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DECONSTRUCTING ABELL 3266: A MAJOR MERGER IN A QUIET CLUSTER

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ABSTRACT

We present results of simple *N*-body simulations that strengthen the suggestion that Abell 3266 is composed of two subunits of comparable mass that have merged recently. Both the real cluster and the *N*-body dark-matter cluster show mixed signals of substructure under statistical tests. However, in a decidedly nonstatistical approach allowed by the wide-area coverage and the large number of redshifts Quintana, Ramírez, & Way measured in A3266, they *sliced the real cluster in redshift space* to uncover a peculiar spatial distribution of galaxies that they suggested was the result of a recent merger. In our simulations, a similar distribution is the result of an ongoing merger between two comparable-mass units that started about 2×10^9 yr ago in the *N*-body simulations. We also find that the distribution of emission-line galaxies in A3266 traces the same structure. We discuss further tests of our merger hypothesis and speculate on the possibility that a similar process might be occurring in other, apparently relaxed clusters at the present epoch.

Subject headings: galaxies: clusters: individual (Abell 3266) — galaxies: interactions — methods: *N*-body simulations

1. INTRODUCTION

There have been numerous analyses of substructure in clusters of galaxies over the past decade (for a review, see, e.g., West 1994). These studies have been motivated, in part, by the expectation that study of the substructure will help unravel the cosmogony underlying the formation of clusters of galaxies. For example, the presence of substructure can teach us about the overall matter density in the universe (Richstone, Loeb, & Turner 1992), although this is subject to the uncertainty in the rate at which substructure is erased (Kauffmann & White 1993; Lacey & Cole 1993). Another example is the spatial distribution of substructure, which can give clues to the formation process (West, Jones, & Forman 1995).

Most studies of substructure have been statistical in nature, with both optical and X-ray studies suggesting that 30%–50% of clusters show evidence of substructure in their galaxy and/or gas distribution (Geller & Beers 1982; Dressler & Shectman 1988; Jones & Forman 1992; Salvador-Solé, Sanromà, & González-Casado 1993; Girardi et al. 1997; Solanes, Salvador-Solé, & González-Casado 1998). A sharper agreement on what fraction of clusters shows substructure in their projected distribution is precluded partly because many features are generically considered as substructure (see a discussion in González-Casado et al. 1998). In addition, the fraction appears to be much larger ($\sim$80%, Bird 1994) when evidence for substructure is also looked for in the form of multimodal velocity distributions. This kind of test is more sensitive to substructure arising from line-of-sight mergers in clusters (Pinkney et al. 1996), which can then appear fairly smooth in their projected distribution. In fact, one is tempted to ask if the remaining $\sim$20% might not be clusters where a line-of-sight merger has comparable-mass subclumps that have substantially decelerated after the cores collided. These would be difficult to uncover in the projected distribution of galaxies in the cluster because of orientation and in the velocity distribution because the subclumps have nearly stopped. Our analysis of A3266 here suggests that it is an example of such clusters.

Studies have also been directed at individual clusters, such as the Coma cluster (see, e.g., Fitchett & Webster 1987; Davis & Mushotzky 1993; White, Briel, & Henry 1993; Burns et al. 1994; Colless & Dunn 1996 and references therein). Other examples include A400 (Beers et al. 1992), A2634 (Pinkney et al. 1993), and a recent study of the A3558 cluster complex (Bardelli et al. 1998). In these studies, one attempts to go beyond simply establishing that there is evidence of substructure and into modeling the possible dynamics that give rise to the observed structure. The study of substructure in individual clusters can be helpful in checking trends expected in cosmological models. For example, it appears that an absence of cooling flows occurs in clusters undergoing a merger (see Burns et al. 1995 and references therein), as expected from hydro/*N*-body simulations (Roettiger, Burns, & Loken 1993). Also, these studies can help unravel whether the substructure is the result of a major merger or an aggregate of accreted small units. This question has also been addressed statistically by González-Casado et al. (1998).

Here we present an analysis of spectroscopic data for galaxies in the ACO galaxy cluster A3266 obtained by Quintana, Ramírez, & Way (1996; QRW), which we interpret by means of simple *N*-body simulations to infer the dynamical state of the cluster. We briefly summarize the

[1] Presidential Chair in Science 1995, 1999.

observations of QRW in the § 2, together with further analysis of the data. We then present simple, 1000-particle N-body simulations of the cluster. We find that simple statistical tests give mixed signals about the presence of substructure in the simulated cluster, much like we find for the real cluster in § 2, despite there being an ongoing merger in the N-body cluster. Finally, we close with a section of discussion of this analysis and the conclusions we draw from it.

2. THE OBSERVATIONS AND FURTHER ANALYSIS OF THE DATA

QRW compiled a total of 387 velocities in an area approximately 1°.8 × 1°.8 centered on A3266, most of which (229) were new velocities obtained from runs at the Cerro Tololo Inter-American (CTIO) and Las Campanas (LCO) observatories. A total of 317 galaxies were identified as cluster members from the distribution of velocities, making it one of the largest data sets of its kind for clusters in the ACO catalog.

The first run was carried out using the Argus spectrograph at the CTIO 4 m telescope during the early parts of two nights on 1990 February 17–19. Three Argus fields were observed in A3266 during this run, securing new spectra for 46 objects. Three 900 s exposures for the first field were taken on the second night of the run. Two 1800 s exposures for the second field and two 1500 s exposures for the third field were taken on the final night. Given the measured stability of the instrument, a single long exposure of the He-Ar comparison lamp was taken every night to calibrate all exposures in wavelength. To compare and check on possible zero-point shifts, several velocities of standard stars and some galaxies with well-known velocities were measured using one of the fibers. Exposures of a white spot in the dome and sky flats were used to correct for pixel-to-pixel, large-scale, and illumination variations in the detector (the 800 × 800 pixels TI # 2 CCD) response. Finally, the grating used was KLGL2, tilted to provide a wavelength coverage from ∼3900 to 5600 Å. The preflashed CCD exposures were binned 2 × 1 in the fibers-slit direction, giving a dispersion of 2.2 Å pixel^{-1} with a FWHM resolution of ∼8 Å.

