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OBSERVATIONS OF THE TWO COMPONENTS OF THE ABELL 98 CLUSTER OF GALAXIES

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ABSTRACT

X-ray and optical observations of A98 show that the cluster is composed of two subclusters. From an estimate of the masses and velocity differences, the two components may merge in about a billion years. These data support the hierarchical clustering model in which clusters occur on all size scales, with larger clusters being formed from mergers of smaller ones.
Subject headings: galaxies: clusters of — galaxies: evolution — X-rays: sources

I. INTRODUCTION

N-body simulations (White 1976; Aarseth, Gott, Turner 1979) indicate that clusters of galaxies grow from the continual formation and merger of subclusters. The very simple model of assuming the creation of galaxy-sized objects by a certain epoch ($z \approx 10$ for $q_0 = \frac{1}{2}$, $z \approx 30$ for $q_0 = 0.05$) and allowing them to interact gravitationally produces many of the observed clustering properties. In particular, the calculated covariance function and three-point correlation function for galaxies agree with that observed (Gott, Turner, and Aarseth 1979; Fall 1978).

If this model is correct, then it has interesting implications for the evolution of cluster X-ray luminosities. During the merger of two subclusters, the X-ray luminosity rises quite sharply (Perrenod 1978; Gingold and Perrenod 1979) because of the rapidly steepening cluster potential. This means that the X-ray luminosities of clusters will be smaller in the past than at present because the single bright cluster has evolved from fainter subclusters. However, this property is difficult to observe because at any given redshift there will be a large spread of cluster ages, so that the sharp increase in luminosity will be smeared out. Only the average luminosity of a large sample of clusters would be a decreasing function of redshift.

In addition to a comparison with observed correlation functions, the predictions of these N-body experiments have also been compared at their end points with observations of nearby bright clusters and groups (see White 1976 and Perrenod 1978, for comparison with the Coma cluster, and Turner *et al.* 1979, for comparison with a sample of groups of galaxies). However, another method of testing these models is by the observation of two condensations that are about to form into a single cluster. In the companion *Letter* to this *Letter*, Forman *et al.* (1981) discuss observations of four clusters in which X-ray emission is double lobed, indicating that a single cluster may be in the process of forming from two subclusters.

For one of these clusters, A98, there is a large body of optical data available (this paper; Dressler 1976; Faber and Dressler 1977, hereafter FD; Dressler 1978*a*, *b*), so that it is possible to perform a more extensive analysis than for the others, which we present here. The optical and X-ray data of the A98 region show two distinct components which we designate A98 N and A98 S. A98 S is centered on the nominal cluster position (Sastry and Rood 1971). Our optical observations did not reveal any active galaxies or QSOs in the error circle projected on A98 N, so we can identify this source with the subcluster itself. The redshifts of the two components are the same, which shows they are physically associated. The most likely interpretation of all the data is that the two components of A98 are in the process of forming a single large cluster.

II. OPTICAL DATA

The initial reduction of the IPC X-ray image revealed the presence of a source ~10′ north of the nominal position of A98. Based on our previous identifications of *Einstein* serendipitous sources obtained with comparable exposures, we expected to find a bright QSO or Seyfert in the error circle. Using the Lick Observatory 3 m Shane telescope and Image Tube Scanner (ITS, Robinson and Wampler 1972), it rapidly became evident that none of the stellar objects to $m_V \approx 18$ were at all unusual, thus ruling out a bright QSO as the identification. During 1979 July and August, we obtained spectra of the brightest galaxies in this region, designated G1, G2, and G3, shown in Figure 1 (Plate L9). The spectra show no evidence for any active galactic nuclei; only normal late-type stellar features are present. Since there appear to be no QSOs or Seyferts in the error circle, we identified the

