onto (or is merging with) the core of A2029. However, the combined kinematic and x-ray data for A2029 argue for an intrinsically large dispersion for this cluster. Based on redshifts for 103 members of A2142, we

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find a dispersion of 1280 km s^{-1}, and evidence for subclustering. With 130 redshifts in the A2319 field, we have isolated a subcluster $\sim 10'$ NW of the cD galaxy. After it's removal, A2319 has a velocity dispersion of 1324 km s^{-1}. The data obtained here has been combined with recent optical and x-ray data for other supposedly high-mass clusters to study the cluster velocity dispersion distribution in a sample of Abell clusters. We find that clusters with true velocity dispersions $\gtrsim 1200$ km s^{-1} are not extremely rare, but account for $\sim 5\%$ of all Abell clusters with $R \geq 0$. If these clusters are in virial equilibrium, then our results are inconsistent with a high-bias ($b \gtrsim 2$), high-density CDM model.

Subject headings: galaxies: clustering – redshifts – cosmology: dark matter

1. Introduction

Most current models of structure formation assume that galaxies and clusters of galaxies grew gravitationally from initially small density fluctuations in the early universe. Of particular interest are the most massive clusters which formed at rare, high-density peaks in the initial density fluctuations. By comparing the observed abundance of massive clusters in the present-day universe with predictions of cosmological models of structure formation we can constrain the models and their input parameters.

The most successful theory of structure formation to date is, arguably, that of cold dark matter (CDM) (Blumenthal *et al.* 1984). One of the appealing aspects of CDM is the fact that the only free parameter in the model, aside from H_o and Ω, is the normalization of the primordial fluctuations (Frenk *et al.* 1990, hereafter FWED). The normalization is characterized by the biasing parameter, b, which is the ratio of the galaxy number contrast to the mass contrast: $b = \delta_n/\delta_m > 1$. A difficult task for CDM is to successfully account for mass fluctuations on all scales with a single value for the bias parameter. Large-scale structure observations imply a smaller value of b, while dynamical mass estimates are best reconciled with larger values of b (Peebles *et al.* 1989).

FWED constructed an ensemble of N-body simulations of a CDM universe, with $h = 0.5$ ($h = H_o/100$ km s^{-1} Mpc^{-1}), $\Omega = 1$ and bias parameters in the range $b = 1 - 3.3$. When the simulated clusters in these models were compared with observed clusters, it was clear that the "standard" CDM model with $b = 2.5$ failed to reproduce the observations. In particular, the observed distribution of cluster velocity dispersions did not match the model predictions well for any value of b. The CDM model with $b = 2.5$ predicts that very few

if any clusters in the universe should have velocity dispersions greater than 1000 $\mathrm{km\,s^{-1}}$. FWED then constructed cluster catalogs from their simulations, using the same techniques that were used to construct the Abell catalog (ie. by looking at the projected galaxy distribution on the sky). They found that a significant fraction of rich clusters identified in projection in their simulations do not correspond to rich 3-dimensional clusters. Instead, rich clusters with high *observed* dispersions resulted from the chance projection of a group, cluster, or set of groups against a single cluster with an intrinsically lower velocity dispersion. The observed cumulative distribution of velocity dispersions agreed well with the CDM models for *projected* clusters with $b = 2 - 2.5$.

Given the FWED results, we began an investigation into the dynamics of reported high velocity dispersion clusters of galaxies (as of 1989), in order to determine if these high dispersions are due to subclustering or contamination effects. Although the recent COBE observations of fluctuations in the cosmic microwave background imply a low-bias universe (Wright *et al.* 1992) , the reality of high dispersion (ie. high mass) clusters is still important for structure formation models. From the Struble & Rood (1987) compilation of redshifts and velocity dispersions, we chose a sample of northern Abell clusters with $z < 0.10$ and having a reported velocity dispersion based on at least 10 member redshifts. We will refer to this sample as our Abell velocity dispersion sample. Ten of these clusters had a reported dispersion, $\sigma > 1200$ $\mathrm{km\,s^{-1}}$ – A85, A399, A401, A426, A1775, A2029, A2142, A2255, A2256, and A2319, and will be referred to as the high dispersion subsample. In this paper, we present new redshifts for galaxies in A1775, A2029, A2142 and A2319, and discuss their dynamics. These results are combined with data for other clusters in our sample which have recently been published to study the massive end of the cluster mass function.

2. Observations

Observations of A1775, A2029, A2142 and A2319 were obtained over the course of three observing runs in 1990-1991 at the KPNO Mayall 4 meter telescope. Spectroscopy of cluster galaxies was obtained with the Nessie multifiber instrument, which utilized the Lockheed Cassegrain Camera as a plate holder for fiber-optic plugboards. Observations were obtained with the "Blue Nessie" which nominally employed 49 fibers of 20 meters in length and $320\mu m$ in diameter (corresponding to $2.1''$ diameter). The fiber cables fed the light into the RC spectrograph, which was located in the Coude room during the observations. Excellent system stability was achieved due to the spectrograph not being mounted on the telescope. A detailed description of Nessie has been given by Barden & Massey (1988).

Observations of A1775, A2029 and A2142 were obtained in March 1990 with a

UV-flooded Texas Instruments 800×800 CCD with $15\mu m$ pixels and read-noise of 9 electrons pixel^{-1} rms. Observations of A2319 and further observations of A2142 were made in October 1990 and July 1991 with a Tektronix 1024×1024 CCD with $24\mu m$ pixels and read-noise of 4 electrons pixel^{-1} rms. All observations employed the KPC-10 grating (300 lines mm^{-1}) with resolution of 7Å. The wavelength coverage was 3700–5200Å (1.75Å pixel^{-1}) with the TI CCD, and 3700–6500Å (2.75Å pixel^{-1}) with the Tektronix CCD. Observations with the TI CCD were typically single exposures of duration 4500–5400 sec. The low read-noise of the Tektronix chip, however, allowed us to take four 1200 sec exposures in each fiber configuration, which aided considerably in removing cosmic rays. Due to bad weather, spectra for only one fiber configuration were obtained for A1775. As it turned out, this cluster was obviously a double cluster, and further redshifts were unnecessary. Two fiber configurations were observed for A2029, and four different fiber configurations were observed in both A2142 and A2319.

Between 10 and 15 of the 49 fibers were either broken or had very low transmittance during our various observing runs and were not used. Typically, $8 - 10$ fibers were devoted to obtaining sky spectra, thereby leaving $28 - 30$ fibers for galaxies. Long He-Ne-Ar comparison lamp exposures were obtained through all fibers at the beginning of the night. During the night, drifts in the wavelength scale were monitored by taking spectra of the Hg dome lamps after each sky exposure. The wavelength drifts were always quite small – the mean drift being smaller than the rms errors in the wavelength calibration. Dispersion curves with internal errors of ~ 0.12Å rms were obtained from low-order polynomial fits to roughly 35 emission lines in the comparison lamp spectra. Fiber flat fields of an illuminated screen inside the dome (the Great White Spot) were obtained for every fiber configuration and were used to compute relative fiber-to-fiber throughput. Sky spectra were combined, scaled according to the fiber throughput for each fiber, and subtracted from each galaxy spectrum. The sky subtraction was generally excellent. The flat-fielding, spectrum extraction, wavelength calibration and sky-subtraction were all performed with the DONESSIE task in IRAF, which was specifically written for Nessie data reduction by Valdes (1990).

Radial velocities of galaxies were computed using the IRAF RV package, which is based on the Tonry & Davis (1979) cross-correlation technique. The galaxy spectra were continuum subtracted, binned in the logarithm of the wavelength, and cleaned of any cosmic rays or emission lines prior to cross-correlation. Templates included spectra of galaxies M32 (-200 km s^{-1}), the nucleus of M31 (-297 km s^{-1}), N3379 ($+922$ km s^{-1}), as well as stars HD 52071 ($+94.7$ km s^{-1}) and AGK2+24 (-49.5 km s^{-1}). Each cluster galaxy was cross-correlated against multiple spectra of these templates, and the results were averaged together (after sigma-clipping to remove spurious values). All spectra were examined by

eye as a sanity check of the cross-correlator, and to identify emission lines. The resulting velocities are given in Tables 1 – 4 for A1775, A2029, A2142, and A2319, respectively. Column 1 contains an identifying number, columns 2 and 3 give the sky coordinates (J2000 equinox), the observed heliocentric velocities, cz in km s^{-1}, are reported in column 4, and various notes about the spectra (such as the presence of emission lines) are reported in the last column. An "e" in the last column indicates the presence of [O II] λ3727 emission and possibly Hβ emission, while an "s" indicates a starburst spectrum with [O II] λ3727, Hβ, and [O III] $\lambda\lambda$4959,5007 in emission. The letter "a" indicates the presence of absorption in the Balmer series. Cross-references of galaxies to those previously measured are also noted in this column. The positions of galaxies were measured from digitized versions of the "Quick V" Palomar survey (epoch 1983), and are internally consistent to less than 0.5″. The absolute positions are accurate to only several arcseconds however. Unless otherwise noted in the tables, the "1σ" internal velocity uncertainty for each galaxy is ~ 50 km s^{-1}. The external (velocity zero-point) error is probably $\lesssim 20$ km s^{-1}. The reader is referred to Hill & Oegerle (1993) for a more detailed discussion of velocity errors.