The whole 1°.8 × 1°.8 field around A3266 was explored in the second run using Shectman's fiber spectrograph mounted on the 2.5 m DuPont telescope at LCO. The run was carried out on the nights of 1990 October 22–25, and a total of 263 new spectra were obtained. Five fields were used to cover (with considerable overlap) an area of approximately 1°.8 × 1°.8, with exposure times adjusted between 80 and 120 minutes depending on the brightness of the selected galaxies in each of the exposures. Standard quartz lamp exposures of the dome were used to correct approximately for pixel-to-pixel variations of the 2D-FRUTTI detector coupled to the spectrograph, but no corrections were made for the (small) dark current in the detector. He-Ne comparison lamp exposures were taken for wavelength calibration before and after each exposure. With a 600 line mm^{-1} grating plus the 2D-FRUTTI detector, spectra covered the range ∼3500–6900 Å with a dispersion of ∼2.6 Å pixel^{-1} and a resolution of ∼10 Å.

A careful analysis was carried out by QRW in order to combine the measurements from the two runs with previous data (mostly from Quintana & Ramírez 1990 and Teague, Carter, & Gray 1990) and create the homogeneous, large catalog of velocities we use here. We first consider the velocity distribution for the 317 members identified in A3266. We find that, even with this large number of velocities, there is no conclusive evidence of non-normality in the velocity distribution, which would be indicative of the presence of substructure. For example, the skewness and kurtosis are .105 and 3.32 respectively. For a Gaussian distribution, values as high as these would occur in 21.7% and 9.64% of cases, respectively (the mean and dispersion are estimated from the data). The Kolmogorov-Smirnov (KS) statistic, however, appears to exclude the Gaussian hypothesis at a much higher confidence level (CL) of 95% (see QRW). This is rather surprising since one would expect order statistic tests to be less sensitive (Bird & Beers 1993). The KS test was not considered in Bird & Beers 1993, but it is easy to carry out the analysis for it. Table 1 presents the fraction of times the KS, skewness, and kurtosis tests would reject a Tukey distribution (see Bird & Beers 1993 and references therein) as non-Gaussian at the 95% CL. It can be seen there that the KS test never outperforms a combined skewness and kurtosis test. In fact, skewness and kurtosis alone were used in the recent analysis of the ENACS (ESO Nearby Abell Cluster Survey) clusters (Solanes et al. 1998), where A3266 would not have been considered as having a non-Gaussian velocity distribution.

The 5% of samples with the highest values of the KS statistic, and drawn from a Gaussian distribution, are biased to high skewness and kurtosis. Values such as those above would occur a fraction of 40.5% and 18.7% of the time (respectively) in that subset of samples. Therefore, the QRW sample might just be an "unlucky" sample out of a Gaussian distribution. After all, 5% is not such a low probability if we bear in mind that confidence levels refer to any set of measurements, not just measurements in A3266. Moreover, we find that if we assume *true* mean and dispersion of ∼17,830 km s^{-1} and ∼1190 km s^{-1}, respectively, which are values well within the measurement errors, all three tests give rather large probabilities (∼30%, ∼35%, and ∼46%, respectively, for the KS, skewness, and kurtosis tests) that the set is drawn from a Gaussian parent. Thus, we conclude that the Gaussian hypothesis cannot be excluded with sufficient confidence.

The distribution of the member galaxies in the plane of

TABLE 1

POWER OF TESTS

Test	Tukey Distribution Parameters (g, h)					
	(0.1, 0)	(0.2, 0)	(0, 0.1)	(0, 0.2)	(0.1, 0.1)	(0.2, 0.2)
KS	0.23	0.73	0.53	0.98	0.68	0.99
Skewness	0.67	0.99	0.24	0.37	0.70	0.90
Kurtosis	0.18	0.52	0.95	1.00	0.96	1.00

the sky can be combined with the velocity information to further search for departures from equilibrium. We find that the central region of A3266 is entirely consistent with a spherical isothermal distribution. The cumulative distribution of right ascensions (R.A.) or declinations (decl.) needed to perform a KS test can be worked out readily for an isothermal distribution. We find that the distribution of R.A., $F(x)$, inside a box of size $2a$ ($2b$) in R.A. (decl.) centered on the cluster must be

$$F(x) = [a \sinh^{-1}(b/a) + b \sinh^{-1}(a/b) + x \sinh^{-1}(b/x) + b \sinh^{-1}(x/b)] \times \{2[a \sinh^{-1}(b/a) + b \sinh^{-1}(a/b)]\}^{-1}; \; x > 0 \; , \quad (1)$$

and $F(x) = 1 - F(|x|)$ for $x < 0$. (We have assumed that the galaxies trace the mass and the cluster core radius is very small, as indicated by gravitational lensing studies of rich clusters. See, e.g., Tyson, Kochanski, & Dell'Antonio 1998). Since the galaxies trace the mass, we take the cluster center to be the center of a smoothed galaxy density map,as shown in Figure 1*a*. A typical Monte Carlo (MC) realization of the data in a window of the same size as in Figure 1*a*, using equation (1), is shown in Figure 1*b*. In the central 0°.5 × 0°.5, the KS statistic is at the 74% (40%) CL for the distribution of R.A. (decl.) positions. The test against a Gaussian distribution for the velocities in the same window gives a 24% CL. [The skewness (kurtosis) of the velocity distribution, −0.016 (2.8), is at the 47% (42%) CL]. As well, the test of Dressler & Shectman (1988), which combines the velocity and position information, is also consistent with a relaxed distribution. Inside the same window, we get $\Delta = 58{,}455$ km s^{-1}, where

$$\Delta = \sum_{i=1}^{N} \delta_i = \sum_{i=1}^{N} [(\bar{v}_i - \bar{v})^2 + (\sigma_i - \sigma)^2]^{1/2} \; , \quad (2)$$

$\bar{v}_i\,(\sigma_i)$ is the average velocity (dispersion) among galaxy i and its ten nearest neighbors, and $\bar{v}(\sigma)$ is the average velocity (dispersion) among all N galaxies in the window. The significance of this is obtained by comparing Δ to the values obtained from 1000 MC reshufflings of the velocities, which put Δ at the 19% CL.

All these numbers are entirely consistent with a relaxed, isothermal core in A3266.[2] These findings are not necessarily in disagreement with those of Mohr, Fabricant, & Geller (1993) since the substructure they claim inside this window in A3266 (inferred from a systematic shift in X-ray isophote centroids) refers to the *gas* distribution. For example, the gas in a cluster can remain perturbed much longer than the matter distribution in the case of a merger (see Roettiger et al. 1993 and the discussion in Pinkney et al. 1993).