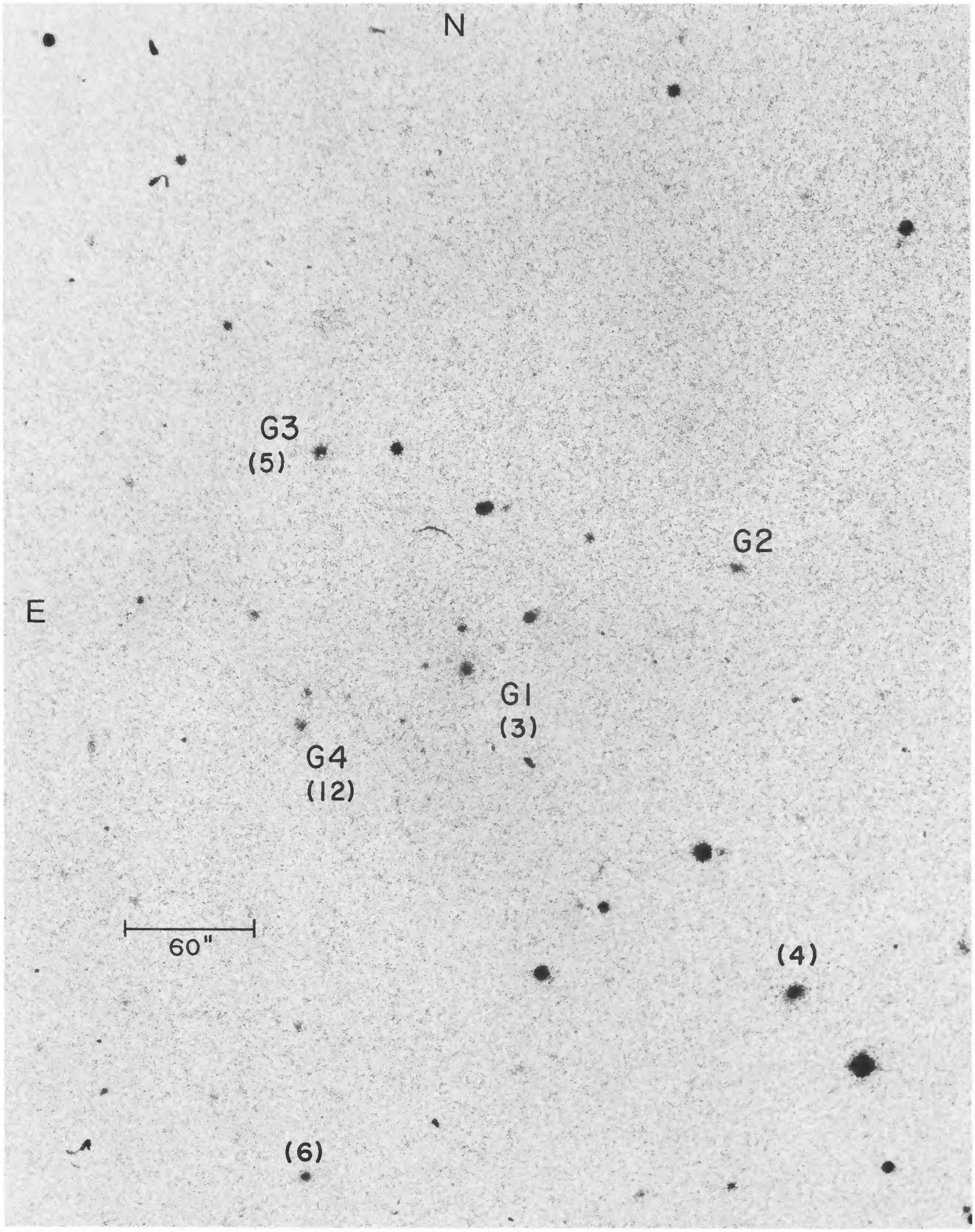

FIG. 1.—The central region of A98 N from a Crossley plate (original scale 38″.6 mm^{-1}) taken by us on 1979 June 22.5 UT. The passband is approximately 5000–6900 Å (Kodak 098-04 plus Schott GG 495 filter).

