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THE DETECTION OF EXTENDED X-RAY EMISSION SURROUNDING cD GALAXIES IN POOR CLUSTERS

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ABSTRACT

The imaging proportional counter on the *Einstein* Observatory has detected extended X-ray emission from MKW 3s and AWM 4, two poor clusters containing dominant galaxies. In each case the X-ray emission is centered on the D or cD galaxy, but in MKW 3s it is symmetric (core radius 2'.5) while in AWM 4 it is not (extended 1' in NW-SE direction). The 0.25–3 keV luminosities, 10^{44} ergs s^{-1} for MKW 3s and 10^{43} ergs s^{-1} for AWM 4, are typical of those observed for the richer Abell clusters. We have measured redshifts of three galaxies in MKW 3s to confirm the physical association of the group. The hot gas present in this cluster is dense enough to confine the relativistic particles in 3C 318.1. As in the rich clusters, the mass of X-ray emitting gas in these two clusters is comparable to the visual mass and is ~10–20% of the virial mass. Our results suggest that poor clusters can collect enough gas to become detectable X-ray sources if they are relatively compact, which the presence of dominant galaxies indicates.

Subject headings: galaxies: clusters of — X-rays: general

I. INTRODUCTION

Achieving a greater understanding of the nature of X-ray emission from clusters of galaxies can deepen our insight into the formation and dynamical evolution of the clusters and their constituent galaxies (e.g., see Binney and Silk 1978). X-ray emission has typically been associated with Abell clusters of moderate size and richness (see reviews by Bahcall 1977*a;* Gursky and Schwartz 1977; and Lea 1977). X-ray luminosities and temperatures have been found to be correlated with cluster morphology (Bautz-Morgan and/or Rood-Sastry type), richness, central density, and velocity dispersion (Bahcall 1977*b;* Mitchell, Ives, and Culhane 1977; Jones and Forman 1978; Mushotzky *et al.* 1979; and Smith, Mushotzky, and Serlemitsos 1979). Recent observations with higher spatial resolution show a connection between the X-ray morphology and the presence of a dominant cD galaxy in a cluster (Schwarz *et al.* 1979; Jones *et al.* 1979). It is difficult, however, to decide which, if any, of these correlations is fundamentally linked to the origin of the X-ray emission since the morphological parameters themselves are interrelated.

We report here the first results of a survey performed with the *Einstein* Observatory imaging proportional counter (IPC) to detect X-ray emission from poor clusters which nevertheless contain dominant D or cD galaxies and could, therefore, be classified as Bautz-Morgan type I. This program has been undertaken for the dual purpose of (1) using this extreme case of morphological type to understand better the correlation of X-ray emission with other cluster properties and (2) using the X-ray observations to probe further the structure of poor clusters by detecting the presence of gas and by tracing the cluster potential well. The poor clusters are taken from the lists of Morgan, Kayser, and White (1975, hereafter MKW) and Albert, White, and Morgan (1977, hereafter AWM). We have detected X-ray emission from the first two clusters observed in our program, MKW 3s and AWM 4. The dominant galaxy in MKW 3s (NGC 5920) was originally suggested as the X-ray counterpart of 2A 1519+082 by Cooke *et al.* (1978). X-ray emission from poor groups has previously been reported by Schwartz *et al.* (1979), Jones *et al.* (1979), Schwartz *et al.* (1978), and Schwartz, Schwarz, and Tucker (1980).

II. OBSERVATIONS

The IPC on the *Einstein* Observatory operates in the 0.1–3.5 keV range with an energy resolution of 30% at 1 keV, a spatial resolution of ~1', and a 75' × 75' field of view (Giacconi *et al.* 1979). We have analyzed our data only between 0.25 and 3.0 keV because of high background at lower and higher energies.

a) MKW 3s

The dominant galaxy in MKW 3s is NGC 5920, which is classified as D4+ by MKW, who wrote that it "may be cD in size but not in brightness." Schild and Davis (1979) find $M_v = -22.71$, compared to $M_v = -23.7 \pm 0.1$ for a set of cD galaxies from Sandage (1976). S. van den Bergh (1977) has noted that the cluster is rather compact and that both NGC 5920 and the second brightest galaxy (D3− and