The single integration on the A1775 field netted the 25 velocities reported in Table 1. In Table 2, we report 54 galaxy redshifts in the A2029 field. The Nessie observations of A2142 and A2319 produced 112 redshifts in each field and are reported in Tables 3 and 4. These datasets were supplemented with galaxy velocities from the literature, as described below.

3. Previous Observations

A1775 is an Abell richness 2 cluster of Rood-Sastry type "binary". Much of the previous interest in A1775 has centered on the double giant elliptical system (VV 5-32-63/64) in the cluster core (Jenner 1974, Chincarini *et al.* 1971, Hintzen 1979). Hintzen also measured the velocities of 8 other galaxies in A1775 and reported a velocity dispersion of 1522 km s^{-1}. Several years later, Kirshner *et al.* (1983, hereafter KOSS) published velocities of galaxies in the A1775 field from their redshift survey conducted in polar cap fields. This data went largely unnoticed by cluster researchers – for instance, the 1987 compilation of cluster velocity dispersions by Struble & Rood (1987) still listed the results obtained by Hintzen, even though several dozen redshifts had been compiled by KOSS. The KOSS data clearly showed the presence of at least two clusters along the line of sight, although the data were not ideal. A1775 was at the edge of their survey field NP5, so only the cluster core and the Northwest quadrant of the cluster were surveyed by KOSS. Furthermore, the KOSS velocities were accurate to only $100 - 200$ km s^{-1}, which is rather poor for studying cluster dynamics (but perfectly fine for the intended goals of the KOSS program).

Our observations were intended to provide a more even sky coverage of the cluster and redshifts with much smaller uncertainties. In addition to the 24 cluster member velocities measured with Nessie and reported in Table 1, we have added 25 redshifts from the KOSS survey and two velocities from Hintzen (1979), resulting in a total of 51 velocities in the range $17000 - 25000$ km s^{-1}. Zabludoff *et al.* (1990) have reported velocities for the two components of the central binary galaxy (note: the Zabludoff *et al.* velocity reported for the SE component is actually the velocity of the NW component, and vice versa). Our velocity for the SE component (G234 in Table 1) agrees very well with the Zabludoff value ($\delta v = 4$ km s^{-1}). Since we did not observe the NW component of this double galaxy, we have adopted the Zabludoff *et al.* value of 22587 km s^{-1} for the NW component. We have also compared the velocities of galaxies observed in common with KOSS – the average difference for 10 galaxies is $\bar{v}(us) - \bar{v}(\mathrm{KOSS}) = 9$ km s^{-1} with a dispersion of 159 km s^{-1}, which is entirely expected based on the velocity uncertainties in the two datasets. In calculating the average and dispersion of differences with KOSS, we excluded one galaxy (our G215 = KOSS23) for which the KOSS value was discrepantly large ($\delta v = -655$ km s^{-1}). We have checked our velocity determination, and believe it is correct. In all cases of re-measurements of galaxies observed by KOSS, we have adopted our Nessie velocities, which generally have smaller uncertainities.

A2029 is an Abell richness 2 cluster of Rood-Sastry type "cD". Galaxy redshifts in this cluster have been reported by Faber & Dressler (1977, hereafter FD), Dressler (1981) and Bower *et al.* (1988, hereafter BEE). Dressler (1981) reports velocities for 47 cluster members (18 of which were previously published by FD). BEE measured velocities for 24 cluster members, of which 13 had been previously observed by Dressler. We have measured velocities for 50 cluster members (Table 2), of which 3 are in common with BEE and 22 are in common with Dressler. The large overlap with Dressler was intended for comparison (bad weather prevented our obtaining more new redshifts). We find excellent agreement for the 3 galaxies observed in common with BEE (our galaxies G201, 229 and 242) – an average difference of +35 km s^{-1} with a dispersion of 13 km s^{-1}. The comparison with Dressler's data was mixed. The Dressler data was obtained at several different telescopes with different detectors (SIT, Reticon, IDS). We find good agreement with velocities for galaxies D1–D18 in Dressler (1981), which were essentially all observed by FD at Lick Observatory. We re-observed 11 of these galaxies and find a mean difference of -35 km s^{-1} and a dispersion of 92 km s^{-1}, completely consistent with the reported uncertainties in our measurements. However, for 9 other galaxies in common, which were measured by Dressler at Las Campanas with the Reticon, we find a mean difference of -153 km s^{-1} and a dispersion of 160 km s^{-1}. We have omitted from this comparison G262 (D31), which Dressler reported an uncertain velocity of 23560 km s^{-1}, which is substantially different

than our value of 21888 km s^{-1}. Dressler reports a possible systematic shift of 200 km s^{-1} between the FD velocities and those obtained with the Reticon at Las Campanas, very similar to that found here. Consequently, we have combined our data with the literature in the following way. First, we adopt our Nessie velocities reported in Table 2, and then add 19 velocities from BEE (except galaxy BEE22, for which BEE believe their slit was off the target). We next add 17 redshifts from Dressler (1981). This results in our having to adopt only 2 of the Dressler redshifts obtained at Las Campanas. Most of the data adopted from Dressler (1981) was obtained with the Digital Spectrograph at the Hale 5m telescope. Finally, we add one velocity from Hu *et al.* (1985; hereafter HCW) – their galaxy 9.

For the record, we note several inaccuracies in the BEE galaxy list. BEE identified the galaxy labeled "α" (BEEα) in their Table 2 as being the same as Dressler galaxy 37 (D37). However, the coordinates listed for BEEα are incorrect – instead, the coordinates of galaxy BEEβ in their Table 2 correspond to D37. Also, BEE list the magnitude of BEEα as V=21.2, which is much too faint. We adopt the redshift for D37 as reported by Dressler (1981) (as did BEE), and we exclude galaxy BEEβ from our compilation, since the identification for this galaxy is unclear. We also note that the coordinates listed in BEE Table 2 for galaxy BEE39 are incorrect; however, the identity of the galaxy is clear from their Plate 1. The correct coordinates for BEE39 are: $\alpha(2000) = 15^h10^m54.66^s$, $\delta(2000) = +05°43'49.4''$.

A2142 is also an Abell richness 2 cluster of Rood-Sastry type "binary". Cluster galaxy redshifts have been reported by Hintzen & Scott (1979, hereafter HS) and HCW. HS reported velocities for 17 galaxies in the A2142 field, of which 13 are cluster members with a velocity dispersion of 1241 km s^{-1}. We have re-observed 8 of these galaxies and found an average velocity difference of 40 km s^{-1} and a dispersion of 160 km s^{-1} between our measurements and those of HS. Again, this is in accord with the uncertainities of 150 km s^{-1} reported by HS. We have supplemented our A2142 dataset with the 5 galaxies from the HS study that we did not observe (HS galaxies 106, 108, 109, 110, 114). In addition, we have also included two galaxies from HCW (their galaxies 3 and 4).

A2319 is an Abell richness 1 cluster with RS Type "cD". FD have measured velocities for 35 galaxies in the field of A2319, of which 31 are cluster members. We re-observed 7 of these galaxies, for which we find an average velocity difference of $\bar{v}(us) - \bar{v}(FD) = 112$ km s^{-1}, but with a dispersion of only 86 km s^{-1}. We conclude that there may be a velocity zero-point offset between our two datasets of order 100 km s^{-1}, but small number statistics prevent a definitive statement. We have chosen to add the 23 velocities from FD to our dataset without applying any corrections. These galaxies make up a relatively small part of the total data, so even if an offset did exist, it should have a negligible affect on our results.

4. Velocity Distributions

Velocity histograms for the observed clusters are shown in Fig. 1. In this figure, the arrow marks the observed velocity of the brightest cluster galaxy, and the dotted line is a normalized Gaussian with a dispersion equal to that of the observed radial velocities (assuming a single cluster model) and extends to $\pm 3\sigma$ in velocity. The mean cluster heliocentric velocities and dispersions are listed in Table 5. The uncertainties in the dispersions have been calculated as described by Danese *et al.* (1980). Below, we discuss the velocity distributions of each cluster.

