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CLUSTERS IN COLLISION?

M. P. ULMER
Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208
G. D. WIRTH
Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064
AND
M. P. KOWALSKI
E. O. Hulburt Center for Space Research, Code 4129, Naval Research Laboratory, Washington, DC 20375
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ABSTRACT

We have determined the positions of the optical and X-ray centers in 13 rich galaxy clusters studied by Dressler. We tested the accuracy and precision of four methods for determining cluster centers: nearest-neighbor density, mean, median, and density-weighted mean; the last two proved superior. With the use of bootstrap resampling to obtain accurate confidence intervals on the positions of the centers, we have quantified the significance of the X-ray/optical offsets. Insignificant offsets were found in Abell 119, 154, 376, 400, 539, 1656, 1991, 2063, and 2634. The offset previously found by Snyder et al. in the Perseus cluster (Abell 426) was reproduced in our study but found to be only marginally significant, as were the offsets in Abell 754 and 2256. Abell 168 exhibits an apparently real discrepancy between its visible and X-ray centers, which we interpret as evidence that this cluster (and by implication other clusters) resulted from the collision of two approximately equal sized clusters.

Subject headings: galaxies: clustering — X-rays: galaxies

1. INTRODUCTION

The formation and evolution of clusters of galaxies is a fascinating topic not only in its own right, but also for the insight it provides into the formation of the large-scale structure of the universe (Sarazin 1986; Evrard 1990). Previous studies of the X-ray emission from galaxy clusters have identified a number of X-ray-bright clusters with bimodal X-ray emission rather than a single, well-defined emission peak (Forman et al. 1981; Ulmer & Cruddace 1982). The possibility that such clusters have formed via the coalescence or collision of two smaller and roughly equal sized clusters seemed to us to be a possible explanation for the offset between the X-ray and optical centers found in the Perseus cluster (hereafter A426; Branduardi-Raymont et al. 1981; Snyder et al. 1990). If one cluster formed via collision, then it is possible that others did as well, and an offset between the X-ray and optical centers of a cluster may be the signature of a merger. Starting from an entirely different point of view (namely, to explain luminosity evolution) Edge et al. (1990), Evrard & Henry (1991), and Henry et al. (1992) have suggested that clusters may form by the coalescence of subclusters. Although our hypothesis is similar, we additionally speculate that during the final stages of evolution these merging subclusters are of comparable size. Despite this difference, the basic concept that we propose is the same as theirs: clusters are still evolving today, and the intracluster medium may not be in hydrostatic equilibrium.

We have investigated 13 Abell clusters in a search for statistically significant offsets between their X-ray and optical centers. Our X-ray data consist of images from the *Einstein* IPC (McMillan, Kowalski, & Ulmer 1989) and, in the case of A426, from *Spartan 1* (Snyder et al. 1990). The positions of optical galaxies were taken from Dressler (1979, 1980) and Bucknell, Godwin, & Peach (1976).

Dressler's clusters have already been analyzed by Beers & Tonry (1986), who argued that the X-ray centers were more reliable tracers of the cluster centers than several methods based on the optical data. In contrast, we consider the possibility that the X-ray-emitting gas and optically emitting galaxies may have distinct centers, and we seek cases in which the two centers disagree. Implicit in our work is the assumption that a rich cluster of galaxies has a gravitational center and that both the hot intracluster medium (ICM) and the galaxies should define the same center if they are closely coupled.

In the following section we describe the methods used to determine the cluster centers, their uncertainties, and the significance of their separations. We then discuss the interesting case of A168 and consider whether the separation found in this cluster is spurious or real. Finally we suggest a possible formation scenario for A168 and other potential clusters with spatially distinct X-ray and optical components.

2. TECHNIQUE

We have analyzed only those Abell clusters for which both X-ray and optical data were available, including A119, A154, A168, A376, A400, A426, A539, A754, A1656, A1991, A2063, A2256, and A2634. Although X-ray images of A548 and A2151 also existed, they were unusable due to poor centering of the clusters within the aperture.

2.1. *Optical Centers*

Determining the optical center of galaxy clusters is not a trivial task, as is shown by the wide variety of approaches that have been taken: methods vary from elementary strip counts (Bahcall 1971) to the multiparameter fitting method espoused by Sarazin (1980). Beers & Tonry (1986) considered the nearest-neighbor density (NND), mean centers, and median centers, and Casertano & Hut (1985) advocated the use of the "density center," a weighted-mean center in which the weighting function reflects the local galaxy density.

Given the diversity of methods for finding the cluster centers, we felt it was prudent to test a representative sample in order to gauge their strengths and weaknesses. Beers, Flynn, & Gebhardt (1990) have assessed the performance of one-dimensional estimators of central location and scale; their paper provides a concise and readable discussion of the issues involved in comparing statistics. We considered four methods which do not assume an a priori analytic form to the galaxy distribution: the mean center, median center, NND center, and density center.