Including galaxy positions outside of this core, on the other hand, we find an increasingly significant deviation from the isothermal distribution, especially in decl. The KS test on positions inside a window 0°.9 × 0°.9 yields a CL of 99.96% (91.1%) for decl. (R.A.). For the entire 1°.8 × 1°.8 field, we find CL's of 99.9999% and 99.8% for decl. and R.A., respectively. The Dressler & Schectman (DS) test gives a Δ for the entire field 5.4 σ above the mean of the MC sets, a highly significant deviation. Thus, the choice of a large field and the measurement of a large number of velocities is crucial in uncovering this large-scale " anomaly " in A3266.

Relaxed dark-matter halos are known not to be spherically symmetric but are well described by triaxial spheroids

[2] Since sampling can introduce noise in the location of the center of the smoothed map, we have also performed the tests and calculated CL's by choosing the center at the mean of the positions in a window. Equation (1) is replaced by a more complicated expression, but we obtain similar results. We have also performed the test introduced by Fitchett & Webster (1987). The statistic $L_{\rm rat} = 1.46$ in this case, which the MC of the data gives a 27% probability. Thus, this is also consistent with the other tests.

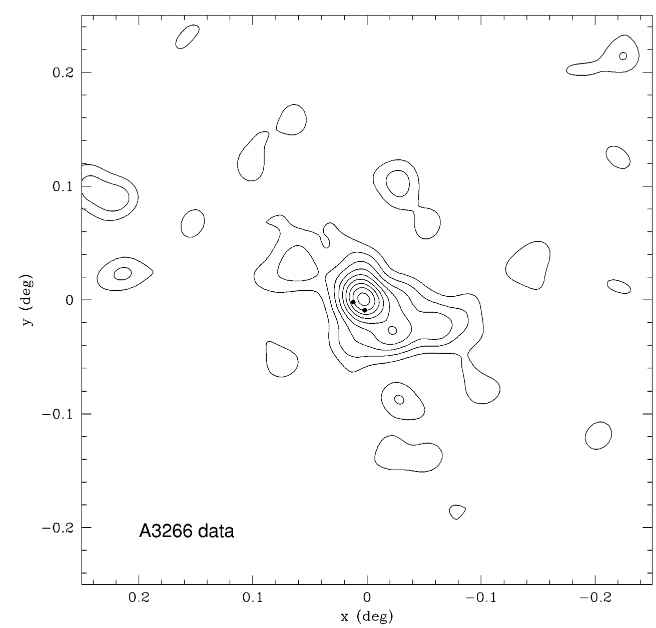

FIG. 1*a*

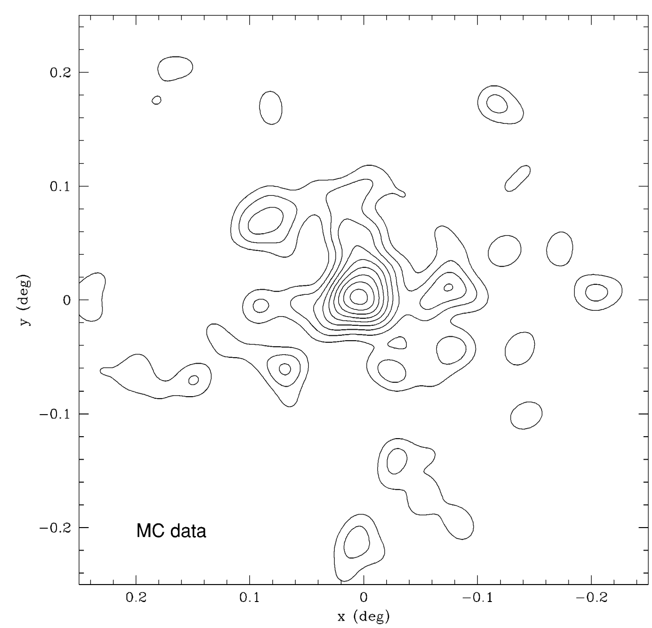

FIG. 1*b*

FIG. 1.—Smoothed galaxy density maps. The data for A3266 are shown in (*a*) smoothed with a Gaussian window of $\sigma = 1'.8$, corresponding to $\sim 35\ h^{-1}$ kpc at the redshift of A3266. This is of the order of the soft core radius seen in weak lensing studies of cluster mass distributions (see Tyson et al. 1998). The filled dots mark the location of the dumbbell components. The center of the plot is at R.A. = 04:30:30.7, decl. = −61:33:25 [1950]. An MC realization of the data is shown in (*b*), smoothed on the same scale. All contours shown are spaced at 10% intervals, starting at 15%, of the maximum density.

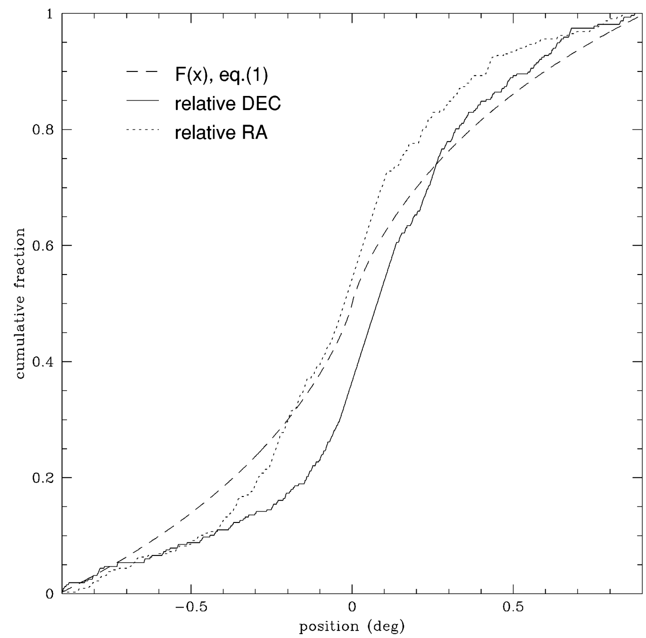

FIG. 2.—Cumulative distribution of decl. (*solid*) and R.A. (*dotted*) in the entire 1°.8 × 1°.8 field covering A3266. The expectation for an isothermal sphere is shown by the dashed line.