4.1. A1775

As can be seen in Fig. 1a, the A1775 system is composed of two clusters separated in velocity by ~ 3075 km s^{-1} in the cluster rest frame. The mean velocity of the low velocity cluster (designated A1775A) is 19462 km s^{-1}, with an internal velocity dispersion of 518 km s^{-1} based on 21 observed members (galaxies with $cz < 21000$ km s^{-1}). The mean velocity of the high velocity cluster (A1775B) is 22767 km s^{-1}, with a velocity dispersion of 394 km s^{-1} based on the 29 galaxies with $cz > 21000$ km s^{-1}. The galaxy with $cz = 24909$ km s^{-1} (KOSS25) has been omitted from A1775B, since it's velocity is $\sim 5\sigma$ larger than the A1775B mean. Therefore, A1775 appears to consist of two poor clusters seen in projection. In Fig. 2, we plot the positions of the observed galaxies; those in A1775A are plotted as open circles, while the A1775B galaxies are shown as solid triangles. The uneven sky distribution is due to coverage of the NW part of the cluster field by the KOSS survey.

The two arrows in Fig. 1a indicate the velocities of the two components of the central binary galaxy (G234 and KOSS5). The velocity of KOSS5 is close to the mean of A1775B, while G234 appears to be a member of A1775A, although it is significantly offset from the A1775A mean velocity. Hintzen (1979) first noted that the two components of the central binary might belong to high and low velocity clusters. However, the chance superposition of these two galaxies, with projected separation of only $\sim 24''$, seemed highly unlikely, so Hintzen concluded that A1775 was a single cluster. The large velocity difference of the double galaxy components was explained as a natural consequence of the large apparent velocity dispersion of the cluster. We now know that A1775 is not a single system. If A1775A and A1775B were simply two clusters being viewed in projection, then we would expect G234 to have a velocity fairly close to the mean of the A1775A. Instead, it has a velocity ~ 1300 km s^{-1} (3σ) higher than the A1775A mean. We conclude from this that

the high and low velocity clusters have interacted, and G234 has been drawn closer to A1775B in velocity-space. This conclusion is supported by reports of isophotal twisting and disturbed light profiles in the central binary galaxy (Hayes & Bhattychara 1990). Given the poor nature of the individual clusters (hence, their low mass) and their large separation in radial velocity, A1775A and A1775B (and the two galaxies comprising the central double) are very unlikely to be gravitationally bound.

4.2. A2029

The velocity histogram for A2029 is shown in Fig. 1b. After excluding several obvious non-members at low velocity, and one galaxy at $cz = 28764$ km s^{-1} (G388), there are 85 cluster members in the velocity range $19000 < cz < 27000$ km s^{-1}, with a mean velocity of 23169 km s^{-1} and a dispersion of 1436 km s^{-1}.

In Fig. 3a, we plot the position of cluster members with velocity coded symbols (see the figure caption for the code). There appears to be some subclustering at the cluster center, so we have turned to a quantitative method of measuring subclustering using the "δ-test" (Dressler & Shectman 1988). In this test, for each cluster member, the term $\delta_n^2 = 11[(\bar{v}_{local} - v_{cl})^2 + (\sigma_{local} - \sigma_r)^2]/\sigma_r^2$ is calculated, where $\bar{v}_{local}$ and σ_{local} are the mean velocity and dispersion for the 10 nearest neighbor galaxies, and v_{cl} and σ_r are the global cluster values. In Fig. 3b, we plot the positions of cluster galaxies, where the diameter of the circle is proportional to e^{δ}. Regions with many nearby large circles (large values of δ) indicate spatially correlated structures which are deviant in velocity and/or dispersion from the global values. The numerous large circles just to the southwest of the cD galaxy indicate subclustering. The significance of this subclustering can be determined quantitatively by computing the cumulative deviation, Δ, by summing the δ_n for all observed galaxies in the cluster. The statistical significance of this cumulative deviation is determined by Monte Carlo simulations in which the observed velocities are randomly assigned to galaxies at the observed galaxy locations, and Δ is computed for each of these simulated clusters. We ran 1000 such Monte Carlo simulations of A2029, and found that in 19% of the cases, the simulated clusters had values of Δ larger than the observed cluster. So, the δ-test does not provide a strong argument for subclustering.

In Fig. 6, we show the velocity distributions for galaxies in the inner $300''$ ($300h^{-1}$ kpc) and for those galaxies outside this region. The galaxies in the core have approximately the same dispersion as the outer galaxies, but have a mean recession velocity that is 634 km s^{-1} less than the outer galaxies. However, the significance of this result $\sim \delta v/(\epsilon_i^2 + \epsilon_o^2)^{1/2} = 1.9$, where ϵ_i and ϵ_o are the uncertainties in the mean velocity of the inner and outer regions,

respectively. Once again, the evidence is suggestive but not statistically significant. Arguably, the strongest evidence for subclustering in the core comes from the peculiar velocity of the cD galaxy, which is 513 km s^{-1} with respect to the galaxies in the inner 300 arcsec. Previous studies have indicated that significantly peculiar cD velocities are the result of subclustering, and that the cD is usually within ~ 200 km s^{-1} of the systemic velocity of the cluster (Oegerle & Hill 1994, Bird 1994). The cD galaxy also has a velocity which is close to that for the outer galaxies, implying that a group or cluster of galaxies of slightly different redshift is projected onto (or is merging with) the core of A2029. This conclusion will be revisited below after reviewing the x-ray data.

4.3. A2142

The velocity histogram for A2142 is shown in Fig. 1c. After removal of obvious foreground and background galaxies, there are 103 cluster members in the velocity range $24000 < cz < 30000$ km s^{-1}, with a mean velocity of 27117 km s^{-1} and a dispersion of 1280 km s^{-1}. The distribution appears reasonably Gaussian, but does have a low-amplitude high velocity tail.

No subclustering is obvious in Fig. 4, at least to the eye. We have used the δ-test, described above, to test this. We ran 1000 Monte Carlo simulations of A2142, and found that in 10% of the cases, the simulated clusters had values of Δ larger than the observed cluster. Consequently, the δ-test provides marginal evidence for subclustering in A2142.

An indirect line of evidence for subclustering in A2142 is provided by the large velocity difference of the two bright galaxies in the cluster core (G201 and G219 in Table 3). If these galaxies had formed in the bottom of the cluster potential, then they should have only a small residual motion relative to the potential well. G201 does appear to lie at the cluster systemic velocity (shown by the arrow in Fig. 1c), while G219 has a velocity ~ 1600 km s^{-1} larger than the cluster mean. On the other hand, if G219 did not form in the cluster core, then a relative velocity of $\sim 1\sigma$ with respect to the cluster would certainly not be unexpected. Based on the available redshift data for 103 cluster galaxies, a velocity dispersion of 1280 km s^{-1} is a likely upper limit.

4.4. A2319

The A2319 velocity histogram is shown in Fig. 1d. The four galaxies with $cz > 22000$ km s^{-1} in Table 4 have been excluded from cluster membership. The remaining

130 cluster members in the velocity range $12000 < cz < 22000$ km s^{-1} have a mean velocity of 16446 km s^{-1} and a velocity dispersion of 1770 km s^{-1}.

FD noted a gap in the velocity distribution of A2319, and argued that A2319 is really two clusters viewed in projection. As can be seen in Fig. 1d, with 4 times more data, we have filled in the velocity distribution, and the evidence for two clusters is not immediately obvious. A plot of observed galaxy positions is shown in Fig. 5a with velocity coded symbols. Note the group of galaxies $\sim$ 10 arcmin NW of the cluster center which has velocities larger than the cluster mean (open circles and plus sign symbols). This "subcluster" corresponds to cluster A2319B in FD's notation (the main cluster is dubbed A2319A). We have employed the δ-test, as described above, to determine the statistical significance of this subclustering. In Fig 5b, we show the plot for A2319 – the subcluster to the NW of the cluster center stands out prominently. In 1000 Monte Carlo simulations of A2319, 12% of the simulated clusters had larger cumulative deviations, Δ, than the actual observed cluster. Hence, there is a $\sim$ 10% chance that A2319B is not a physical association.