2.1.1. *Accuracy*

We ran a series of tests intended to measure the accuracy of each technique, involving Monte Carlo realizations of clusters. In our tests we generated King-model and power-law clusters and included three potential sources of systematic error: uniformly distributed "background" galaxies (up to 10% of the total), centering error (up to half the plate width), and presence of a subcluster of galaxies (up to 10% of the total). The examples in Figure 1 demonstrate the behavior of the mean, median, and density centers in the presence of varying amounts of potential bias. Although a complete statistical discussion of the properties of these methods lies beyond the scope of this paper, our simulations allow us to make some general statements regarding the performance of our four center estimators:

NND: The NND center of a cluster is defined as the galaxy whose Nth nearest neighbor lies at a minimum projected distance. We found no significant differences in the behavior of the NND centers when N was set to values between 6 and 12. Although very accurate in rich, power-law clusters, the NND center performs poorly in clusters with uniform-density cores, such as the King model (Beers & Tonry 1986). Since its accuracy is suspect, and its precision is difficult to estimate, we eliminated the NND center from further consideration.

Mean: The mean center is simply the average of the (x, y) galaxy positions and its ease of computation is its chief benefit; see Beers et al. (1990) for comments on the shortcomings of the mean. The mean center is susceptible to all three kinds of bias we identified: background galaxies at large distance from the cluster center have a pronounced effect on the mean; centering error biases the mean far more than the median or density centers; and the presence of substructure will generally bias the mean more than the median. Given its inferior accuracy in our tests, we did not use the mean center in our analysis.

Median: In the case of one-dimensional data, the median is considered a fairly robust statistic (Beers et al. 1990), so we desired to include it in our analysis. Unfortunately, the median value of a two-dimensional distribution is not in general uniquely defined: a rotation of the (x, y) coordinate system (e.g., using Galactic instead of celestial coordinates) will alter the order of the points along the axes, yielding a shift of the median center. We found this "wandering" effect to shift the center by an amount comparable to the size of the 1 σ confidence interval, and we felt this was unacceptably large.

To counter this effect we have defined our "median" center as the average of a number N of real median centers, each evaluated at a different rotation angle θ relative to the original celestial coordinates. For N sufficiently large ($N \approx 100$) we found that any remaining center wander was insignificant relative to the width of the 1 σ confidence interval.

Our "median" center performed well in the tests: it consistently outperformed the mean, but was in general less resistant to background contamination and centering bias than the density center (although it performed comparably for the specific parameters represented in Fig. 1). The median proved the most resistant of all to substructure bias of the type we considered.

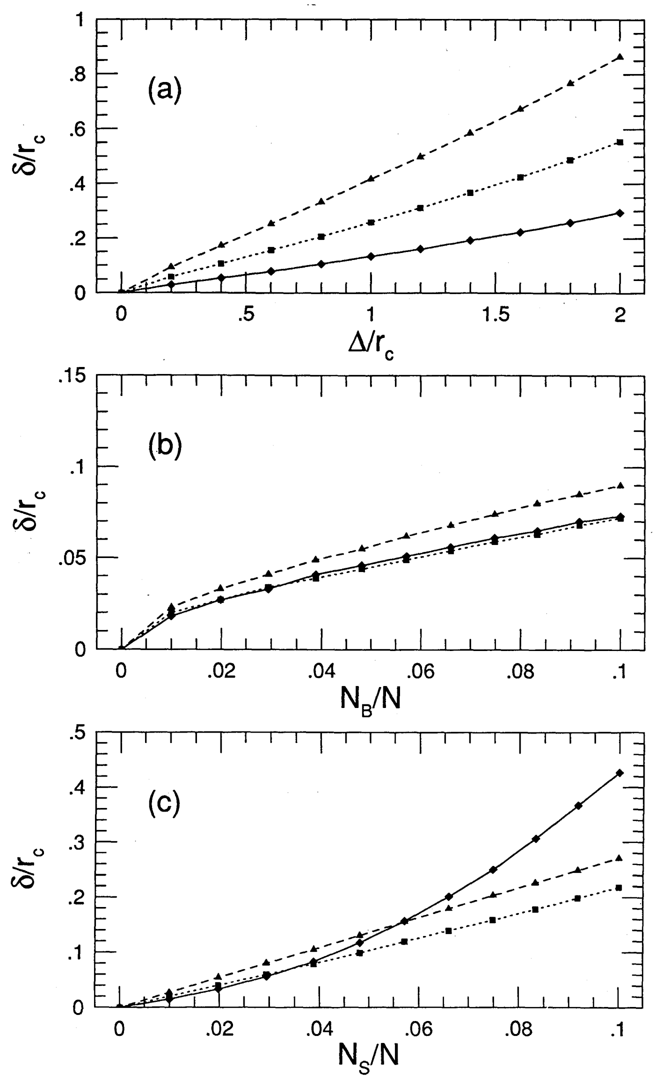

FIG. 1.—The susceptibleness of center estimators to three sources of bias in our simulations. Each data point represents the results of 1000 realizations of an $N \approx 100$ King-model galaxy cluster "imaged" on a square plate of width $5r_c$. Mean centers are denoted by the triangles and dashed lines, median centers correspond to squares and dotted lines, and density centers are represented by diamonds with solid lines. (*a*) Centering bias: the shift δ of the center (in units of the core radius r_c) relative to the zero-bias position, as a function of the distance, Δ, of the true cluster center from the plate center (also in core radius units). There is a 10% background in each case, and no explicit substructure. (*b*) Background bias: center shift as a function of N_B/N, the ratio of background galaxies to total galaxies on the plate. The cluster center is offset by $1r_c$ from the plate center, and there is no explicit substructure. (*c*) Subcluster bias: center shift as a function of N_S/N, the ratio of galaxies in a subcluster to total galaxies on the plate. The subcluster is $1r_c$ in radius and centered $3r_c$ from the cluster center, which is itself offset $1r_c$ from the plate center. No background galaxies are included.