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$M_v = -22.48$) have extended envelopes. NGC 5920 is actually somewhat removed from a subgrouping of galaxies, and MKW considered its physical association to be in doubt, explaining the "s" in their designation (denoting a supplementary cluster possibly not a true member of this list of clusters). We tested for cluster membership by obtaining spectra of NGC 5920 and two other galaxies in the subgroup with the Mark II photon counting spectrometer (Schectman and Hiltner 1976; Canizares, McClintock, and Ricker 1978) on the 1.3 m telescope at the McGraw Hill Observatory.[1] The redshift of each object is listed in Table 1. (The errors refer to the relative velocities only and are determined from the scatter among the various features used to calculate the redshift. The difference between our redshift for NGC 5920 and that determined by Schild and Davis (1979) is 490 km s^{-1} and could reflect overall systematic errors in our measurement.) All lie within 600 km s^{-1} of the mean, strongly suggesting that the cluster is physically associated. The spectrum of NGC 5920 shows a normal continuum with absorption lines and no emission lines. NGC 5920 is also associated with the steep-spectrum radio source 3C 318.1 (Slingo 1974).

X-ray observations of MKW 3s were made using the IPC in two successive pointings on 1979 February 4 for a total of 4500 s. The observed counting rate of 0.49 counts s^{-1} is consistent with the previously reported value of 1.3 counts s^{-1} detected by *Ariel 5* (Cooke *et al.* 1978). Contours of constant X-ray intensity superposed on a Palomar Sky Survey print are shown in Figure 2. (Plate L2). The emission is extended and radially symmetric. The centroid of the X-ray emitting region ($15^h19^m23^s.2$, $7°52'41''$ [1950]) lies 35″ to the SW of the nucleus of NGC 5920, but systematic errors in determining IPC positions are typically 40″, so the X-ray source could be centered on the galaxy. The radio source 3C 318.1 is similarly offset from NGC 5920 and is included within our error circle.

TABLE 1

REDSHIFT IN MKW 3s

Galaxy[a]	cz (km s^{-1})
NGC 5920.......	13510±200
No. 1............	14090±470
No. 2............	13230±210

[a] Galaxies are marked in Fig. 2.

Figure 1 illustrates the radial surface brightness distribution of the X-ray emission. Although it is unlikely that a self-gravitating isothermal gas sphere describes the actual physical conditions, to parametrize the size of the X-ray emitting region we have convolved the IPC point response function with a point source plus a King (1972) approximation to a self-gravitating isothermal gas sphere. Only data in the 1.5–3.0 keV band were used in the fit to the radial intensity distribution since the point response function of the IPC is approximately constant in this range. An isothermal sphere of core radius $2'.5 \pm 0'.2$ (190 ± 16 kpc at 260 Mpc) plus a 6% point source contribution fit the data well ($\chi^2 = 12.4$ for 15 degrees of freedom). The excess emission at the center of the distribution which we have parametrized with a point source is not necessarily due to a discrete central source, however, but may well reflect that the central regions have a higher density and/or temperature than expected for a self-gravitating gas sphere.

Currently the IPC is not well enough calibrated to permit the accurate determination of spectral parameters. To estimate a temperature for MKW 3s we have compared the pulse-height distribution above 1.0 keV with those from observations of Perseus and A2256 which were made at the same gain setting of the IPC. We ignored data below 1.0 keV to avoid confusion among differing low-energy cutoffs. All three pulse-height distributions agree within statistics, so we

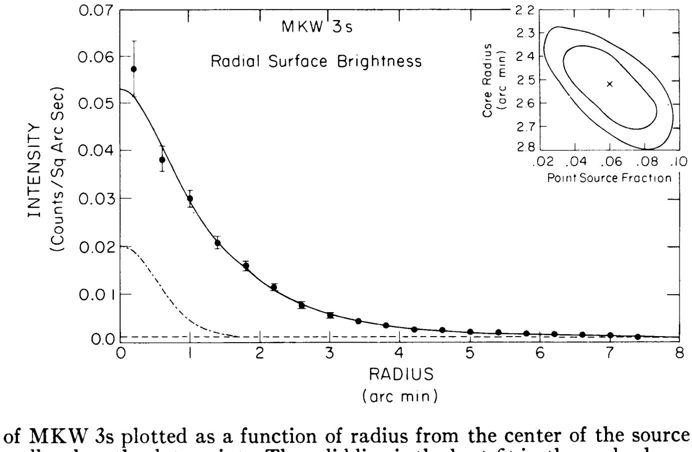

FIG. 1.—Surface brightness of MKW 3s plotted as a function of radius from the center of the source. Error bars are ±1 σ. Beyond a radius of 3′ the error bars are smaller than the data points. The solid line is the best-fit isothermal sphere plus point source convolved with the IPC response. Confidence levels of 68% and 90% around the minimum $\chi^2 = 12.4$ for core radius versus point source fraction are plotted in the upper right. The contours were chosen as prescribed by Avni (1976) for two parameters. The dashed line is the best-fit background level and the dot-dash line shows the point source contribution.