We have attempted to decompose the velocity distribution into two components based on the correlation of velocities with sky position. A unique model is not possible, since the two clusters are seen in projection and overlap in velocity. Nevertheless, a representative decomposition was made in the following manner: The group of galaxies 10 arcmin NW of the cluster center (A2319B) was assumed to be a physical assocation. All galaxies in this region of the sky with velocities greater than 18600 km s^{-1} were assumed to be members of A2319B. Galaxies with velocities $<$ 18600 km s^{-1} were assigned to either A2319A or B depending on their sky location, and with an effort to keep the velocity distribution of A2319B Gaussian. The results are shown in Fig. 7. A2319A contains 100 observed members with a mean velocity of 15727 km s^{-1} and a dispersion of 1324 km s^{-1}. A2319B contains 28 observed members, mean velocity of 18636 km s^{-1} and a dispersion of 742 km s^{-1}. The mean velocities of A2319A and B in this model are not significantly different than that assumed by FD. We find that A2319B has only $\sim$ 1/4 as many galaxies as in A2319A, compared to FD's estimate of 1/2. We also derive a much larger velocity dispersion for A2319A – 1324 km s^{-1} versus FD's estimate of 873 km s^{-1}.

Although this model for A2319 is not unique, it is at least consistent with the available data. The principal question that we are interested in answering here is "how small can we make the velocity dispersion of A2319A?" We have therefore considered models with more of the observed galaxies assigned to A2319B, and, hence, fewer high velocity galaxies in A2319A. We found in doing this that there was a limit to the number of galaxies that we could reasonably ascribe to A2319B. If A2319B was made too large, then subclustering became apparent in A2319B; the low velocity galaxies were distributed fairly evenly over a

large area of sky, while the galaxies at $v \gtrsim 18500$ km s^{-1} are clumped in the NW region. It is clear that in this case we are incorrectly assigning galaxies to A2319B that belong to A2319A. By placing a requirement on our decomposition that it produce two clusters which do not themselves contain subclustering, we find after some experimentation a lower limit to the velocity dispersion of ~ 1250 km s^{-1} for A2319A.

5. X-ray data

In Fig. 8, we show *Einstein* maps of x-ray emission from the four clusters studied here. Interestingly, the x-ray map of A1775 shows no evidence for the cluster's multiple nature, which is shown very clearly in the redshift data. On the other hand, both A2142 and A2319 have asymmetric x-ray distributions. The asymmetry in A2142 extends to the southeast of the cluster center; however, there does not appear to be a subcluster in velocity-space at this position. In Fig. 4b, one can see galaxies which appear as discrepant in the Dressler-Shectman plot, but they are discrepant in velocity dispersion (ie. the galaxies do not appear to be a cohesive merging group). The A2319 x-ray emission is also asymmetric, with an extension to the NW which coincides with the location of subcluster A2319B. The weakness of the x-ray emission from A2319B is in accord with our estimate of its relative richness compared to A2319A. Recent observations of the hot gas within 2 arcmin of the center of A2319 by the ASCA x-ray satellite yield a temperature of $T \sim 12$ keV (Mushotzky 1994), consistent with the high velocity dispersion of 1324 km s^{-1} that we derive for A2319A. The x-ray surface brightness of A2029 appears almost symmetric, with no indication of a superposed cluster to the southwest of the cluster core, as suggested by the δ-test (see Fig. 3b).

Many x-ray emitting clusters contain cooling flows; *eg.* models of the x-ray emission from the intracluster gas predict that the cooling time of the gas at the cluster center is less than the Hubble time (Arnaud 1988). The cooling of the gas leads to an inward flow which is required to maintain pressure equilibrium (Fabian *et al.* 1991). There appears to be some correlation between the lack of a cooling flow and the morphology of the cluster. In the Edge *et al.* (1992) sample of 55 clusters, the four clusters which did not have cooling flows were Coma, A2255, A2256 and A3667, which all contain two dominant galaxies in their cores. This fact supports the model proposed by McGlynn & Fabian (1984) in which cooling flows are disrupted when similar mass clusters merge. A2029 contains a strong cooling flow, while A2142 and A2319 have intermediate and weak cooling flows, respectively (Edge *et al.* 1992). This line of evidence then argues against recent mergers of massive subclusters in the cores of A2029, A2142, or A2319.

6. Discussion

6.1. A2029, A2142, A2319

The redshift data for A2029 provides some indication of subclustering in (or projected onto) the cluster core. However, this putative subcluster is not in evidence in the x-ray data. We conclude that if this subcluster exists, it must be of low mass – a group or poor cluster with low velocity dispersion and hence low x-ray flux. If the mean velocity of this subcluster is $\sim 500 - 1000$ km s^{-1} less than the systemic velocity of A2029, as suggested by Fig. 6, then the instrinsic dispersion of A2029 must be somewhat *larger* than the observed value of 1436 km s^{-1} (the addition of low and high dispersion clusters with similar mean redshifts will result in an observed dispersion which is intermediate). Alternatively, if the subcluster has been disrupted by passage through (or close to) the A2029 core, it may have an inflated dispersion. In this case, the intrinsic dispersion of A2029 could be slightly less than the observed value. We note that the stong cooling flow in A2029 argues against the recent passage of a subcluster through the core. We conclude that the evidence for an intinsically large velocity dispersion ($\gtrsim 1400$ km s^{-1}) for A2029 is strong. The virial mass, M_{VT}, of A2029 is estimated from the following standard formula, which assumes spherical symmetry:

$$M_{VT} = \frac{3\pi}{G}\sigma_r^2 \left\langle \frac{1}{r} \right\rangle^{-1},$$

and the harmonic mean radius, $\langle 1/r \rangle^{-1}$, is given by

$$\left\langle \frac{1}{r} \right\rangle^{-1} = DN_p \left(\sum_{i>j}^{N} \frac{1}{\theta_{ij}} \right)^{-1}$$

where $N_p = N(N-1)/2$ is the number of galaxy pairs, θ_{ij} is the angular separation of galaxies i and j, D is the cosmological distance of the cluster, and σ_r is the radial velocity dispersion. We find a virial mass of $1.24 \times 10^{15} h^{-1} M_\odot$ for A2029.

The δ-test for subclustering and the asymmetric x-ray distribution in A2142 indicate that either a merger has taken place in this cluster or that clusters are seen in projection. Consequently, the observed velocity dispersion of 1280 km s^{-1} is an upper limit to the true value. Consider a model in which A2142 is the merger/projection of two clusters whose brightest cluster galaxies (BCGs) are the two bright galaxies in the A2142 core (G201 and G219). G201 has a velocity that is very close to the observed mean cluster value, while G219 is ~ 1600 km s^{-1} larger (in the cluster rest frame). The subcluster containing G219 must then be less than half as rich as the cluster containing G201 (based on the velocity

distribution, Fig. 1c). If we specify the G219 subcluster as having a mean velocity given by its BCG, then the cluster containing G201 would have a dispersion of ~ 1100 km s^{-1}. Although this binary merger model for A2142 is possible, we have no means of determining its probability, so we provide it only to show that the intrinsic disperison of A2142 could be $\sim 20\%$ less than the observed value. Given the uncertain nature of the cluster, we have not calculated a virial mass.

The δ-test and the x-ray data for A2319 provide fairly convincing evidence for a subcluster (A2319B) containing about 30% as much mass as the main cluster (A2319A). Based on the subcluster model shown in Fig. 7, we derive virial masses of 1.47 and $0.42 \times 10^{15} h^{-1} M_\odot$ for A2319A and A2319B, respectively. The limits on bound orbits for the two clusters can be determined by the requirement

$$V_r^2 R_p \leq 2GM_{tot} \sin^2\alpha \cos\alpha,$$

where V_r is the relative radial velocities of the clusters, R_p is their projected separation, M_{tot} is the total virial mass, and α is the angle between the plane of the sky and the line joining the two clusters (Beers, Geller & Huchra 1982). The projected separation of A2319A and A2319A is $R_p = 0.5h^{-1}$ Mpc, and $V_r = 2600$ km s^{-1} in the cluster rest frame. The resulting constraints on V_r for bound orbits are shown in Fig. 9, as a function of the projection angle, α. The solid curve in this plot separates the regions of bound and unbound orbits in the (V_r, α) plane, and the dotted line is the observed value of V_r. A2319B is bound to A2319A only if $28° \lesssim \alpha \lesssim 78°$. Consequently, there is a reasonably high probability that these clusters are not bound and will never merge.

6.2. Other Clusters

In the Introduction, we listed 10 clusters which previously had been reported as having velocity dispersions greater than 1200 km s^{-1}. Data for several of these of clusters have recently been published. Malumuth *et al.* (1992) reported velocities for 126 galaxies in the field of A85. The distribution of redshifts is complex, and Malumuth *et al.* derive velocity dispersions ranging from 699 to 1087 km s^{-1} depending on which galaxies are included as cluster members. Bird (1994), using a galaxy partitioning algorithm, finds a velocity dispersion of 810 km s^{-1} based on the same dataset. In any event, the previously reported dispersion of 1443 km s^{-1} (Jones & Forman 1984) based on 15 redshifts is clearly spurious.