Density: The density center (von Hoerner 1963) is a mean center in which each galaxy is weighted by the distance to its Nth nearest neighbor, where we select $N = 6$ as advocated by

Casertano & Hut (1985). This technique has the desirable property of giving increased weight to the galaxies in the core, and reduced weight to isolated outliers; on the other hand, substructure of more than N galaxies can also bias the center placement. In our tests the density center was clearly the best in terms of resistance to bias from background galaxies and centering error, but proved the most susceptible to substructure-induced error when the number of galaxies in a single substructure exceeds N.

The median and density centers are thus the preferred methods for obtaining optical centers from among the four we considered, and we have used both in computing our cluster centers. Fortunately, their strengths are complementary: the density center is resistant to the effects of background contamination and centering error, whereas the median will be more resistant to significant substructure.

2.1.2. *Precision*

Having considered the relative accuracy of the center techniques, we next estimated the precision of the median and density center. The two center types required different approaches.

For the median center we have used bootstrap resampling (Efron & Tibshirani 1986; Efron 1987) to determine the statistical uncertainties. The bootstrap is the preferred method for determining confidence intervals in one-dimensional center estimators (Beers et al. 1990), and we have simply generalized it to the two-dimensional case. To obtain the 68% confidence intervals on our median center we randomly resampled, with replacement, the original galaxy distribution 1000 times; each of these subsamples defined a "bootstrap median" center. The circle which contains 68% of these bootstrap median centers, and is centered on the original median center, represents the 68% (i.e., "1 σ") confidence contour for the position of the median center. Although it does not account for systematic bias such as substructure, background contamination, and centering error, the bootstrap technique reliably determined the statistical error for the median center in both King and power-law clusters we generated.

Unfortunately the density center was not amenable to bootstrap analysis; thus we derived an empirical relationship for the uncertainty in the density center. Casertano & Hut (1985) give a formula for the rms error in the density center as a function of the cluster "density radius" r_d (analogous to the core radius in three-space) and the number of cluster members. We empirically tested this relationship through Monte Carlo simulations, using the projected density radius s_d instead of r_d, and found $\sigma = 2.30 s_d N^{-1/2}$, which is in rough agreement with Casertano & Hut values. As a double check we compared the precision of the density center and mean center: we found that they agreed quite well for simulated King model clusters, and in most of our Abell cluster sample the 68% confidence radii agreed within 20%.

We were thus able to derive confidence intervals for our median and density centers, reflecting the random errors in center placement. We computed the uncertainty for each cluster center, given as $r_{0.68}$, the 68% confidence radius (i.e., the radius of the circle within which the true center has a 68% chance of falling). Although the distribution of the bootstrap median centers for our cluster sample indicates that the error distribution is lighter tailed than the bivariate Gaussian, we assumed a Gaussian error distribution in order to simplify the interpretation of the confidence intervals and regard the results derived under this assumption as somewhat conservative.

2.2. *X-Ray Centers*

The IPC X-ray images were constructed for a 0.5–3.5 keV passband (McMillan et al. 1989), while the *Spartan 1* image of A426 is for 1–10 keV (Snyder et al. 1990). From the positions of bright points in the maps we conclude that both relative and absolute positions are good to about 16″. Comparison between the optical data of Dressler (1976, 1980) for A2256 and independent measurements by Fabricant, Kent, & Kurtz (1989) indicate that galaxy positions are accurate enough for our purposes, as positions agree to better than 20″, whereas the uncertainties of the optical centers determined here are typically 1′–3′.

For all clusters we generated logarithmically spaced X-ray contours (i.e., separated by a factor of 1.5 in intensity), starting from the peak pixel value and descending. The lowest contour is at least 3 σ above the noise level of the map. We calculated X-ray centers using all pixels in each annular region bordered by two given contours.

A number of potential problems must be considered with this procedure. Not all of the IPC images were well centered on the cluster; those clusters where an obstructing IPC rib might have affected the center determination are discussed in detail in the next section. Also, some images contain contaminating sources along the line of sight. To address this problem we examined the sensitivity of our center determinations to the inclusion or deletion of detected point sources.

Weighting by the intensity is not viable for the X-ray emission if a strong point source lies within the field of view, as with A426. For the other clusters we defined the X-ray center as the simple center of the X-ray counts, which effectively weights the data by luminosity. However, to be consistent with our analysis of A426, we have applied the same analysis to each cluster. An examination of Table 2 indicates that these two centers differ in a statistically significant manner, and we will consider this point in the discussion section of this paper.

The data were Gaussian-smoothed (see McMillan et al. 1989 and references therein) on the scale of the pixel size; thus the data are not strictly independent, but this extra smoothing is equivalent to inserting another optical element in the system that causes Gaussian spreading of the final result. This should pose no problem because (a) analyzing data with more pixels/resolution elements than the inherent instrument response/resolution is an accepted procedure (for applications to spectral lines see Simpson & Meyer-Hasselwander 1986), and (b) the determination of errors for these X-ray data is dominated by measurement effects rather than by statistical errors; the latter were estimated via the bootstrap. For completeness, we report both the X-ray peaks and the centers of the inner X-ray contour, although they are statistically identical.