(Dubinski & Carlberg 1991; Warren et al. 1992). Therefore, the deviation from our test fit does not immediately imply the presence of substructure. However, it can readily be seen that the deviation detected by the R.A. and decl. KS tests is not caused by flattening. Figure 2 shows the cumulative distribution of positions as a function of position along the R.A. and decl. axes. It can be seen there that the distribution of declinations is highly asymmetric, indicating a clear excess of particles on the north side of A3266. The distribution of R.A.'s is more symmetric, indicating somewhat of an excess on the east side of A3266. This excess of galaxies to the north-northeast of the cluster can be easily understood in terms of the "wedge" structure suggested by QRW in a redshift slice through the cluster (see, e.g., Fig. 19 in QRW and Fig. 4*b* below). Indeed, we find that removing that slice from the data makes the decl. distribution much more symmetric. However, the possibility that the angular positions of galaxies in the slices in front and behind the cluster (Fig. 15 vs. Fig. 16 in QRW) are drawn from the same distribution is excluded only at the 86% CL by a KS test.

By contrast, the highly significant signal for substructure in the DS test does not come from the "wedge" structure. The DS test suggests a "clumpy" type of substructure, as is shown in Figure 3. Figure 3*a* shows the distribution of δ_i's. Given the clear excess of galaxies with $\delta_i > 600$ km s^{-1}, in Figure 3*b* we show the spatial distribution of all such galaxies. Several clumps can be seen there, but no "wedge" of galaxies. Also, despite appearances, most of the 5.4 σ signal is confined to the periphery near and outside the virial radius (marked by the dotted circle). The CL of Δ reaches 90% outside 90% of the virial radius and reaches 96% at the virial radius. Thus, the signal here appears entirely consistent with expectations for a relaxed cluster in a bottom-up hierarchical formation of structure where subclumps continue to accrete onto a relaxed core formed early on.

QRW suggested the wedge could be interpreted as a plume of galaxies resulting from the recent merger of two subunits, with one subunit having passed through the center from the southwest front of the cluster and then given rise to a plume of outflying galaxies. Here we present further evidence in favor of this hypothesis; § 3 shows that such a feature in the data (and other characteristics of the data) can

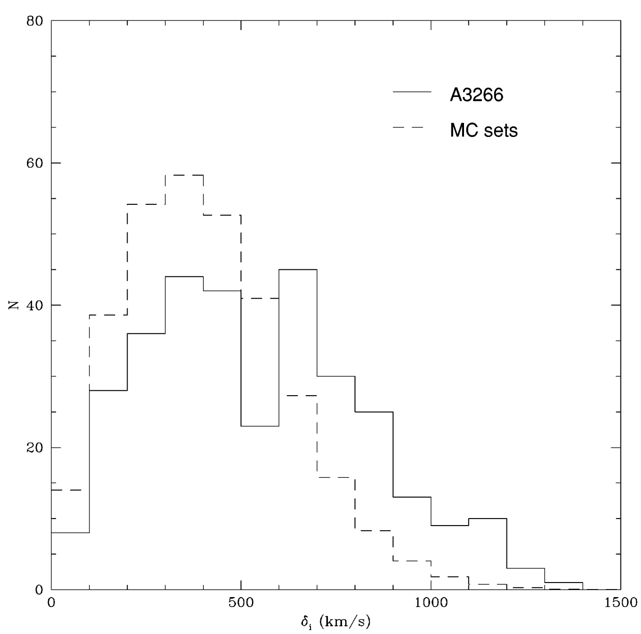

FIG. 3*a*

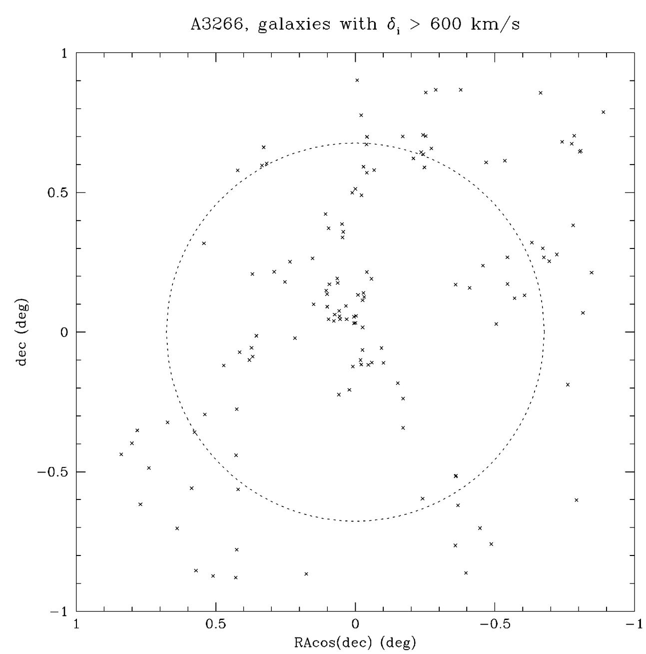

FIG. 3*b*

FIG. 3.—(*a*) Distribution of deviations δ_i (eq. [2]) for all the galaxies in A3266 (*solid line*) and the average distribution for the 1000 MC reshufflings of their velocities (*dashed line*). (*b*) Position in the sky of all the galaxies in A3266 with $\delta_i > 600$ km s^{-1}. The virial radius of the cluster is indicated by the dotted circle.

indeed be understood as a result of a recent merger that we simulate by means of a simple N-body simulation.

The tidal fields resulting from a merger could be expected to significantly affect the star formation rate in disk galaxies given the strong distortions induced in such galaxies when passing through cluster cores (Dubinski 1999). Therefore emission-line galaxies (ELGs) can serve as tracers of such an environment. Many galaxies in the QRW data are ELGs; therefore, we have tested if such galaxies indeed trace the plume seen in the redshift slice of QRW. This would make it plausible that indeed there is a physical association among those galaxies. In Figure 4, we plot the position of ELGs (*a*) below and (*b*) above the mean velocity. Indeed, there is a striking difference in their distribution. The distribution seen in Figure 4*b* suggests once again that a subclump of galaxies has shot past from the lower front to the upper back of the cluster. The possibility that the angular positions of the ELGs in front and behind the cluster trace the same distribution is excluded at the 98.8% CL by a KS test. We believe that these results put on much firmer ground the hypothesis that the galaxies in the plume are physically associated.