Abell 399 and 401 are a gravitationally bound pair of clusters, and were recently studied by Hill & Oegerle (1993) and Oegerle & Hill (1994). We found velocity dispersions of 1165 and 1130 km s^{-1} for A399 and A401 based on redshifts for 91 and 123 galaxies,

respectively. These new values supercede previous estimates of 1424 and 1294 $\mathrm{km\,s^{-1}}$, respectively, based on small numbers of galaxies. We found no evidence for subclustering in either A399 or A401.

Briel *et al.* (1991) have studied the A2256 cluster with the ROSAT x-ray observatory, and found clear evidence for substructure. From an analysis of the PSPC data they conclude that a poor cluster is merging with A2256. Furthermore, they have made a simultaneous fit of two Gaussians to the observed redshift distribution of 87 galaxies (Fabricant *et al.* 1989) and derive best-fit dispersions of 1270 $\mathrm{km\,s^{-1}}$ for A2256 and 350 $\mathrm{km\,s^{-1}}$ for the merging subcluster.

No new redshift data is available in the literature for A426 or A2255. We note however, that a ROSAT PSPC image of A426 shows an asymmetric x-ray surface brightness distribution (Böhringer 1992), so the cluster's observed velocity dispersion of 1277 $\mathrm{km\,s^{-1}}$ is a likely upper limit. Oegerle *et al.* (1994) have obtained spectra of several hundred galaxies in A2255 with the MX and Hydra multifiber spectrographs. Preliminary reductions of a portion of this dataset indicate that A2255 has a large velocity dispersion ($\gtrsim 1300$ $\mathrm{km\,s^{-1}}$) with no major subclustering. An analysis of the full A2255 dataset will be presented in a later paper, and will not be discussed further here.

6.3. Cluster Mass Function

Based on the data presented here for A1775, A2029, A2142 and A2319 plus recent data from the literature for A85, A399, A401 and A2256, we find that projection effects, subclustering and/or small number statistics were responsible for the large velocity dispersions previously reported for about half of these clusters. After corrections are made for subclustering, we find that a number of the clusters in our sample have large velocity dispersions: A399 ($\sigma = 1165$ $\mathrm{km\,s^{-1}}$; Oegerle & Hill 1993), A2029 ($\sigma = 1436$ $\mathrm{km\,s^{-1}}$), A2256 ($\sigma = 1270$ $\mathrm{km\,s^{-1}}$; Briel *et al.* 1991) and A2319 ($\sigma = 1324$ $\mathrm{km\,s^{-1}}$). We have omitted A2142 from this list since its dynamics are uncertain.

We have updated our Abell cluster velocity dispersion sample from the newer compilation of redshifts and dispersions by Struble & Rood (1991) plus redshift data published since 1991. This gives us a sample of 89 Abell clusters, which of course contains the high dispersion subsample studied here. It is of interest to investigate whether our Abell sample is a fair representation of the general Abell catalog. In our sample, 19% of the clusters have Abell richness $R = 2$ (ie. the number of cluster galaxies, N_c, within $1.5h^{-1}$ Mpc of the cluster center in the magnitude range $m_3 < m < m_3 + 2$ is $80 \leq N_c < 130$). In comparison, $\sim 15\%$ of the entire Northern Abell catalog of clusters with $R \geq 0$ have $R = 2$.

So, our Abell velocity dispersion sample is not composed of just the richest clusters, but appears to be similar in richness distribution to the general Abell catalog.

We have found that $\approx 5\%$ of the clusters in our Abell dispersion sample have $\sigma \gtrsim 1200$ km s^{-1}. Zabludoff & Geller (1994; hereafter ZG) have also investigated the distribution of velocity dispersions in a well-defined sample of 31 dense CfA2 groups plus 25 Abell clusters. This sample is more fairly weighted to the poor clusters than our Abell cluster sample. Neverthless, ZG find $n(> 1200 \text{ km s}^{-1})/n(> 550 \text{ km s}^{-1}) \sim 0.02$, which is within a factor of ~ 2 of that found here. The abundance of high dispersion clusters as determined by ZG and the present study is a factor of 3-6 less than that estimated by FWED using observational data on hand in 1989. As stated above, the previously derived abundance of high dispersion clusters was inflated by subclustering, projection effects and small number statistics in some clusters.

Although we claim above that our Abell velocity dispersion sample is fairly representative of the Abell catalog, a further question is whether or not it is representative of the general cluster population. For this purpose we rely on comparison with the ZG sample of dense groups and Abell clusters, which was extracted from a relatively small survey volume of $3.8 \times 10^6 h^{-3}$ Mpc^3. Consequently, their survey, while fairly sampling the poorer groups, undersamples the richer and higher velocity dispersion clusters. Similarly, the Abell catalog is incomplete for poorer systems. Finally, we have not observed all the potential high dispersion clusters in our Abell sample, some of which may be true high dispersion systems. Consequently, we believe that our result that $\approx 5\%$ of the clusters in our Abell dispersion sample have $\sigma \gtrsim 1200$ km s^{-1} is probably accurate to within a factor of ~ 2 for the general cluster population as well.

Recently, Bahcall & Cen (1993; hereafter BC) have used relations between cluster masses (via the virial theorem), richnesses and velocity dispersions to construct an "observational" cluster mass function:

$$n(> M) = 4 \times 10^{-5} (M/M^*)^{-1} \exp(-M/M^*) h^{-3} \text{ Mpc}^{-3},$$

with $M^* = (1.8 \pm 0.3) \times 10^{14} h^{-1} M_\odot$. Using the relation between cluster mass (within $1.5h^{-1}$ Mpc) and velocity dispersion employed by BC, $M = 0.68 \times 10^{13} (\sigma/100)^2 M_\odot$, the abundance of clusters with $\sigma > 1200$ km s^{-1} relative to the number with $\sigma > 550$ km s^{-1} (typical for an $R = 0$ Abell cluster with mass of $2 \times 10^{14} h^{-1} M_\odot$) is $\sim 3 \times 10^{-3}$. This is a factor of ~ 15 smaller than indicated from our observed Abell velocity dispersion sample.

In their analysis of the optical data for clusters, BC fit a function of the form $\sigma \propto N_c^{1/2}$ to the data for velocity dispersion *vs* optical richness (this functional form appears reasonable; if M/L ratios for clusters are constant, then $M \propto N_c$, and hence $\sigma \propto N_c^{1/2}$

follows from the virial theorem). Although noting the large scatter, BC found a best fit relation $\sigma = (90 \pm 20)N_c^{1/2}$. This fit was used to derive a relation between cluster mass and optical richness (using somewhat circuitous reasoning), which then yielded a cluster mass function from a sample of optically selected clusters. In Fig. 10, we plot the observed data from our velocity dispersion sample and the BC fit. In addition to very large scatter, there seems to be little justification for a relation of the form $\sigma \propto N_c^{1/2}$, based on the data. For instance, a linear fit to the data, shown as the solid line in Fig. 10, has the same residuals as the BC fit. We conclude that *observationally* there appear to be more high dispersion clusters than predicted by the BC relation $\sigma = (90 \pm 20)N_c^{1/2}$. Either the data is still seriously affected by substructure (yielding inflated dispersions), or there is no simple relation between velocity dispersion and optical richness.

BC were motivated to derive a cluster mass function in order to compare with their theoretical cosmological models, which did not have the required resolution to directly compare with observed velocity dispersion distributions. Translating cluster dispersions into masses can be frought with difficulties (cf. Merritt 1987), including the possibility of non-virialization as discussed above. BC concluded from their model comparison that an unbiased ($b \sim 1$), low density ($\Omega = 0.3$) universe fit their observationally determined mass function the best. Models with $\Omega = 1$ did not fit their mass function for any value of the biasing parameter. White *et al.* (1993; hereafter WEF) have continued the numerical simulation work of FWED, and arrived at apparently different conclusions. WEF find that the biasing depends strongly on the cosmological density parameter. Based on their assumed cluster mass function, these authors find $b \sim 1.7$ for a critical density universe, and $b \sim 0.7$ for a low density universe ($\Omega = 0.2$).