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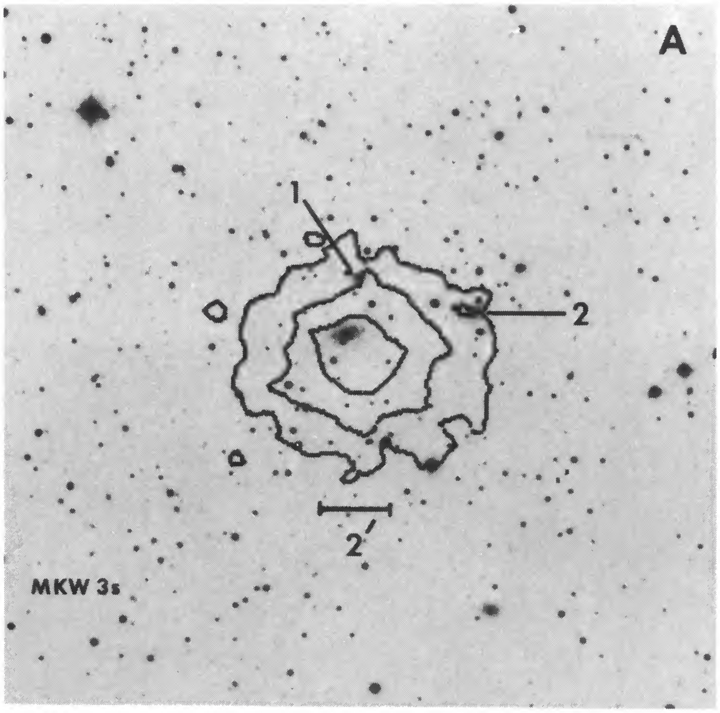
[1] The McGraw Hill Observatory is operated jointly by the University of Michigan, Dartmouth College, and the Massachusetts Institute of Technology.



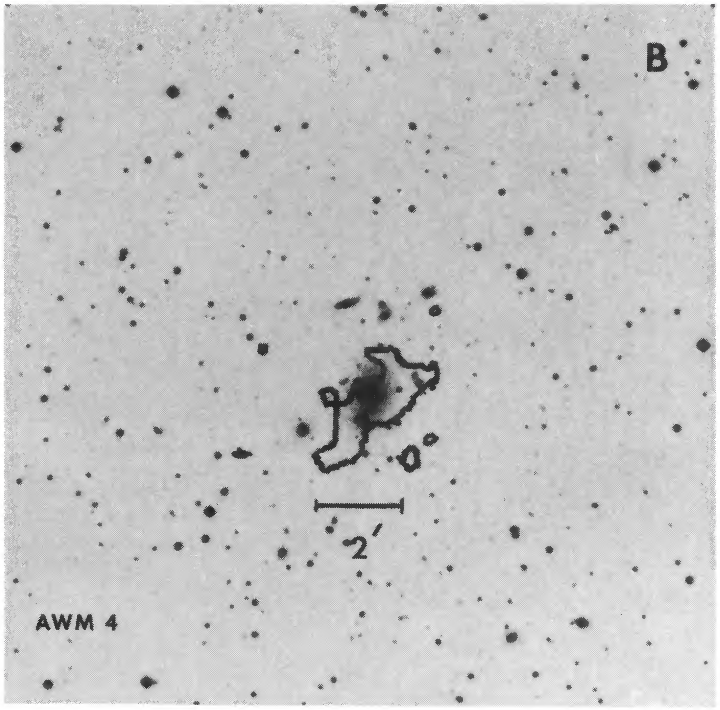


Fig. 2.—(*Top*) Contours of constant X-ray intensity in the full 0.1–3 keV band for MKW 3s. North is at the top, east to the left. The horizontal bar is 2′ across and is approximately equal to the mean FWHM response of the IPC for this whole band. The contour levels are 35, 88, and 175 (counts per square arcmin). The two other galaxies in the cluster for which we have measured redshifts are indicated.

Fig. 3.—(*Bottom*) Contours of constant X-ray intensity in the full 0.1–3 keV band for AWM 4. North is at the top, east to the left. The horizontal bar is 2′ across and is approximately equal to the mean FWHM response of the IPC for this whole band. The contour levels are 12 and 21 (counts per square arcmin).