3. THE SIMULATIONS

We have performed simple N-body simulations of 1000 particles in order to investigate the feasibility of the merger scenario proposed by QRW. The particles start in Hubble expansion within an isolated, uniform density sphere representing the precollapse phase of a cluster. A small amount of angular momentum is added to represent the angular momentum that would result from the tidal torquing by nearby condensations. Of course, the collapse and formation of a cluster is far more complex than what we represent here. Our aim is simply to explore if a merger giving rise to something like the plume seen in the data (and with characteristics that would perform similarly under statistical tests) would happen in this simple, top-hat approximation to the real collapse of a dark-matter halo. We use the N-body code described in Blumenthal et al. (1986) and carry out dissipationless simulations that represent the evolution of the dark matter.

Figure 5 shows the evolution of a simulation that we analyze in this section. In this simulation there is a major merger at the center because the Poisson noise introduced by the discrete realization of the top-hat initial condition has made the center slightly underdense; therefore, the center gets evacuated (a void forms) and eventually the matter falls in and the merger occurs. Figure 5*a* shows (clockwise) the evolution of all the particles, from the time the system is near maximum expansion until the time it resembles the situation in A3266. At this time, the velocity distribution of the system closely resembles that of A3266, and it is the only time at which it does so. In Figure 5*b*, we show the evolution of the densest groups we can identify prior to the major merger. The first (*top left*) panel shows the bottom right panel of Figure 5*a* with the group members identified and follows the evolution (*clockwise*) of those groups alone until the time of the bottom left panel in Figure 5*a*. The groups have mass ratios of 1:2.2:5.5. In the last panel, the solid-dot group is moving away and has developed into a wedge-shaped plume that bears a striking resemblance to the plume uncovered by QRW.

The top panels of Figure 6 show the distribution of the particles in velocity slices of the same relative thickness as the 1500 km s^{-1} slices in QRW, both immediately below (*left*) and above (*right*) the velocity average. It can be seen that the plume is still clearly visible in the panel on the right. The bottom panels show a random sampling of the N-body data, of the size of the A3266 sample, that is more directly comparable to the A3266 data (assuming the galaxies closely trace the dark matter distribution). The plume can still be discerned there, and a KS test on the angular dis-

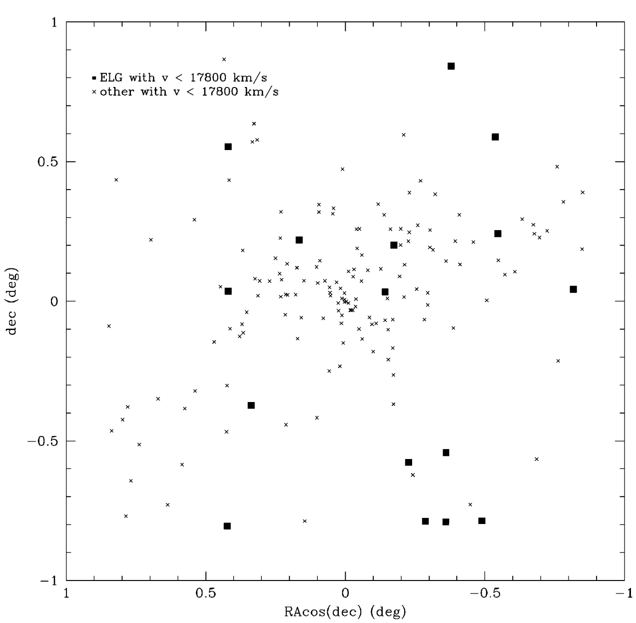

FIG. 4*a*

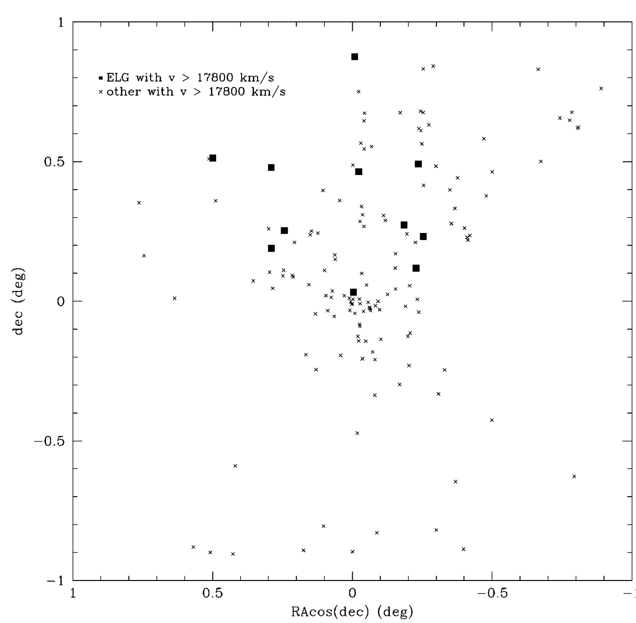

FIG. 4*b*

FIG. 4.—Position in the sky of the galaxies in A3266 with velocities (*a*) below and (*b*) above the mean for the cluster. ELGs are shown by solid squares and others by crosses.