At least some, if not all, of the differing conclusions of these studies can be attributed to the assumed observational cluster mass functions. For instance, for an assumed median cluster velocity dispersion of 850 $\mathrm{km\,s^{-1}}$, WEF derive a cluster mass of $5.5 \times 10^{14} h^{-1} M_\odot$ within 1 Abell radius ($1.5h^{-1}$ Mpc), and a number density of clusters with mass larger than this of $n(>M) = 4 \times 10^{-6} h^3$ $\mathrm{Mpc^{-3}}$. However, for the same cluster mass, M, BC find a number density $n(>M) = 6 \times 10^{-7} h^3$ $\mathrm{Mpc^{-3}}$, which is a factor of 6 times smaller than the WEF value. For comparison, ZG find $n(\sigma > 850\ \mathrm{km\,s^{-1}}) \sim 1.5 \times 10^{-6} \mathrm{h^3\ Mpc^{-3}}$, which is about mid-way between the BC and WEF estimates. Consequently, BC and WEF are comparing their CDM models against different assumed mass functions, so different conclusions are not unexpected. While the form of the mass functions assumed by BC and WEF are probably similar, the normalizations appear to be quite different; the BC mass function has significantly fewer high mass clusters than assumed by WEF. The purpose of our paper is to provide the observational data to improve the derived cluster mass function, and thereby allow more meaningful comparisons with CDM models as they evolve.

7. Summary

We summarize our results as follows:

1. We have obtained redshifts for 303 galaxies in fields of the clusters A1775, A2029, A2142, and A2319, and combined this data with velocities from the literature for these clusters.

2. A1775 is a superposition of two poor clusters, which are apparently interacting. The clusters are separated in velocity space by ~ 3075 km s^{-1}.

3. A2029 has a measured velocity dispersion of 1436 km s^{-1}, based on 85 redshifts. There is some evidence that the mean velocity of galaxies in the cluster core ($< 300h^{-1}$ kpc) is ~ 600 km s^{-1} less than the galaxies at larger radii. Furthermore, the peculiar velocity of the cD galaxy with respect to the core galaxies is 513 km s^{-1}, which is anomalously high. In conjunction with the x-ray data, we conclude that a group or poor cluster of galaxies at slightly lower redshift is projected onto the cluster core, and that the intrinsic dispersion of A2029 is large (> 1400 km s^{-1}).

4. A2142 has a measured dispersion of 1280 km s^{-1}, based on 103 cluster member velocities. The Dressler-Shectman "δ-test" indicates the existence of substructure at the 90% confidence level. The *Einstein* IPC x-ray map also shows an asymmetric x-ray surface brightness distribution. We are unable to isolate a subcluster either spatially or in velocity space, so the dynamical picture of A2142 remains confused. Evidence for projection effects or merging seems fairly strong.

5. Based on 130 redshifts in the A2319 field, we have isolated a subcluster (A2319B) ~ 10 arcmin NW of the central cluster (A2319A). After it's removal, A2319A has a velocity dispersion of 1324 km s^{-1}, based on 100 members. There is a $\sim 50\%$ chance that A2319A and A2319B are not bound, and will not merge.

6. The observations discussed above, combined with recent optical and x-ray results for other clusters with previously reported large dispersions (A85, A399, A401, A2256), have improved our knowledge of the number of true velocity dispersions greater than 1200 km s^{-1}. The estimated fraction of clusters with $\sigma > 1200$ km s^{-1} is about three times lower than indicated by data in the literature 5 years ago. The number of high dispersion clusters was previously inflated by substructure, projection effects and small number statistics.

7. We conclude that clusters with dispersions $\gtrsim 1200$ km s^{-1} are not exceedingly rare, as suggested by Frenk *et al.* (1990), but comprise $\sim 5\%$ of all Abell clusters with richness $R \leq 2$. If these high dispersion clusters are in virial equilibrium, then we derive

an abundance of high mass clusters which is significantly larger than that predicted by the Bahcall & Cen (1993) cluster mass function. However, our results are in reasonable agreement with the cumulative distribution of velocity dispersions for the sample of dense groups and Abell clusters studied by Zabludoff & Geller (1994). Any viable cosmological model of cluster formation must account for the abundance of high dispersion clusters reported here. Our results are inconsistent with a CDM model with a bias parameter $b \gtrsim 2$.

8. Acknowledgments

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Table 1. A1775 Redshift Data

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
201	13 42 06.67	26 16 20.3	22718	BCM (A1775B), KOSS35
204	13 41 43.83	26 17 37.7	22682	
211	13 42 02.45	26 20 44.0	22513	
213	13 41 50.60	26 21 11.8	22781	KOSS62
215	13 42 02.80	26 21 39.2	22625	KOSS23
217	13 42 06.83	26 22 15.3	23059	KOSS67
228	13 41 47.13	26 27 35.0	23303	KOSS40
234	13 41 50.44	26 22 13.8	20785	BCM (A1775A), KOSS4
236	13 42 58.99	26 15 50.5	20186	
246	13 42 57.42	26 25 31.4	21911	
250	13 42 41.44	26 28 14.2	19130	
252	13 42 31.90	26 29 15.4	19619	
253	13 42 47.18	26 21 55.0	19404	
257	13 40 53.44	26 21 01.3	23121	
263	13 41 00.50	26 29 08.3	22796	
271	13 42 05.10	26 34 49.9	22647	KOSS26
282	13 41 51.81	26 05 58.5	19807	KOSS16
292	13 42 25.62	26 12 45.8	19740	KOSS12
293	13 42 32.57	26 13 58.9	7085	
294	13 43 18.23	26 14 09.9	19866	
295	13 42 41.91	26 14 22.7	19595	
297	13 43 15.29	26 10 03.4	19408	
298	13 43 07.53	26 03 29.0	20210	
306	13 40 48.90	26 04 18.9	19673	KOSS32
308	13 42 26.19	26 32 13.6	22891	KOSS46

[a]Galaxy cross-references: prefix KOSS = Kirshner *et al.* (1983)

Table 2. A2029 Redshift Data

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
201	15 10 56.10	05 44 40.8	23399	BCM, D1
204	15 11 11.92	05 39 13.3	25284	e
206	15 10 39.89	05 39 19.1	22914	
208	15 10 35.05	05 39 24.8	24328	D14
210	15 10 43.75	05 40 17.5	24336	s, a
215	15 11 03.78	05 41 13.7	25308	D25
217	15 11 06.37	05 41 23.1	24226	e, D24
218	15 10 58.73	05 41 30.8	21740	D23
219	15 11 15.91	05 41 48.0	25045	
221	15 10 51.32	05 42 29.1	20618	D22
223	15 10 42.45	05 43 07.8	21907	D5
229	15 10 52.74	05 43 29.0	21580	D20, BEE36
230	15 11 05.49	05 43 48.1	22491	D45
233	15 11 19.77	05 44 40.0	23373	
235	15 10 42.47	05 44 51.0	23619	
242	15 11 00.05	05 46 58.5	23480	D3, BEE16
251	15 11 16.91	05 49 48.1	21959	
258	15 10 38.24	05 51 13.2	20416	
262	15 11 15.15	05 52 19.0	21888	D31
263	15 11 10.36	05 48 51.4	23951	D8
271	15 11 27.98	05 45 40.2	20081	D17
272	15 11 33.66	05 45 46.9	25459	
276	15 11 25.24	05 48 34.8	24296	e, $\pm$100 km s^{-1}
279	15 11 22.40	05 49 06.5	22404	D18
281	15 11 46.80	05 49 56.4	26930	
285	15 12 04.05	05 51 32.5	23386	e
289	15 11 19.73	05 52 39.8	22029	D11
290	15 11 02.45	05 52 41.5	26591	D10
291	15 11 07.73	05 53 04.3	23184	
293	15 11 03.22	05 53 48.9	24068	D30
299	15 12 13.78	05 57 12.7	13030	s, a
300	15 11 46.28	05 57 37.5	23445	
308	15 11 22.58	05 59 37.6	15900	
317	15 11 52.28	06 01 47.2	24455	
323	15 12 00.43	06 03 38.0	22875	

Table 2—Continued

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
372	15 10 25.40	05 50 28.2	22304	D13
380	15 10 32.36	05 53 29.6	22209	D12
388	15 09 59.34	05 56 02.2	28764	$\pm$100 km s^{-1}
396	15 10 40.38	05 57 21.6	23367	
406	15 10 26.55	06 00 23.7	23123	
416	15 10 46.03	06 03 32.3	15831	
418	15 09 45.73	06 05 13.7	21970	$\pm$100 km s^{-1}
433	15 09 36.95	05 46 30.6	22877	$\pm$100 km s^{-1}
476	15 11 07.43	05 32 59.5	25438	D27
478	15 11 33.05	05 33 49.0	22075	
479	15 11 16.49	05 34 31.1	24416	
481	15 11 49.07	05 35 34.3	15671	
494	15 11 43.14	05 40 04.3	27177	
520	15 10 30.28	05 30 06.5	21957	
524	15 09 35.60	05 31 46.0	25160	
527	15 10 55.05	05 33 31.4	23760	
528	15 10 17.32	05 33 31.2	24088	
535	15 10 12.95	05 36 13.7	23715	D29
556	15 10 10.36	05 34 15.9	22957	D28