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estimate MKW 3s to have a temperature of ~6 keV, similar to Perseus and A2256 (Mitchell, Ives, and Culhane 1977; Mushotzky *et al.* 1979). Since the IPC is insensitive to temperatures above a few kilovolts, the temperature could range anywhere above 3 keV. This has little effect on the luminosity, however, which we determine as 1×10^{44} ergs s^{-1} in the 0.25–3.0 keV band, comparable to that of other X-ray clusters (Gursky and Schwartz 1977; Mushotzky *et al.* 1979; Jones *et al.* 1979).

Our fit to an isothermal sphere for MKW 3s plus the luminosity permit us to estimate the central density of the X-ray source. Using the King approximation for the density profile, the thermal bremsstrahlung emissivity for a self-gravitating isothermal gas sphere of cosmic abundance is

$$j_v = 6.2 \times 10^{-39} T^{-1/2} g e^{-E/kT} n_0{}^2 / (1 + r^2/a_c{}^2)^3 \text{ ergs cm}^{-3}\text{ s}^{-1}\text{ sr}^{-1}\text{ Hz}^{-1} ,$$

where g is the Gaunt factor, n_0 is the central density, and a_c is the core radius (Allen 1973). Integrating this over all space and a finite bandwidth (E_1 to E_2) gives the luminosity in that band as

$$L_x = 3.19 \times 10^{-28} T^{1/2}[\exp(-E_1/kT) - \exp(-E_2/kT)]\bar{g} n_0{}^2 a_c{}^3 \text{ ergs s}^{-1} .$$

The central density is even less sensitive to temperature than luminosity. If we permit the temperature to range from 3 to 10 keV we find that n_0 ranges 0.021 to 0.026 cm^{-3}. So we estimate the core mass to be $M_c = \pi a_c{}^3 n_0 \mu = 1.3 \times 10^{13}\, M_\odot$ for $\mu = 0.6\, m_{\rm H}$, the average particle mass for a gas of cosmic abundance (Allen 1973).

b) *AWM 4*

The question of cluster membership for AWM 4 has been studied by Stauffer and Spinrad (1978). They determined redshifts for four of the galaxies near NGC 6051, which is the dominant galaxy in AWM 4. Only one has a redshift comparable to that of NGC 6051. The others are several thousand kilometers per second higher. So the number of galaxies physically associated with AWM 4 is much less than seems apparent visually and may include only some of the smaller galaxies in the field. AWM classified NGC 6051 as cD4 and noted that it was much brighter than the second brightest galaxy. This dominance is made more extreme when the spurious galaxies are neglected. Schild and Davis (1979) find $M_v = -22.92$. AWM 4 also contains the radio source Pks 1602+24 = 4C24.36, which is coincident with NGC 6051 (Dixon 1970).

X-ray observations of AWM 4 were performed on 1979 February 28 with the IPC for 915 s. The centroid of the X-ray emission ($16^{\rm h}2^{\rm m}47^{\rm s}.3$, 24°3′12″ [1950]) coincides with the nucleus of the cD galaxy, with an error circle of ~40″. Contours of constant X-ray intensity are shown in Figure 3 (Plate L2). In this case the emission is distinctly asymmetric. The minor axis of the distribution is unresolved, but the major axis is broadened beyond the IPC point response by an amount corresponding to a Gaussian with a full width half-maximum of 60″ ± 40″ (90% confidence level). A possible alternative to extended, asymmetric emission from AWM 4 is a combination of point sources associated with NGC 6051 and the 12.5 mag star on its southern edge. Future HRI observations should resolve this question. As with MKW 3s, we compared the pulse-height distribution of AWM 4 above 1.0 keV to Perseus and A2256 and found it to be significantly harder. So we set its temperature as ≥6 keV. The total X-ray luminosity in the 0.25–3 keV band is $L_x = 1 \times 10^{43}$ ergs s^{-1}, comparable to the lower end of the cluster luminosity scale.