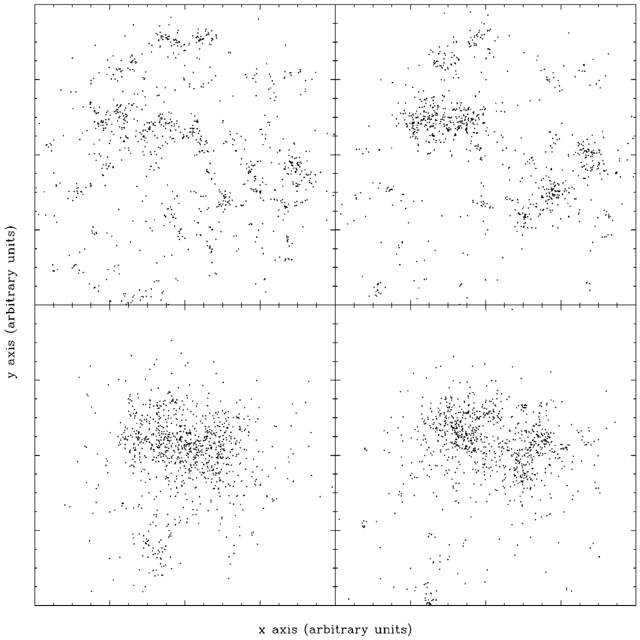

FIG. 5*a*

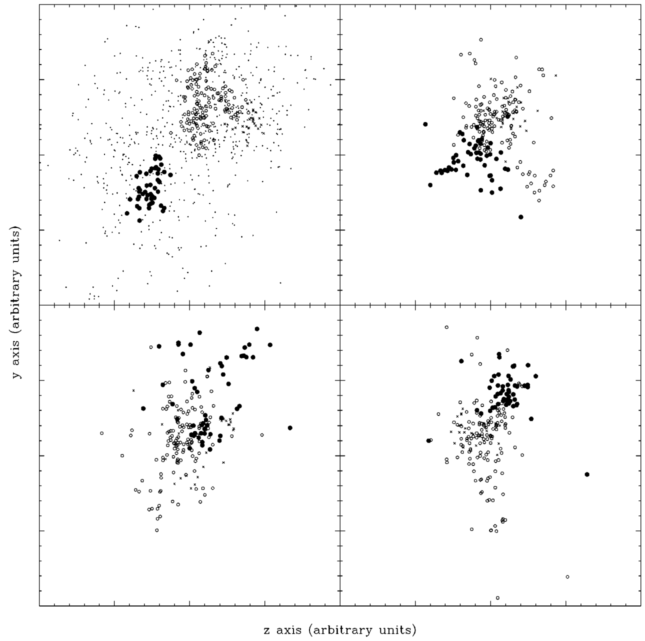

FIG. 5*b*

FIG. 5.—Major merger in *N*-body simulation. In (*a*) we show the time evolution (*clockwise from top left*) of the system as a whole. The panels have the same size and show the projected distribution of particles in the simulation onto the plane perpendicular to the system's angular momentum. The system is near maximum expansion in the first frame, and the last frame shown is the time at which the particle velocity distribution is similar to that of A3266. The softening parameter is 1/160 of the size of the frames. In (*b*) we show the time evolution of the three densest groups, identified at the time shown in the bottom right panel in 5*a*. The panels have half the size shown in 5*a*. The figures show the projected distribution of particles in the groups onto the plane perpendicular to the *x*-axis of 5*a*, which points out of the figure. Only the first panel shows all the particles, with those not in the groups shown by small symbols. The time is that of the bottom right panel in 5*a*. Subsequent panels show the evolution (*clockwise*) of the groups until the time of the bottom left panel in 5*a*.

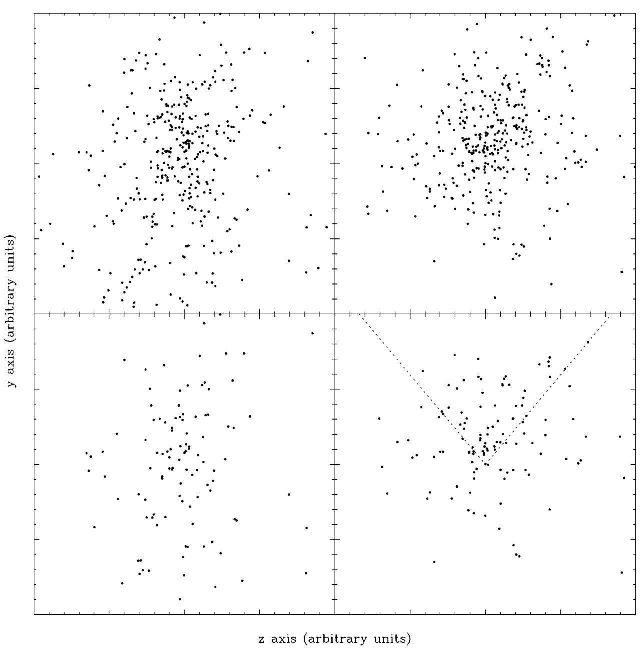

FIG. 6.—Velocity slices through the dark matter distribution, perpendicular to the *x*-axis of Fig. 5, after the major merger has taken place. The time is that of the bottom left panel in Fig. 5*a*. All panels show velocity slices of thickness (relative to dispersion) equivalent to 1500 km s^{-1} slices for A3266 (see Figs. 17–20 in QRW). The panels on the left are slices immediately below the mean, whereas those on the right are above the mean. The top panels show all the particles, whereas those at the bottom show those of a random sample of size as the A3266 data set. Dotted lines mark the angular sector where the distribution of position angles of the particles in the slice is markedly above that of the slice on the left. See the discussion in the text for further explanation.

tributions rejects their compatibility at a very high confidence level.

The velocity distribution of the particles in the simulation is shown in Figure 7 (*top panel*) together with the same distribution for A3266. They look remarkably similar, but the difference in peak heights of the dark matter distribution is not a sampling artifact and suggests that the structure seen in A3266 might be caused by a merger of like-mass subclusters rather than the heavy-light merger seen in the simulation.[3] A random sample from the *N*-body data, of the same size as the A3266 sample, is shown in the bottom panel. In this case, the KS test on the *N*-body distribution excludes the Gaussian hypothesis at a higher (99%) CL than that for A3266. The skewness (-0.30) excludes the Gaussian hypothesis at the 99% CL (the kurtosis, 2.97, is consistent). For most samplings of the *N*-body data, however, only the skewness test rejects the Gaussian hypothesis with high significance. Obviously, the skewness test picks up the intrinsic asymmetry caused by the unequal mass nature of the *N*-body merger. Thus, for an equal-mass merger, the results would resemble more closely those for A3266.

Finally, the DS test on 317 particle samples gives Δ's $\sim 5\ \sigma$ above the mean of the MC sets. As in the case of A3266, the spatial distribution of the particles with high δ_i's does not trace the plume seen in the redshift slice above the *N*-body cluster's mean velocity. This is shown in Figure 8 for two typical samples. Also, the inner core (half the size of the

[3] The equal height of the peaks in A3266 *is* a sampling-binning artifact, but even with taking this into account, this difference between the simulation and A3266 remains.