[a]Galaxy cross-references: prefix D = Dressler (1981), BEE = Bower *et al.* (1988)

Table 3. A2142 Redshift Data

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
201	15 58 20.09	27 14 01.4	27092	BCM, HS101
202	15 58 37.20	27 08 18.3	27117	
203	15 58 19.18	27 08 48.6	44310	
204	15 58 17.89	27 09 37.9	26093	
205	15 58 20.20	27 09 49.3	25289	
206	15 57 58.63	27 10 44.2	26779	
207	15 58 09.01	27 10 24.0	26209	
208	15 58 08.02	27 11 13.2	30681	e
209	15 58 24.58	27 11 26.5	27350	
210	15 58 45.37	27 11 53.1	26182	
211	15 58 04.80	27 11 50.3	24764	e
212	15 57 54.96	27 11 52.1	25246	
213	15 57 56.20	27 13 26.6	26695	
214	15 58 28.40	27 13 48.4	27403	
215	15 57 43.21	27 13 38.1	25977	
216	15 58 23.13	27 14 04.1	27658	
218	15 58 25.50	27 14 46.2	27154	
219	15 58 13.35	27 14 53.9	28936	HS102
220	15 58 41.48	27 15 11.2	26486	
221	15 58 01.34	27 15 03.3	25561	
222	15 58 33.90	27 15 37.9	25251	
223	15 58 17.56	27 16 10.2	25161	e, HS103
224	15 58 39.32	27 16 18.9	26769	
225	15 57 51.74	27 16 06.2	27356	
226	15 58 14.37	27 16 20.1	28644	HS111
227	15 58 06.50	27 16 27.9	26107	
228	15 58 13.84	27 16 46.1	27029	
229	15 57 43.67	27 16 37.7	26615	
230	15 58 12.81	27 17 00.1	25793	
231	15 57 49.77	27 18 13.6	28075	
232	15 58 43.72	27 18 59.6	19311	
233	15 57 47.09	27 18 58.1	30237	e
234	15 58 26.71	27 19 12.5	27760	
235	15 58 43.66	27 20 07.4	28324	
237	15 58 20.97	27 20 02.9	26878	HS104

Table 3—Continued

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
238	15 58 16.77	27 20 55.0	27102	
240	15 58 31.59	27 21 44.4	30004	
241	15 58 01.06	27 21 48.9	28364	
242	15 58 39.63	27 13 52.6	26930	
243	15 58 39.10	27 14 01.9	27034	
244	15 58 24.72	27 13 47.1	26470	
245	15 58 18.82	27 14 20.9	24247	HCW2
246	15 58 07.57	27 14 45.3	26817	
248	15 59 14.91	27 10 23.6	27189	
249	15 59 21.48	27 11 48.5	27382	
250	15 59 24.61	27 13 01.5	27948	
251	15 59 23.98	27 15 17.9	27308	
252	15 58 47.03	27 15 53.4	24443	s (strong)
253	15 59 04.48	27 16 08.2	27306	
254	15 59 14.74	27 17 24.6	27439	
255	15 58 56.66	27 18 24.3	29279	
256	15 58 59.04	27 19 22.5	24511	
258	15 59 18.80	27 20 03.7	26885	
259	15 59 22.91	27 20 48.8	27146	
260	15 58 55.78	27 16 41.0	28182	
263	15 56 55.24	27 12 51.9	27660	
264	15 57 32.91	27 15 06.5	25805	
266	15 57 40.43	27 15 57.3	26028	
267	15 56 53.90	27 15 51.0	45826	
269	15 57 19.37	27 16 32.4	29438	
270	15 56 49.05	27 17 13.7	28589	
273	15 57 03.43	27 18 13.8	28220	e
274	15 57 24.34	27 18 48.8	27093	
275	15 57 30.19	27 18 57.1	27585	
277	15 57 37.47	27 20 38.7	28339	
279	15 57 49.96	27 23 00.6	27401	
280	15 57 51.22	27 23 33.4	29263	
281	15 57 56.53	27 23 53.1	27214	
282	15 57 49.67	27 26 12.2	26655	
284	15 58 29.41	27 27 35.2	28433	

Table 3—Continued

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
285	15 57 43.58	27 27 55.1	9350	e
286	15 58 32.08	27 28 25.3	9333	s, HS201
287	15 57 44.63	27 29 25.9	26298	
292	15 58 01.08	27 32 09.2	26880	
293	15 58 18.89	27 32 42.1	9495	HS211
294	15 58 08.08	27 32 59.2	27344	
304	15 58 54.57	27 00 50.1	19322	s, a
305	15 59 22.24	27 03 40.0	19374	s
309	15 58 49.63	27 05 17.2	26241	
310	15 59 12.46	27 06 00.3	25884	
315	15 57 42.42	27 00 17.8	25116	HS204
317	15 57 42.02	27 02 05.0	27226	
318	15 56 57.05	27 03 00.0	27619	
320	15 57 26.48	27 03 48.5	20745	
322	15 57 19.43	27 04 18.1	20388	s
326	15 57 40.28	27 06 24.0	33433	
327	15 57 39.32	27 06 57.9	28561	e
328	15 57 06.62	27 07 10.5	20277	
330	15 58 31.73	26 56 33.2	25607	
334	15 58 43.10	26 59 08.1	27078	
335	15 57 45.01	27 01 21.8	29208	
337	15 58 12.23	27 03 36.6	20461	e
338	15 58 21.09	27 05 27.3	25406	
340	15 58 05.09	27 05 32.1	27222	
341	15 58 40.04	27 06 21.1	27399	
342	15 58 29.65	27 06 56.2	25466	
343	15 58 32.69	27 07 26.0	32049	± 100 km s^{-1}
344	15 57 55.69	27 07 41.3	29091	
346	15 58 39.05	26 58 37.7	19839	
347	15 58 40.01	26 58 40.8	19321	
348	15 58 42.88	27 07 37.7	26003	s, a
350	15 58 47.29	27 24 29.5	28567	
351	15 58 55.94	27 26 30.8	27042	
352	15 58 49.76	27 26 39.9	25467	s, HS107
357	15 58 56.63	27 30 39.9	27097	HS402

Table 3—Continued

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
364	15 58 50.54	27 23 26.4	28237	s, a
365	15 57 39.98	27 22 49.8	27373	
366	15 57 08.91	27 23 16.0	27985	
367	15 57 28.96	27 25 46.0	26229	
372	15 57 36.85	27 27 50.7	26790	
373	15 57 24.74	27 28 18.5	29519	
376	15 57 00.58	27 31 04.0	24652	

[a]Galaxy cross-references: prefix HS = Hintzen & Scott (1979), HCW = Hu, Cowie & Wang (1985)

Table 4. A2319 Redshift Data

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
200	19 21 22.15	44 04 03.1	16262	
201	19 21 26.14	44 03 00.5	16169	
202	19 21 27.39	44 01 59.1	15769	
203	19 21 17.72	44 01 08.7	15156	
204	19 21 22.56	44 02 15.6	19403	
206	19 21 05.68	44 04 42.0	39161	s, a
207	19 21 15.09	44 04 48.8	18548	
208	19 21 10.60	44 07 09.4	16668	
209	19 21 11.07	44 00 05.1	14418	
213	19 21 12.24	44 04 03.0	16728	
214	19 20 46.76	44 01 10.2	15421	s (weak), ± 100 km s^{-1}
215	19 20 50.41	44 03 17.6	15550	
216	19 20 55.89	44 05 01.5	19714	
217	19 21 07.79	43 59 13.5	14004	
220	19 20 41.19	44 08 44.2	17266	
226	19 20 41.39	43 57 16.0	18220	
227	19 20 42.39	43 56 36.5	14943	FD7
228	19 20 35.21	43 57 47.0	11980	
229	19 20 33.50	43 57 50.7	14593	
230	19 20 13.64	43 57 55.2	15812	e
231	19 20 32.24	44 00 47.1	26579	e
232	19 20 32.77	44 01 05.1	14413	s
233	19 20 50.76	43 57 33.8	18521	
234	19 20 38.16	44 01 03.6	15791	
236	19 20 00.84	44 05 08.2	17578	
237	19 19 46.52	44 00 58.2	15552	
239	19 19 43.19	44 05 06.8	18737	
240	19 20 20.13	43 58 34.0	18289	FD26
241	19 20 10.10	43 51 21.0	16306	
242	19 20 04.53	43 51 55.8	12052	
243	19 20 23.83	43 50 41.5	17245	
244	19 19 57.77	43 54 55.3	28350	
245	19 20 42.73	43 52 51.1	16538	
246	19 20 44.44	43 51 38.4	17436	± 150 km s^{-1}
247	19 20 59.34	43 53 22.9	16031	