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source with the subcluster A98 N as a whole. Based on this, we performed the analysis given in § III, which shows the X-ray source to be extended, thus confirming the identification.

We have used the data of Dressler (1976), who gives the coordinates and magnitudes of galaxies in the A98 region, to determine surface and azimuthally averaged galaxy distributions. These are shown in Figures 2*b* and 3*c* and 3*d*, respectively, for galaxies brighter than $m_F = 19.2$. For the azimuthally averaged distributions shown in Figure 3 (both X-ray and galaxy), in order to avoid contamination of one component by the other, we have used only data in the southern (northern) half-plane for A98 S (A98 N) for distances greater than 3'.3 from either component. The background to $m_F = 19.2$, determined from Figure 2 of Oemler (1974), was 0.22 galaxies arcmin^{-2}. To characterize the size of the galaxy distributions, we have fitted King (1972) models of the form $N(r) = N_0(1 + r^2/a_0^2)^{-1}$, where N is the number of galaxies arcmin^{-2}. The best-fitting curves are superposed on the data in Figures 3*c* and 3*d*, and the core radii are given in Table 1. For A98 S we obtained the same core radius as did Dressler (1978*b*).

Galaxies G1 and G3 were also observed spectroscopically by FD as their numbers 3 and 5, respectively. The radial velocities that we derive for G1 and G3 confirm those of FD but are less accurate since we did not use a cross-correlation technique. Therefore, we determined the redshift of galaxy G2 by measuring the displacement of the λ4000 break, the G-band, and Mg *b* λ5175 with respect to galaxy G1. The resultant mean-velocity displacement is 1450 ± 260 km s^{-1}, yielding cz = 32,202 km s^{-1}.

Since the galaxy and X-ray distributions are double lobed (see above and § III), we have divided the optical

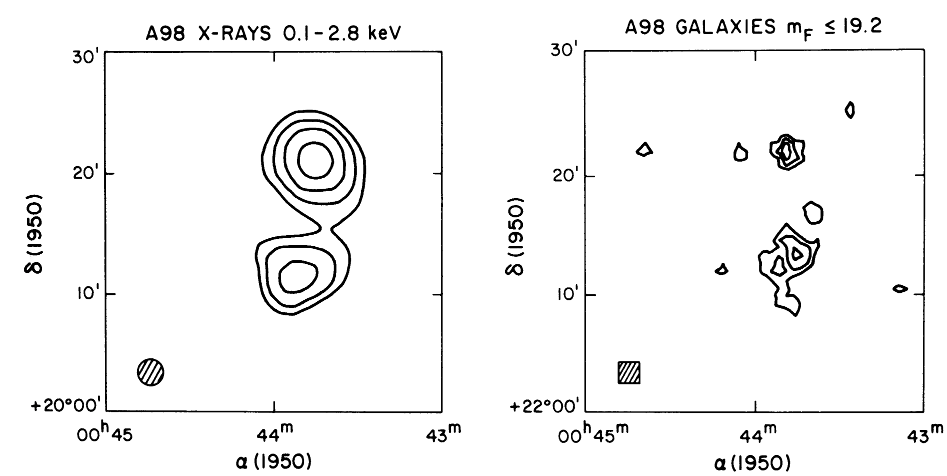

FIG. 2.—(*a*) *Left:* A contour plot of the Wiener filter of the X-ray image of the A98 region obtained in the 0.1–2.8 keV band. The point response function (FWHM) is shown by the circle at the lower left. Contour levels are at 6.4, 8.25, 11.0, and 15.6 IPC counts arcmin^{-2} = 97.1, 125.2, 166.9, and 236.7 keV cm^{-2} s^{-1} sr^{-1} keV^{-1} at 1.8 keV. The background for this observation in this energy band was 4.3 IPC counts arcmin^{-2}. (*b*) *Right:* A contour plot of the galaxy counts in the A98 region smoothed by a running mean taken with a 1'.93 × 1'.93 box (*shown in the lower left*). Contours are at 1.9, 2.4, and 3.2 galaxies arcmin^{-2}. The background is 0.22 galaxies arcmin^{-2}, from Oemler (1974).