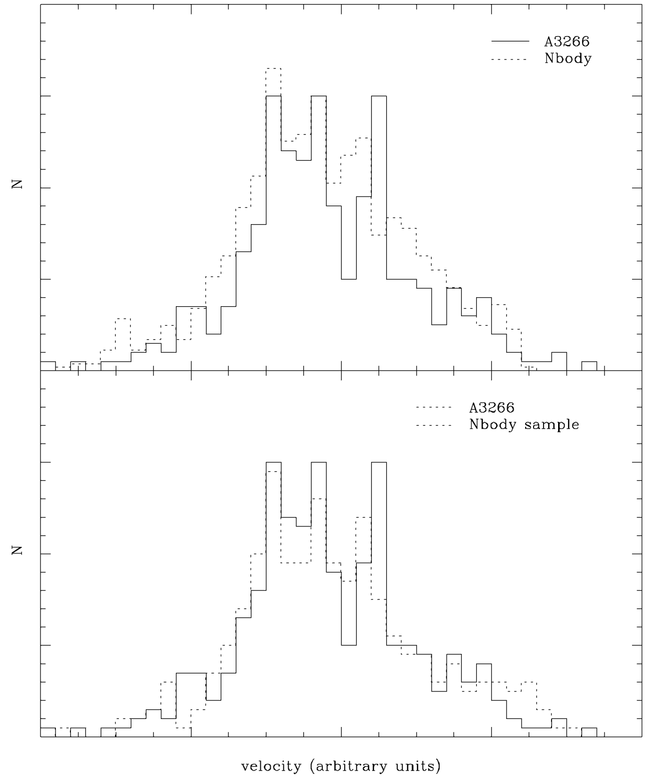

FIG. 7.—Velocity distributions. The top panel shows the distribution of galaxy velocities in A3266 (*solid line*) and particle velocities in the simulation discussed in the text (*dotted line*). The bins are 200 km s^{-1} wide for A3266 and proportionately (relative to dispersion) thick for the simulation data. The height of the middle peak has been set equal for comparison. The bottom panel shows the A3266 data compared with that for particles in a random sample of the size of the A3266 set. See text for further discussion.

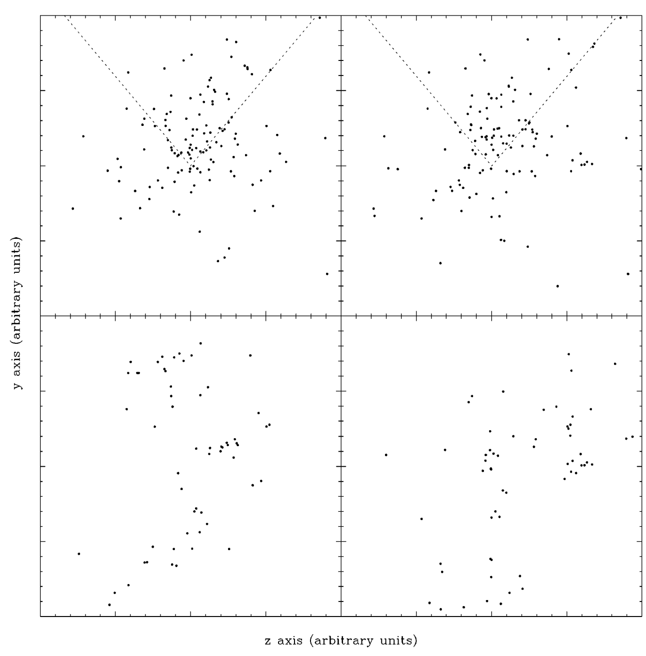

FIG. 8.—The top panels show the position of particles in the velocity slice above the mean (see Fig. 6) for two random samplings of the size of the A3266 data set. The bottom panels show the positions of the particles with the highest δ_i's in the random sample above. The threshold in δ_i was chosen in the same manner as the A3266 case (see Fig. 3). The dotted lines marking the angular sector shown in Fig. 6 have been kept for the top panels.

window shown in Fig. 8) is entirely consistent with a relaxed distribution.

4. DISCUSSION AND CONCLUSIONS

The simulations and the analysis of the data that we have carried out in the preceding sections clearly show that the data of QRW on A3266 can be well explained as the result of a relatively recent, major merger at the core of A3266. If we fit the *x*-axis velocity dispersion and the virial mass of the simulation to the values for A3266, 1161 km s^{-1} and 5×10^{15} $M_\odot$, respectively, then we find that the time elapsed since the cores of the two massive subclumps roughly coincided is $\sim 2 \times 10^9$ yr.[4] We also find that in this case the true mass has been overestimated by about 70%. This large a factor is to be expected in this kind of situation (see Pinkney et al. 1996).

There are many questions that our analysis is not able to address. Foremost among them is the relation of the merger we claim here and the merger claimed by Mohr et al. (1993). Their claim for evidence of a merger was based on their evidence that the cluster is not relaxed and evidence by Teague, Carter, & Gray (1990) of an east-west alignment preference for galaxies at the extremes of the velocity distribution. However, QRW (as well others; see QRW) have noticed many discrepancies in velocities deemed uncertain by Teague et al. (1990), and it can be seen in Figures 18 and 20 of QRW that there is no east-west enhancement of such galaxies. Furthermore, Mohr et al. (1993) point out the agreement in morphology (elongated) and orientation of the smoothed X-ray intensity and galaxy density contours, as well as the presence of a secondary peak in the galaxy density map, as further evidence for substructure in A3266. However, we estimate that the galaxy map results could be the result of sparse sampling of an otherwise smooth, isothermal distribution in about 20% of cases. We show an example in Figure 9. Naturally, a hydrodynamical simulation of a major merger like the one we have advocated here could better test whether or not the X-ray and optical data are all consistent with such a merger.

Another issue we have not been able to address is that of the dumbbell system in A3266, most likely itself the result of the merger we have discussed here. Our simulations do not have nearly the level of resolution that would be needed to explore if the dumbbell parameters (separation, relative velocity, and orientation in the sky) could be explained by the merger hypothesis. Simulations in the style of those discussed by Dubinski (1999) would be able to address this question. Here we just note that it is perhaps significant that the dumbbell is not centered on the density map, Figure 1*a*—which is what would be expected if the system had been formed in a recent merger. There are many examples of cD galaxies that do not sit at the bottom of cluster potential wells, precisely in clusters that show evidence of a recent merger (Bird 1994).

There is much observational follow-up work that can be suggested to further test our merger hypothesis. First, the nature of the merger in A3266 advocated here, nearly along the line of sight, makes the core of A3266 an ideal target for a search of weak gravitational lensing. The redshift of A3266 is low, but there are examples of weak lensing at this

[4] We have, self-consistently, fit the dispersion and mass within a projected window that we then ensure does correspond to 1°.8 × 1°.8 at the redshift of A3266.