2.3. *Significance of Offsets*

Based on the methods described above, we determined both the position and uncertainty of the X-ray and optical cluster centers. The final and most important piece of information is the significance of the offset between the cluster centers. Specifically we want to know the following: assuming a bivariate (two-dimensional) Gaussian probability distribution, what is the likelihood that a separation as large or larger than the observed separation could be produced randomly? Put another way, at what level of confidence can we reject the null

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hypothesis that the two distributions being compared actually have the same center?

Although a simple way to attempt an answer is to combine in quadrature the uncertainties for the two centers being compared, this procedure is valid only in the case of a univariate (one-dimensional) Gaussian distribution and could greatly overestimate the likelihood of coincidences (i.e., understate the significance of the discrepancy). Instead, we take this approach: supose the centers are the same, and generate a possible position of each center based on the measured uncertainty, then compute the separation of these fake centers. Repeated N times, this empirical method gives the number of times $N_{\rm bigger}$ that a separation of this magnitude could randomly occur; thus the probability of achieving this discrepancy in the centers randomly is $P = N_{\rm bigger}/N$. In practice we employ $N = 10^5$.

3. RESULTS

The various centers for our cluster sample are listed in Table 1; Table 2 presents the median centers' uncertainty and distance from X-ray centers (top) and corresponding information for the density centers (bottom). The uncertainties in the optical centers are mostly within the 1′–2′.5 range and depend strongly on the number of galaxies in the field. In contrast the X-ray uncertainties vary little among the clusters, since they were influenced primarily by pixel size and angular extent; these are approximately equal for all sources in our sample. Nominal total X-ray uncertainties were 1′ for the outer contours, 0′.8 for the inner contours, and roughly 1 pixel ≃16″ for the position of the X-ray peak.

The majority of our clusters do not have X-ray/optical offsets that are significant at the 99% confidence level (i.e., they do not have $P < 0.01$ in Table 2). Although the A754 and A2256 data suggest an offset between the X-ray maximum and optical centers, only A168 contains a very significant offset between all of its X-ray and optical centers. We now focus on this cluster.

Figure 2 shows the optical and X-ray centers of A168, as well as the X-ray emission and galaxy positions. Both the centroid for the outer contour and the X-ray peak position are clearly separated from the optical centers, and no obvious well-defined local density enhancement of galaxies occurs near the X-ray peak. The hypothesis that the X-ray centers and the optical centers are the same for all the cases in this cluster can be rejected at better than or equal to the 0.0001 significance level, and at a redshift $z = 0.045$ the nearly 10′ X-ray/optical offset corresponds to an 800 kpc projected separation (assuming $q_o = 0, H_o = 50\ {\rm km\ s^{-1}\ Mpc^{-1}}$).

We considered three possible causes for the large separation: (1) the uncertainty in the X-ray and/or optical centers has been underestimated; (2) the positions of the X-ray and/or optical centers is biased through some systematic error; (3) the X-ray and optical centers are truly offset. Before presuming the reported offset to be real, we must investigate the other two options.

First, could the derived uncertainties for A168 be wrong? The optical median and density uncertainties (defined as the radius of the circular 68% confidence interval, or $r_{0.68}$) are 1′.7 and 1′.9, respectively, which are about average for the clusters in our sample. The estimate of the median uncertainty was determined from bootstrap resampling, which reliably determined confidence intervals in our many simulations, while $r_{0.68}$ for the density center came from an analytic relation which was accurate for simulated King-model clusters. We found that bootstrap-derived confidence intervals on the mean centers accurately estimated the density center uncertainty for King-model clusters and overestimated the uncertainty of density centers in clusters with central cusps. The mean center uncertainty for A168 is 1′.7, which suggests that the value of 1′.9 from the analytical approximation is not a significant underestimate. Thus the optical uncertainties in A168 appear correct and are not likely to have caused the discrepancy.

The X-ray center uncertainties are not as well determined, and an inspection of Table 2 reveals some possible problems;