TABLE 1

PROPERTIES OF A98 (H_0 = 50 km s^{-1} Mpc^{-1})

Parameter	A98 N	A98 S
z	0.1038±0.0016	0.1035±0.0013
σ (km s^{-1}) (line of sight)	983(+309, −280)	634(+253, −222)
Optical core radius (arc minutes, Mpc)	3.0(+4.0, −1.8), 0.54(+0.72, −0.33)	2.7±1.0, 0.48±0.18
Central virial density (g cm^{-3})	4×10^{-26}±(×10)	2×10^{-26}±(×4)
Bautz-Morgan class	I–II	II
Rate (IPC counts s^{-1})(0.16–2.8 keV)	6.0±0.6×10^{-2}	5.1±0.6×10^{-2}
F_E [2 keV/(1+z)](keV cm^{-2} s^{-1} keV^{-1})	3.3±0.3×10^{-4}	2.5±0.3×10^{-4}
L_x(0.5 keV, 4.5 keV)(ergs s^{-1})	9.5±0.9×10^{43}	7.3±0.8×10^{43}
X-ray core radius (arc minutes, Mpc)	5.7(+1.0, −1.7), 1.03(+0.18, −0.31)	4.3(+0.9, −0.5), 0.78(+0.16, −0.09)
X-ray central gas density (g cm^{-3})	9.9±2.4×10^{-28}	1.4±0.2×10^{-27}