Table 4—Continued

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
250	19 21 10.16	43 56 43.5	16365	BCM; FD1
251	19 21 07.28	43 56 54.2	17025	
252	19 21 16.45	43 56 55.2	19194	
253	19 21 16.62	43 55 39.8	15448	
255	19 21 03.33	43 53 40.2	16435	
256	19 21 21.43	43 54 51.1	16335	
257	19 21 23.11	43 56 07.5	18611	
258	19 21 23.77	43 51 52.1	14211	
259	19 21 27.76	43 53 04.2	13345	
261	19 21 10.98	43 55 02.2	16805	e (weak)
263	19 21 09.39	43 58 08.3	14560	
265	19 21 22.37	43 57 10.8	17831	
266	19 21 15.06	43 57 07.7	14166	
267	19 21 38.75	43 55 01.9	14536	
268	19 21 07.56	43 53 42.6	14844	
269	19 21 09.71	43 56 53.5	17134	
270	19 21 12.39	43 55 54.0	15559	
271	19 21 11.45	43 54 25.6	16865	FD21
272	19 21 41.79	43 57 47.2	14831	FD3
273	19 21 46.35	43 57 04.3	13752	
274	19 21 44.16	43 56 13.5	17183	
275	19 21 03.85	43 57 07.6	15143	
276	19 21 04.13	43 59 16.0	16906	
278	19 21 22.68	43 54 42.6	17844	
279	19 20 19.15	43 48 37.1	19377	FD15
280	19 20 10.14	43 47 30.7	17213	
281	19 20 52.92	43 48 52.6	16218	
283	19 21 06.61	43 47 46.0	13999	
284	19 21 33.58	43 50 28.5	21589	s (weak)
285	19 21 39.00	43 48 13.0	16055	
287	19 21 00.69	44 07 34.7	16875	
289	19 21 13.10	43 57 33.6	16960	
295	19 22 26.28	44 09 38.8	17873	
296	19 22 46.49	44 05 44.0	14348	
302	19 22 04.53	44 02 28.2	16398	

Table 4—Continued

ID	RA(2000)	DEC(2000)	cz (km s^{-1})	Comments[a]
307	19 21 33.90	44 13 33.2	17474	
308	19 20 49.49	44 12 07.8	19770	
309	19 21 09.68	44 11 17.8	16475	
310	19 21 01.05	44 10 56.0	16230	
311	19 21 27.51	44 10 57.9	13894	
317	19 20 26.49	44 12 58.1	15984	
318	19 20 36.93	44 11 12.2	13454	s
320	19 20 10.92	44 11 32.8	17652	
336	19 19 34.85	44 01 56.4	14480	s
337	19 19 25.77	44 05 05.1	15521	
338	19 19 23.65	44 11 06.8	12443	e
341	19 22 36.83	43 55 14.9	13785	s (weak)
342	19 22 50.09	43 53 23.9	21823	
345	19 22 15.68	43 48 20.0	16004	s, FD24
347	19 22 43.27	43 45 33.1	17660	
348	19 22 24.07	43 47 59.2	15117	
349	19 22 42.96	43 41 32.3	15984	
350	19 22 29.15	43 38 38.9	17150	
355	19 21 53.88	43 41 56.8	14958	
360	19 21 24.27	43 38 03.7	14034	
364	19 21 07.70	43 44 33.7	22468	s (weak)
366	19 20 51.45	43 38 34.9	16567	s (weak)
367	19 21 17.49	43 43 57.3	17068	
368	19 21 44.54	43 46 42.4	18033	e (weak)
369	19 22 08.38	43 46 29.0	17532	
371	19 21 52.47	43 51 00.9	13832	
372	19 21 56.25	43 49 38.1	17399	
373	19 21 57.66	43 49 29.8	16273	
375	19 20 10.31	43 44 48.7	15857	
376	19 20 38.99	43 40 10.1	18013	
377	19 20 35.12	43 38 06.3	15001	
378	19 20 39.05	43 35 40.5	15758	
382	19 19 53.30	43 41 55.1	13869	e
385	19 20 28.07	43 36 20.0	15417	
404	19 19 25.85	43 42 45.2	17597	

Table 4—Continued

ID	RA(2000)	DEC(2000)	cz (km s^{-1})		Comments[a]
405	19 20 43.56	44 02 49.2	18705		
406	19 20 33.69	44 07 15.6	19467		
408	19 20 38.60	44 07 15.6	18625		
409	19 20 49.54	44 03 21.1	18815		
410	19 20 19.39	44 08 31.5	19223		
411	19 20 41.58	44 06 17.5	18460		
412	19 20 28.43	44 01 32.9	19577	s	

[a]Galaxy cross-references: prefix FD = Faber & Dressler (1977)

Table 5. Cluster Velocities and Dispersions

Cluster	N	cz (km s^{-1})	σ (km s^{-1})
A1775A	21	19462 ± 123	518^{+106}_{-66}
A1775B	29	22767 ± 81	394^{+65}_{-44}
A2029	85	23169 ± 168	1436^{+125}_{-99}
A2142	103	27117 ± 130	1280^{+94}_{-76}
A2319	130	16446 ± 164	1770^{+121}_{-101}
A2319A	100	15727 ± 139	1324^{+105}_{-85}
A2319B	28	18636 ± 151	742^{+125}_{-84}

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Figure Captions

Fig. 1.— Histograms of observed velocities for (a) A1775, (b) A2029, (c) A2142, and (d) A2319. The bin size is 200 $\mathrm{km\,s^{-1}}$. The arrow marks the velocity of the cD galaxy. The 2 arrows in (a) represent the 2 components of the A1775 central binary galaxy. The dotted line is a Gaussian centered at the cluster mean velocity with dispersion equal to the calculated line-of-sight velocity dispersion, σ_o. The dotted line extends to $\pm 3\sigma_o$ in velocity from the cluster mean.

Fig. 2.— Positions of observed galaxies in A1775, plotted with velocity-coded symbols. Open circles represent galaxies with $v_{obs} > 21000$ $\mathrm{km\,s^{-1}}$ (A1775B), and solid triangles are galaxies with $v_{obs} < 21000$ $\mathrm{km\,s^{-1}}$ (A1775A). North is at the top of the plot, with sky parity.

Fig. 3.— (a) Upper panel. The positions of A2029 cluster member galaxies with velocities $\bar{v} - 3\sigma_r \leq v_{obs} < \bar{v} - \sigma_r$ are plotted as filled triangles, those with $\bar{v} - \sigma_r \leq v_{obs} < \bar{v}$ are plotted as filled squares, those with $\bar{v} \leq v_{obs} < \bar{v} + \sigma_r$ as open circles, and those with $\bar{v} + \sigma_r \leq v_{obs} \leq \bar{v} + 3\sigma_r$ as plus signs. The brightest cluster galaxy is plotted at coordinates $(x, y) = (0, 0)$. North is at the top of the plot, with sky parity. (b) Lower panel. Cluster member galaxies with measured velocities are plotted as open circles, where the diameter of the circle is proportional to e^{δ}, from the Dressler–Shectman test.

Fig. 4.— Same as Fig. 3, for A2142.

Fig. 5.— Same as Fig. 3, for A2319.

Fig. 6.— Velocity histograms of A2029 galaxies with radius $< 300''$ (lower panel) and radius $> 300''$ (upper panel).

Fig. 7.— Decomposition of the velocity distribution of A2319 into A2319A (upper panel) and A2319B (lower panel).

Fig. 8.— Grey-scale maps of *Einstein* x-ray emission in the 4 clusters indicated. The images have sky parity with North up, and field of view for each map is 51.2 arcmin (24 arcsec $\mathrm{pixel^{-1}}$).

Fig. 9.— The solid curve marks the boundary between bound and unbound orbits as a function of α, the projection angle of A2319A and A2319B, and V_r, their relative radial velocities. The dotted vertical line at $V_r = 2600$ kms^{-1} is the relative radial velocity between the two clusters (in their rest frame). The clusters are bound only for $28° \lesssim \alpha \lesssim 78°$.

Fig. 10.— Velocity dispersion for the clusters in our Abell dispersion sample plotted against optical richness, N_c. The solid line is a linear fit to the data, and the dashed line is the relation $\sigma = 90N^{1/2}$ proposed by BC.