TABLE 1

CLUSTER CENTERS

CLUSTER (1)	MEDIAN CENTER α (1950) (2)	MEDIAN CENTER δ (1950) (3)	DENSITY CENTER α (1950) (4)	DENSITY CENTER δ (1950) (5)	X-RAY PEAK α (1950) (6)	X-RAY PEAK δ (1950) (7)	X-RAY MAXIMUM α (1950) (8)	X-RAY MAXIMUM δ (1950) (9)	X-RAY MINIMUM α (1950) (10)	X-RAY MINIMUM δ (1950) (11)
A119	$0^{h}53^{m}42^{s}.2$	−01°31′02″	$0^{h}53^{m}42^{s}.7$	−01°30′37″	$0^{h}53^{m}44^{s}.6$	−01°30′38″	$0^{h}53^{m}42^{s}.7$	−01°30′46″	$0^{h}53^{m}54^{s}.0$	−01°31′50″
A154	1 08 22.7	+17 23 00	1 08 24.6	+17 23 02	1 08 24.0	+17 23 22	1 08 23.0	+17 23 34	1 08 23.3	+17 23 20
A168	1 12 40.4	−00 01 33	1 12 37.9	−00 00 59	1 12 24.0	+00 08 44	1 12 25.7	+00 07 14	1 12 25.9	+00 04 58
A376	2 42 51.0	+36 38 56	2 42 51.2	+36 39 18	2 42 59.5	+36 42 06	2 42 58.1	+36 42 00	2 42 46.1	+36 41 34
A400	2 55 18.2	+05 49 13	2 55 21.6	+05 50 27	2 55 00.7	+05 49 18	2 55 01.0	+05 49 08	2 55 09.8	+05 47 12
A426E	3 16 18.5	+41 19 12	3 16 17.9	+41 18 24	3 16 30.7	+41 20 04	3 16 30.7	+41 20 08	3 16 43.9	+41 20 20
A426S	3 16 18.5	+41 19 12	3 16 17.9	+41 18 24	3 16 29.3	+41 19 50	3 16 30.0	+41 20 04	3 16 45.1	+41 19 26
A539	5 13 52.8	+06 23 12	5 13 53.3	+06 24 00	5 13 55.9	+06 23 02	5 13 57.1	+06 23 26	5 14 07.4	+06 25 14
A754	9 06 17.4	−09 27 35	9 06 24.8	−09 27 46	9 06 49.2	−09 28 40	9 06 51.4	−09 28 14	9 06 33.8	09 27 50
A1656	12 57 12.2	+28 12 16	12 57 11.8	+28 11 48	12 57 26.2	+28 12 28	12 57 25.4	+28 12 50	12 57 08.6	+28 12 02
A1991	14 52 16.5	+18 46 13	14 52 16.5	+18 48 05	14 52 14.2	+18 50 38	14 52 14.2	+18 50 52	14 52 07.7	+18 49 29
A2063	15 20 37.9	+08 45 30	15 20 35.9	+08 46 33	15 20 40.1	+08 47 38	15 20 40.1	+08 47 30	15 20 30.2	+08 46 58
A2256	17 06 18.9	+78 44 35	17 06 33.6	+78 43 27	17 06 54.0	+78 43 18	17 06 43.9	+78 42 52	17 07 16.1	+78 41 23
A2256T	17 07 24.1	+78 41 33	17 07 27.8	+78 40 48	17 06 54.0	+78 43 18	17 06 43.9	+78 42 52	17 07 16.1	+78 41 23
A2634	23 36 01.4	+26 44 41	23 36 02.9	+26 45 14	23 35 58.6	+26 45 10	23 35 53.5	+26 47 08	23 36 00.0	+26 45 38

NOTES.—Col. (1) Cluster name in Abell catalog; cols. (2)–(3) Median center (mean position of 100 different median centers) of cluster in the optical galaxy catalog of Dressler 1980, except for A2256T from Dressler 1976, and A426 from Bucknell et al. 1979; cols. (4)–(5) Density-weighted mean center of optical galaxies; cols. (6)–(7) Position of the X-ray emission peak from the data of McMillan et al. 1989, except for A426E and A426S which come from Snyder et al. 1990 and Branduardi-Raymont et al. 1981, respectively; cols. (8)–(9) Centroid of the pixels between the highest X-ray emission contour and the peak; cols. (10)–(11) Centroid of the pixels between the two lowest X-ray emission contours.