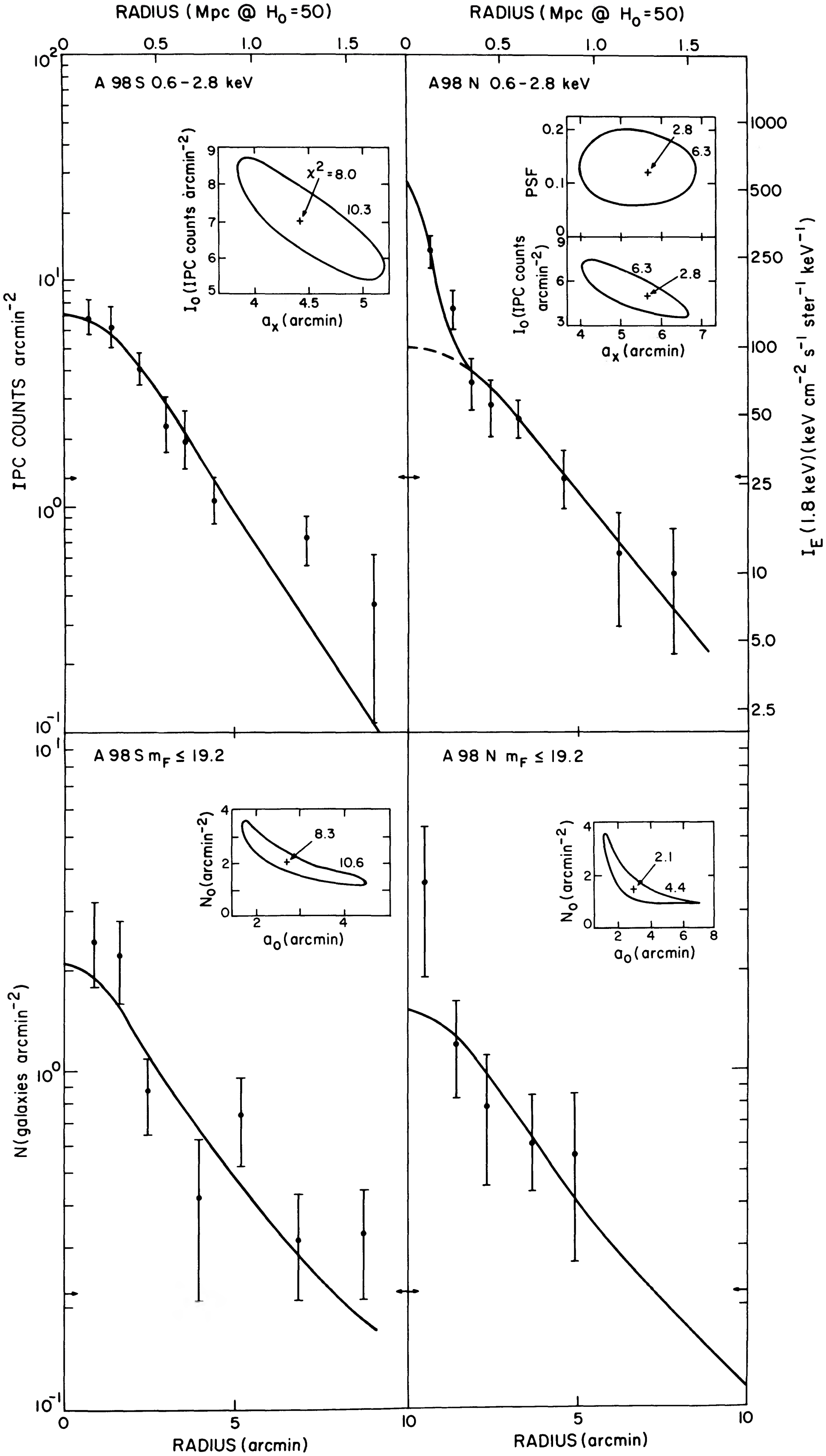

FIG. 3.—Azimuthally averaged surface brightness distributions with best-fitting isothermal distributions superposed (see text for details). The insets are the χ^2 contours at the 1 σ level for two or three parameters. The arrows mark the levels of the background which has been subtracted from the data. Note that to optimize the spatial resolution, the X-ray data are in a different energy band than those of Fig. 2. When comparing the two figures, only the absolute (not the instrumental) units should be used.

cluster members measured by FD and G2 into two groups according to whether they are associated with the northern or southern component. The mean velocity and velocity dispersion of each subgroup, computed according to the procedure of Danese, De Zotti, and di Tullio (1980), are shown in Table 1. The results are consistent with the cluster L_x-σ relation given by Hintzen and Scott (1979). From the data in Table 1 we can calculate the central virial density from $\rho_0 = 9\sigma^2/4\pi G a_0^2$ (Rood *et al.* 1972), where σ is the line-of-sight velocity dispersion. Since the measured quantities enter as the square, the error for ρ_0 is large. To estimate the error in the most conservative manner, we have combined the extreme values of σ and a_0 in the way which gives the extreme estimates of ρ_0. The range of ρ_0 is plus or minus a factor of 10 for A98 N and plus or minus a factor of 4 for A98 S.

We can estimate the Bautz-Morgan class (BM) of the subclusters using the technique developed by Dressler (1978*c*). We compute a quantity $\Delta \equiv (m_2 - m_1) + (m_3 - m_1)$, which is an indicator of the contrast between the first and the second and third brightest galaxies in a cluster. From the photometry of Dressler (1976), which was a part of the calibration of BM with Δ, we find for A98 N that $\Delta = 2.2$ (BM = I–II), for A98 S $\Delta = 1.9$ (BM = II) and for A98 $\Delta = 1.1$ (BM = II–III). The Bautz-Morgan classes for the subclusters are listed in Table 1.

III. X-RAY DATA

We have observed the A98 region with the imaging proportional counter (IPC) of the *Einstein* X-ray Observatory. Some of these data were reported by Henry *et al.* (1979), where the cluster referred to as A98 is A98 S. The exposure time for these observations was 3873 s in the energy band 0.1–2.8 keV.