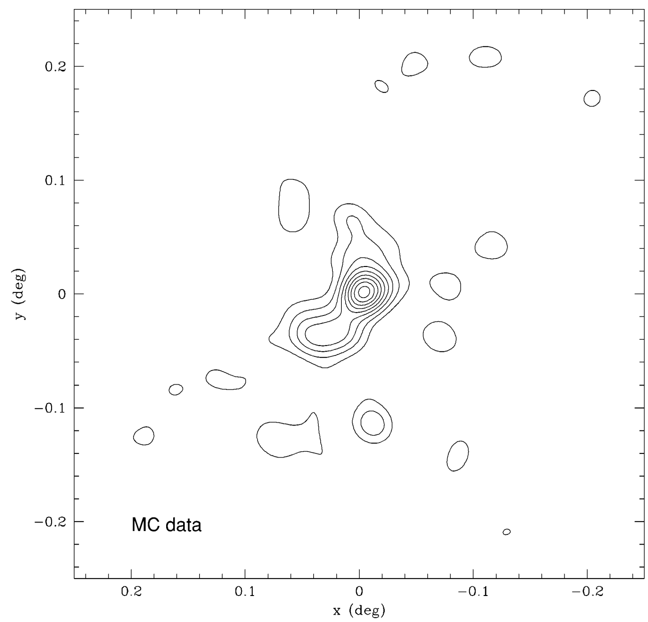

FIG. 9.—Smoothed "galaxy" density map of an MC realization of an isothermal sphere, using eq. (1), with sample size same as that of A3266. Contours shown are spaced at 10% intervals, starting at 15%, of the maximum density. See text for further explanation.

low a redshift (Campusano, Kneib, & Hardy 1998). In this case, the cluster is very massive, and the elongated mass distribution resulting from the merger will further enhance the weak lensing relative to a spherical cluster with the same velocity dispersion. We plan to carry out such observations in the near future. Second, a detailed morphological study of the galaxies in A3266 could help further verify the reality of the merger we have advocated here. For example, spirals and elliptical might have characteristically different spatial distributions as a result of type segregation in the premerger subclusters and owing to the different effect of tidal fields in the inner and outer parts of the merging subclusters. We also plan to carry out such a study in the near future.

We have analyzed the optical data available on A3266 carefully and have interpreted it with the help of simple *N*-body simulations to conclude that there is good evidence in the data that a major merger of comparable-mass components has occurred relatively recently in this cluster. This analysis has required a wide-area coverage in the cluster, as well as a large number of galaxy spectra in order to uncover the large-scale plume of galaxies we have advocated here as a telltale sign of a recent, major merger. This opens the prospect that, under similar scrutiny, other—perhaps many? (of the 20% we have mentioned)—apparently relaxed clusters might be discovered to be undergoing a major merger. The frequency with which such a process is seen to occur in nearby clusters might then tell us about the underlying cosmogony generating them.

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REFERENCES

Bardelli, S., Pisani, A., Ramella, M., Zucca, E., & Zamorani, G. 1998, MNRAS, 300, 589
Beers, T. C., et al. 1992, ApJ, 400, 410
Bird, C. M. 1994, AJ, 107, 1637
Bird, C. M., & Beers, T. C. 1993, AJ, 105, 1596
Blumenthal, G. R., Faber, S. M., Flores, R., & Primack, J. R. 1986, ApJ, 301, 27
Burns, J. O., et al. 1995, ApJ, 446, 583
Burns, J. O., Roettiger, K., Ledlow, M., & Klypin, A. 1994, ApJ, 427, L87
Campusano, L. E., Kneib, J. P., & Hardy, E. 1998, ApJ, 496, L79
Colless, M., & Dunn, A. M. 1996, ApJ, 458, 435
Davis, D. S., & Mushotzky, R. F. 1993, AJ, 105, 409
Dressler, A., & Shectman, S. A. 1988, AJ, 95, 985
Dubinski, J. 1999, in ASP Conf. Proc. 182, Galaxy Dynamics, ed. D. R. Merritt, M. Valluri, & J. A. Sellwood (San Francisco: ASP), 491
Dubinski, J., & Carlberg, R. 1991, ApJ, 378, 496
Fitchett, M. J., & Webster, R. L. 1987, ApJ, 317, 653
Girardi, M., et al. 1997, ApJ, 482, 41
Geller, M. J., & Beers, T. C. 1982, PASP, 94, 421
González-Casado, G., Salvador-Solé, E., Serna, A., & Alimi, J. M. 1998, Astron. Lett., 36, 133
Jones, C., & Forman, W. 1992, in Clusters and Superclusters of Galaxies, ed. A. C. Fabian (Dordrecht: Kluwer), 49
Kauffmann, G., & White, S. D. M. 1993, MNRAS, 261, 921
Lacey, C. G., & Cole, S. 1993, MNRAS, 262, 627
Mohr, J. J., Fabricant, D. G., & Geller, M. J. 1993, ApJ, 413, 492
Pinkney, J., et al. 1993, ApJ, 416, 36
Pinkney, J., Roettiger, K., Burns, J. O., & Bird, C. M. 1996, ApJS, 104, 1
Quintana, H., & Ramírez, A. 1990, AJ, 100, 1424
Quintana, H., Ramírez, A., & Way, M. J. 1996, AJ, 112, 36 (QRW)
Richstone, D., Loeb, A., & Turner, E. L. 1992, ApJ, 393, 477
Roettiger, K., Burns, J., & Loken, C. 1993, ApJ, 407, L53
Salvador-Solé, E., Sanromà, M., & González-Casado, G. 1993, ApJ, 402, 398
Solanes, J. M., Salvador-Solé, E., & González-Casado, G. 1998, A&A, 343, 733
Teague, P. F., Carter, D., & Gray, P. M. 1990, ApJS, 72, 715
Tyson, J. A., Kochanski, G. P., & dell'Antonio, I. P. 1998, ApJ, 498, L107
Warren, M. S., Quinn, P. J., Salmon, J. K., & Zurek, W. H. 1992, ApJ, 399, 405
West, M. J. 1994, in Proc. 14th Moriond Astrophysics Meeting, Clusters of Galaxies, ed. F. Durret, A. Mazure, & J. Trân Thanh Vân (Gif-sur-Yvette: Editions Frontières), 23
West, M. J., Jones, C., & Forman, W. 1995, ApJ, 451, L5
White, S. D. M., Briel, U. G., & Henry, J. P. 1993, MNRAS, 261, L8