TABLE 2

UNCERTAINTY AND DISTANCE FROM X-RAY CENTERS

CLUSTER	OPTICAL UNCERTAINTY	OPTICAL–X-RAY PEAK		OPTICAL–X-RAY MAXIMUM		OPTICAL–X-RAY MINIMUM		X-RAY MAXIMUM–X-RAY MINIMUM		X-RAY PEAK–X-RAY MAXIMUM	
(1)	$r_{0.68}$ (2)	Δ (3)	*P* (4)	Δ (5)	*P* (6)	Δ (7)	*P* (8)	Δ (9)	*P* (10)	Δ (11)	*P* (12)
					Median Center Offsets						
A119	1′.5	0′.7	0.8	0′.3	1.0	3′.1	0.03	3′.0	0.0017	0′.5	0.7
A154	1.1	0.5	0.8	0.6	0.8	0.3	0.9	0.2	1.0	0.3	0.9
A168	1.7	11.1	<0.00001	9.5	<0.00001	7.5	<0.00001	2.3	0.03	1.6	0.020
A376	1.7	3.6	0.006	3.4	0.02	2.8	0.10	2.4	0.016	0.3	0.9
A400	2.8	4.3	0.06	4.3	0.08	2.9	0.3	2.9	0.003	0.2	0.9
A426E	1.7	2.4	0.10	2.5	0.14	4.9	0.0009	2.5	0.014	0.1	1.0
A426S	1.7	2.1	0.18	2.3	0.17	5.0	0.0007	2.9	0.003	0.3	0.9
A539	1.9	0.8	0.8	1.1	0.7	4.2	0.011	3.1	0.0011	0.5	0.7
A754	2.3	7.9	<0.00001	8.4	<0.00001	4.1	0.05	4.4	<0.00001	0.7	0.5
A1656	1.5	3.1	0.007	3.0	0.03	0.8	0.8	3.8	0.00006	0.4	0.8
A1991	3.5	4.4	0.17	4.7	0.15	3.9	0.3	2.1	0.05	0.2	0.9
A2063	1.8	2.2	0.20	2.1	0.3	2.4	0.2	2.5	0.013	0.1	1.0
A2256	1.3	2.1	0.06	2.1	0.13	4.2	0.0006	2.2	0.04	0.7	0.5
A2256T	0.5	2.3	<0.00001	2.4	0.0007	0.4	0.9	2.2	0.04	0.7	0.5
A2634	1.5	0.8	0.8	3.0	0.03	1.0	0.7	2.1	0.05	2.3	0.0003
					Density Center Offsets						
A119	1.9	0.5	0.9	0.1	1.0	3.1	0.10	3.0	0.0017	0.5	0.7
A154	1.1	0.4	0.9	0.6	0.8	0.4	0.9	0.2	1.0	0.3	0.9
A168	1.9	10.4	<0.00001	8.8	<0.00001	6.7	0.000010	2.3	0.03	1.6	0.020
A376	1.6	3.3	0.012	3.0	0.04	2.5	0.15	2.4	0.016	0.3	0.9
A400	3.2	5.3	0.04	5.3	0.05	4.4	0.14	2.9	0.003	0.2	0.9
A426E	2.0	2.9	0.10	3.0	0.13	5.2	0.002	2.5	0.014	0.1	1.0
A426S	2.0	2.6	0.17	2.8	0.15	5.2	0.002	2.9	0.003	0.3	0.9
A539	1.4	1.2	0.5	1.1	0.6	3.7	0.005	3.1	0.0011	0.5	0.7
A754	2.4	6.1	0.0008	6.6	0.0004	2.2	0.4	4.4	<0.00001	0.7	0.5
A1656	1.8	3.2	0.03	3.2	0.06	0.8	0.9	3.8	0.00006	0.4	0.8
A1991	4.3	2.6	0.7	2.8	0.6	2.5	0.7	2.1	0.05	0.2	0.9
A2063	1.7	1.5	0.4	1.4	0.5	1.5	0.5	2.5	0.013	0.1	1.0
A2256	1.2	1.0	0.5	0.8	0.7	2.9	0.02	2.2	0.04	0.7	0.5
A2256T	0.7	3.0	<0.00001	3.0	0.00004	0.8	0.6	2.2	0.04	0.7	0.5
A2634	2.2	1.0	0.8	2.8	0.18	0.8	0.9	2.1	0.05	2.3	0.0003

NOTES.—Col. (1) Cluster name in Abell catalog; col. (2) For median center offsets, radius of circle containing 68% of the bootstrap median centers—i.e., 68% confidence radius for median centers of the optical galaxy catalogs; for density center offsets, radius of circular 68% confidence contour for the density-weighted mean centers of the optical galaxy catalogs; cols. (3)–(12) Angular separation Δ of various centers and the probability *P* that the centers are the same based on a bivariate Gaussian error model.

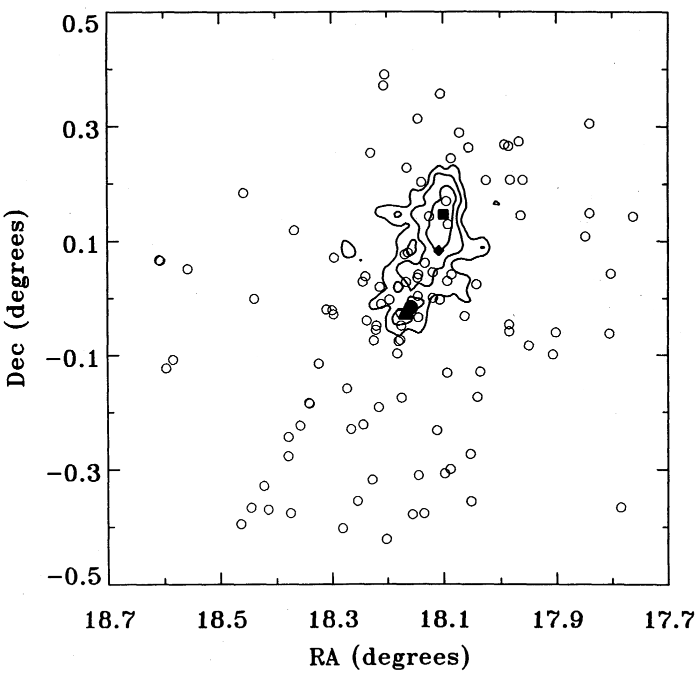

FIG. 2.—The 0.5–3.5 keV X-ray map of Abell 168 is superposed on the galaxy distribution. X-ray contours are spaced by factors of 1.5 in intensity from the peak. The circles are the positions of the galaxies from Dressler (1980). The filled triangle is the median center of the galaxy distribution, and the filled circle represents the density center. The filled square denotes the center of the highest X-ray contour, and the filled diamond locates the centroid of the lowest X-ray contour.

for example, 11 of the 13 clusters have X-ray peak/X-ray maximum offsets that are more than 50% likely to arise randomly; that is, agreement is better than expected based on the error estimates. This overabundance of high probabilities of coincidence suggests that we have overestimated the uncertainty of one or both of the these positions. In contrast, 12 of the 13 X-ray minimum/X-ray maximum offsets are of 5% or lower probability, implying that these offsets are statistically significant or that we have underestimated the uncertainty in at least one of these. Since the first case suggests that we have overestimated the X-ray maximum uncertainty, we only consider below the possibility that we have underestimated the X-ray minimum uncertainties.