In Figure 2*a*, we show the Wiener filter of the X-ray image as an isointensity plot. The Wiener filter divides the Fourier transform of the data, attenuated by a factor estimating the signal and noise powers, by the Fourier transform of the point response function (cf. Arp and Lorre 1976). This should be compared with a contour plot of the galaxy counts shown in Figure 2*b*. There are obvious similarities between the X-ray and optical data, but the stronger X-ray component is associated with A98 N, where there are fewer galaxies. The emission between the two components is 0.20 ± 0.10 of the peak, which is consistent with the calculations of Gingold and Perrenod (1979).

The measured count rates, observed fluxes at Earth at 2 keV in the cluster frame, and luminosities in the 0.5–4.5 keV band are given in Table 1. The conversion of count rate to flux and luminosity is described by Henry *et al.* (1979). Briefly, we folded an assumed thermal bremsstrahlung spectrum (with unit normalization) through the IPC. By comparing the observed count rate with that predicted by the assumed spectrum, we obtain the proper normalization. We assumed that the temperature $kT = 7$ keV at the source and the column density $N_X = 3 \times 10^{20}$ cm^{-2} in our Galaxy. An analogous procedure was used to convert counts per solid angle to surface brightness.

We obtained azimuthally averaged surface-brightness distributions of the unfiltered data centered on the X-ray positions of the two components. We avoided contamination of one component by the other in the manner described for the galaxy counts. These distributions are shown in Figures 3*a* and 3*b*. Background was determined from regions adjacent to the sources. Vignetting corrections, which were never more than 25% and usually less than 10%, were determined at the mean energy of 1.7 keV. We have restricted our analysis to only those events in the upper half of the pulse-height analyzer (0.6–2.8 keV for this observation), where the spatial resolution is independent of energy and equal to 0$'$.65 (HWHM).

To parametrize the sizes of the two components, we have fitted the surface brightness produced by thermal bremsstrahlung radiation from a self-gravitating isothermal sphere to the two azimuthally averaged distributions. While this model is not self-consistent, it does fit the data and is useful in comparing with other results. In the self-gravitating isothermal sphere model, the gas density is $n_e(r) = n_0(1 + r^2/a_x^2)^{-3/2}$, where n_e is the electron (∼ion) density, so that the surface brightness is $I(r) = I_0(1 + r^2/a_x^2)^{-5/2}$. We have not convolved this with the IPC point-spread function, since a_x is much larger than the spatial resolution. The best-fitting curves are superposed on the data in Figures 3*a* and 3*b*, and the core radii are given in Table 1.

A98 S was well fitted by the simple model described above, but for A98 N we found it was necessary to include a point source at the origin. This reduced the χ^2 from 14.3 for 6 degrees of freedom to 2.8 for 5 degrees of freedom. Using the method described in Malina, Lampton, and Bowyer (1976), from the reduction in χ^2, the zero point-source hypothesis can be rejected with a probability greater than 99.9% [$P(\chi_1^2 > 11.5) < 10^{-3}$]. The best-fitting point source fraction (PSF), with respect to the diffuse emission extrapolated to infinity, was 0.12 ± 0.08. This emission need not, of course, be from a point but only from a region smaller than the instrumental resolution. The pointlike component is associated with G1, which is the dominant member of the subcluster.

We may use the central surface brightnesses and core radii to compute the central particle densities, assuming thermal bremsstrahlung from an isothermal sphere. In this case, $I_E[E/(1 + z),0](1 + z)^3 = 3.24 \times 10^{-16}\, g(T, E) \exp(-E/kT)(kT)^{-1/2} a_x n_0^2$ keV cm^{-2} s^{-1} sr^{-1} keV^{-1}, where $g(T, E)$ is the Gaunt factor, kT is in keV, n_0 is the central electron density in cm^{-3}, $I_E(E, 0)$ is the observed central surface brightness per unit energy at Earth, and a_x is measured in cm. The results for n_0 multiplied by the proton mass are given in Table 1 assuming $kT = 7$ keV. The gas central density is of order 5% of the virial density, which is typical of isolated clusters.