The outer annuli we used for the X-ray minimum were at least 3 σ above the noise level of the map; thus the noise in the map should not have been a major source of error. However, in cases such as A1656 for which the X-ray image is actually larger than the IPC field, the X-ray minimum value was probably affected by an artificial cutoff due to blockage by the IPC. For the remaining clusters, the image size was smaller than the IPC field and the differences between X-ray minimum and X-ray maximum may well be real.

In general, real X-ray minimum/X-ray maximum offsets could result from an X-ray enhancement due to a subcluster that is offset from the gravitational center of the cluster. Even in the unlikely event that we had underestimated the uncertainty in the X-ray minimum center by a factor of 3, the X-ray minimum/optical separation in A168 would still be significant at the 98% significance level. Therefore neither errors in the X-ray nor in the optical uncertainties are likely to be the source of the offset in A168.

Next we entertain the possibility that systematic errors have biased the position of either the optical or X-ray centers, contributing to the apparently large separation. The *Einstein* X-ray image of A168 abuts an IPC obstructing rib at the north (top) end, implying that the true X-ray centroid of the outer contours might be further to the north of the position we calculated; however, the optical centers are already well displaced to the south. That the IPC image was not well centered on the X-ray emission cannot explain the offset between the X-ray and optical centers, although it probably does cause the relatively large discrepancy between the X-ray peak and the center of the maximum X-ray contour for this cluster.

Bias in the optical centroids is also unlikely to explain the difference in the centers. We have already discussed three sources of potential bias in the optical centroids: background galaxies, centering error, and subclusters. In A168 the offset between the X-ray and optical centers is around 9′, whereas the density radius $s_d = 8'.7$ and thus the core radius of the cluster is $r_c \approx 9'$. As shown in Figure 3*a*, even if the X-ray center represented the true center of the cluster, the median and density centers would be expected to shift by only $0.3r_c$, assuming an unlikely 10% background contamination. Figure 3*b* shows that for a cluster offset by $1r_c$ from the plate center, the median and density centers, are, on average, not sensitive to the effects of uniformly distributed background galaxies.

The effects of substructure are more difficult to determine. Figure 3*c* shows the error caused by adding various amounts of substructure to an $N \approx 100$ cluster offset by $1r_c$ from the plate center. In this case a subcluster containing a half-dozen galaxies yields an error of only $0.3r_c$, insufficient to produce the observed separation. Although different amounts and varieties of substructure could influence the density center by more than a few $0.1r_c$, a variety of tests for substructure performed by others on A168 (Geller & Beers 1982; West, Oemler, & Dekel 1988; Dressler & Shectman 1988; West & Bothun 1990) detected no subclustering. Since we require significant substructure to produce the offset seen in A168, we expect that bias in the optical centers is not the cause of the discrepancy.

At the suggestion of the referees, we have run tests which are intended to measure the robustness of the median and density centers. We split the galaxies in the cluster into two equal subsamples, one consisting of those galaxies nearest the optical center, the other containing those more distant. The centers of these subsamples are computed and compared, the expectation being that they will agree with each other and with the overall optical center if they are not being greatly affected by galaxies far from the cluster center. In A168 the subcluster density centers were offset from each other about 3′ in the east-west direction, but both were consistent with the overall cluster center, within their respective uncertainties. For the median centers, we found a 4′ distance between the subsample centers, with the inner sample within 1′ of the overall center and the outer center displaced 4′ to the south. The results of this test suggest that biasing of the optical centers by galaxies is not a problem in A168.

Having shown that neither random nor systematic errors are likely to be the source of the difference in the optical and X-ray centers of A168, we now consider the implications of the third option: that the observed offset represents a real difference between the distribution of X-ray-emitting gas and visible galaxies.