IV. DISCUSSION

Will A98 N merge with A98 S? We may employ Newtonian mechanics in answering this question, since the separation of the components is small compared with the characteristic scale of the universe (H_0/c). In this case, the subclusters are bound to each other if $V < (2GM/D)^{1/2}$, where V is the velocity of one subcluster away from the other, D their separation, and, as is indicated by the data in Table 1, we assume equal masses M. We can estimate M from the central virial density of 3×10^{-26} g cm^{-3} and an optical core radius of 0.5 Mpc. The mass within 1 Mpc is 7.6×10^{47} g = $3.8 \times 10^{14}\, M_\odot$. We can also estimate M from the mass needed to bind the X-ray gas at radius R; $M = (kTR)/(G\mu m_p)$, where T is the temperature of the gas. This implies for $R = 1$ Mpc a confining mass of $2.6 \times 10^{14}\, M_\odot$ (kT/7 keV), which is in good agreement with the previous estimate. For $M = 3.8 \times 10^{14}\, M_\odot$ and $D =$ 1.5 Mpc, V must be less than 1500 km s^{-1} for the subclusters to be bound to each other. From Table 1, we find $c\Delta z < 870$ km s^{-1} at the 2 σ level. This indicates that the subclusters will merge, but there are unknown and different projection factors in the determination of V and D for which corrections are difficult. Another criterion of whether the subclusters will merge is the value of the overdensity, $\delta\rho/\rho$, associated with the region around them. With a mass of 1.5×10^{48} g contained in a sphere of radius 1.5/sin i Mpc, where i is the inclination of the line joining the subclusters to the plane of the sky, we find $\delta\rho/\rho \approx 380 q_0^{-1}$ (sin i)^3 independent of H_0. This number could be uncertain by as much as a factor of 50 because of uncertainties in $\delta\rho$ and i, but it does indicate the subclusters are bound (i.e., $\delta\rho/\rho > 1$). Indirect evidence for merger can be obtained from Figure 2 which is very similar to Figure 1*c* in White (1976) and Figure 2 of Gingold and Perrenod (1979) who present numerical calculations of a merger. In addition, the X-ray luminosities of the two components are comparable to the premerger values given by Gingold and Perrenod (1979), which are scaled to the Coma cluster parameters. Since the richness of A98 is about 90% of Coma (Dressler 1978*b*), this is the appropriate scaling. We conclude from all of this that a likely description of A98 is one in which the cluster is in the process of becoming a Coma cluster. There is not sufficient data to determine the relative motion of the subclusters, i.e., whether they are moving toward or away from each other. It would be interesting to determine this, as it would determine more definitively whether merger will occur.

The data presented in the previous two sections are evidence for the hierarchical clustering model in which clusters occur on all size scales, with larger clusters being formed from mergers of smaller ones. Our data also lend support to the evolving potential models of Perrenod (1978), where the cluster X-ray luminosities increase with time. This is in agreement with the suggestive results reported by Henry *et al.* (1979). We can make a crude estimate of the time remaining before the merger of the two components of A98 by considering the free-fall time for two equal-mass objects initially at rest with respect to each other, neglecting the expansion of the universe. For this case, $T = (\pi/4)D\sqrt{(D/GM)}$, which is about 10^9 yr.

All the available evidence taken as a whole suggests that A98 N is more evolved than A98 S, although each individual measurement is inconclusive. The Bautz-Morgan class is earlier, the velocity dispersion is higher, the central galaxy density is lower (cf. Figs. 3*c* and 3*d*), and the X-ray luminosity is higher. The pointlike component associated with galaxy G1 is very similar to that of the cD galaxy NGC 1275 in the Perseus cluster (Gorenstein *et al.* 1978; Helmken *et al.* 1978), where the emission is from an extended source of about 3′ in diameter, which would be unresolved by the IPC at the distance of A98. The association of the pointlike X-ray component, suggesting a massive central galaxy, with the subcluster that seems to have fewer galaxies is consistent with the idea that massive galaxies grow by cannibalizing their neighbors (Hausman and Ostriker 1978).

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