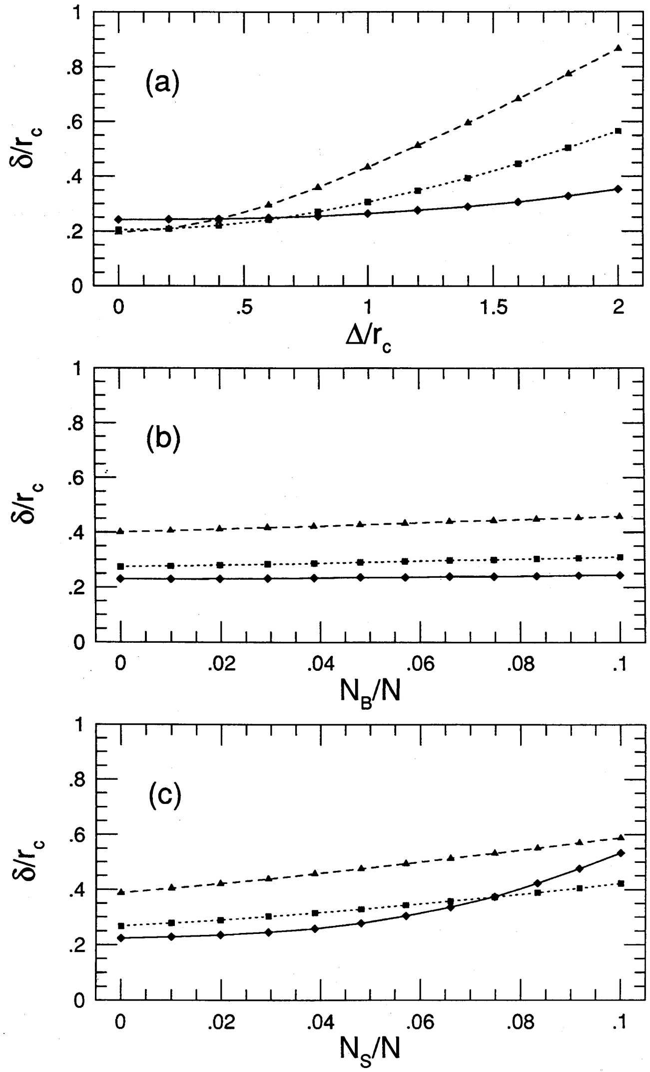

FIG. 3.—Average error (random and systematic) in tests of our center estimators on simulated King-model clusters. See notes to Fig. 1 for details. (*a*) Centering error: the average distance δ of the estimated center from the true cluster center (in units of the core radius r_c) as a function of the offset Δ between the plate center and the true center. (*b*) Background error: δ as a function of background fraction. (*c*) Substructure error: δ as a function of subcluster fraction.

4. DISCUSSION

We have shown that it is plausible that the X-ray and optical centers are disjoint in at least one of the 13 clusters we sampled, A168. As noted in the introduction, it is implicit in the comparison between X-ray and optical centers that both the galaxies and the ICM are influenced by the same gravitational potential well(s). Therefore, that the optical galaxy counts are spread over a much larger region of the sky than the X-ray emission should not significantly affect our result. Furthermore, if new X-ray observations find that emission extending over the entire optical survey region is centered on the optically determined cluster center, clusters with displaced optical centers relative to the core X-ray emission still exist; these examples will still require explanations such as those we suggest.

We now consider the implications of a true physical offset in A168. One possibility is that dark matter dominates the potential in these clusters and that while the X-ray emission tracks this potential, the galaxies do not because their distribution has not yet relaxed. A second possibility is that the cluster is not only dominated by dark matter, but also that the X-ray-emitting gas is not yet in hydrostatic equilibrium (Evrard 1990). A third explanation, which we favor, is that A168 (and perhaps other clusters as well) has formed by the collision or coalescence of two smaller clusters. In principle if the gas-to-galaxy ratios for these two colliding systems are not the same, then the resulting collision can produce an offset between the X-ray and optical centers and the resulting gas need not be in hydrostatic equilibrium; detailed calculations are, however, beyond the scope of this work. That some clusters may still be forming today is not a new idea; for example, see Fitchett (1988), Edge et al. (1990), Henry et al. (1992) and references therein. That we found several clusters with offsets between the X-ray peak position and the X-ray center determined from the outermost contours of the X-ray images can be taken as further evidence that clusters are still in the process of forming today and contain X-ray subclusters.

Our "cluster collision" hypothesis also provides a natural explanation for the elliptical appearance of some clusters. It would also explain why some clusters may have relatively smooth X-ray maps and *appear* to be simple, yet require complex models to describe simultaneously the optical and X-ray components (Fabricant et al. 1986, 1989). After this paper was first submitted, Briel et al. (1991) further reinforced our hypothesis by inferring from *ROSAT* data that A2256 consists of two smaller clusters that are in the process of merging.

Finally, some clusters have been found in which the cD galaxy appears to have a significant motion with respect to the average velocity of the cluster (Bothun & Schombert 1988, 1990; Bower, Ellis, & Efstathiou 1988; Hill et al. 1988; Sharples, Ellis, & Gray 1988). Whether or not these velocity differences are real is under discussion (Gebhardt & Beers 1991; J. O. Burns 1990, private communication). If so, one explanation is that such clusters evolved in a fashion similar to A168; however, the one cluster with a "high-velocity" cD that is in our current sample, A2634, does not exhibit a statistically significant optical/X-ray offset. As the velocity measurements are line-of-sight, and the optical/X-ray offsets are produced from positions measured perpendicular to the line of sight, it may be difficult to find systems in which there is both a measurable cD motion as well as a significant X-ray and optical offset.

5. SUMMARY AND CONCLUSIONS

In summary, we have presented evidence that the distribution of hot gas is offset from the galaxy distribution in the rich galaxy cluster A168. The 12 remaining clusters in our sample did not show statistically significant offsets in our tests, which compared the centers of the concentrated and diffuse X-ray emission with the position of the median and density centers for the galaxies. But there were several clusters that showed offsets that were large enough to suggest further study. We hypothesize that A168 (and perhaps other clusters as well) has formed by the collision of two smaller clusters. Our work also corroborates previous work by Fabricant et al. (1986, 1989), who showed that seemingly "simple" clusters with smooth X-ray maps require complicated models to produce a self-consistent picture of the galaxy and gas components.

With *ROSAT* observations and with scans of optical plates becoming commonplace, it will soon be possible to produce a much larger sample than used here and hence determine the pervasiveness of this result. Also, in a larger sample it may be possible to find correlations with other cluster properties.

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