III. COMPARISON TO OTHER X-RAY CLUSTERS OF GALAXIES

In Table 2 we list typical ranges of values for the rich cluster X-ray sources along with the physical parameters we have derived for MKW 3s and AWM 4. Both poor clusters have characteristics typical of previously observed X-ray clusters. The cluster X-ray sources observed before *Einstein* generally have a mass for the X-ray emitting gas that is 10–20% of the cluster virial mass and comparable to the visual mass of the cluster, assuming mass-to-light ratios of order 10. MKW 3s falls in this category also. The cD galaxies have average masses of $\sim 10^{13}\, M_\odot$ (Bahcall 1977*a*) and magnitudes of $M_v = -23.7 \pm 0.1$ (Sandage 1976). If we scale using the photometry of Schild and Davis (1979), we estimate that MKW 3s may have a mass on the order of $5 \times 10^{12}\, M_\odot$. Ten to twenty other cluster members of normal mass (a few times $10^{11}\, M_\odot$) will give the whole cluster a visible mass comparable to that of the X-ray emitting gas. In terms of X-ray morphology, MKW 3s has a size and luminosity similar to the smooth, centrally peaked Bautz-Morgan type I clusters described by Jones *et al.* (1979). They find core radii for these clusters of ~250 kpc and luminosities in the range 10^{44}–10^{45} ergs s^{-1}. AWM 4, on the other hand, is more similar in size and luminosity to the poor group A2666, which also contains a cD galaxy.

TABLE 2

X-RAY PARAMETERS FOR MKW 3s AND AWM 4

Parameter[a]	MKW 3s	AWM 4	Rich Cluster Sources
Distance[b] (Mpc).....	260	190	
L_x (0.1–3) (ergs s^{-1})..	1×10^{44}	1×10^{43}	10^{42}–10^{45}
kT (keV)............	~6	~6	2–10
a_x (kpc).............	190	~55	100–2000
$\langle n_e n_i \rangle\ V$ (cm^{-3})......	3×10^{67}	...	0.5–50×10^{67}
$\langle n \rangle$ (cm^{-3})...........	0.005	...	0.001–0.01
M ($M_\odot$).............	$\sim10^{13}$	...	10^{12}–10^{14}

[a] L_x is luminosity, kT is temperature, a_x is estimated core radius. $\langle n_e n_i \rangle\ V$ is emission integral, $\langle n \rangle$ is average particle density, M is mass.

[b] From Schild and Davis (1979) for $H_0 = 50$ km s^{-1} Mpc^{-1}.

IV. DISCUSSION

The existence of X-ray detectable hot gas has been invoked to explain the presence of steep-spectrum radio galaxies in clusters of galaxies (Baldwin and Scott 1973; Slingo 1974). The expansion of ejected radio lobes is thought to be halted by either thermal pressure or ram pressure, thereby extending their lifetimes, so that the radio spectrum steepens by synchrotron and/or inverse-Compton losses (cf. Longair, Ryle, and Scheuer 1973). In the case of 3C 318.1 = NGC 5920, one of the strongest of the steep-spectrum radio sources in clusters, the confinement model is attractive because 3C 318.1 exhibits both an unusually steep spectrum and an unusually high ambient gas density compared with those of other rich clusters. The observed X-ray emitting gas exerts a thermal pressure of $\sim 1 \times 10^{-11}$ ergs cm^{-3}, which just balances the estimated minimum energy density in the radio components. Slingo (1974) estimates the radio components to be $\sim$40 kpc in size with a lifetime up to 10^9 yr. This implies a very slow mean expansion velocity ≤ 100 km s^{-1}. However, unless the radio-emitting material is ejected at very low velocities, it is doubtful that thermal pressure alone could have confined it to such a small volume in the past. Ram pressure, on the other hand, is more efficient during the early, high-velocity stages of lobe expansion, and could have confined 3C 318.1 while the expansion velocities exceeded 100 km s^{-1}. The high-velocity stage must have endured only for a small fraction of the total lifetime, so 3C 318.1 should exhibit today a relaxed radio morphology consistent with confinement by an isotropic thermal pressure. The confinement model is therefore viable, although we cannot eliminate other models (e.g., recent ejection with high velocity and steep spectrum).

That all clusters of galaxies contain intergalactic gas, some of which attains detectable X-ray temperatures, has been suggested by Silk and Tarter (1973) as a means for binding the clusters. Bierman, Clarke, and Fricke (1979) infer that poor groups of galaxies must contain an intergalactic medium of density $\gtrsim 5 \times 10^{-4}$ cm^{-3} that strips S0 galaxies through ram pressure. Our observations demonstrate that this intergalactic medium is present in at least some poor clusters. Since we have observed a restricted morphological type, it is possible that only those poor groups dominated by a D or cD galaxy contain a substantial amount of gas. This would still include a large number of poor clusters since White (1978) estimates that half of the cD galaxies are not in rich clusters. Alternatively, all groups of galaxies may contain gas, but a detectable X-ray temperature and surface brightness is achieved only in those which are sufficiently compact. This would correlate the X-ray emission with the size and depth of the cluster potential well. If cD galaxies are formed by the process of galactic cannibalism (Hausman and Ostriker 1978, and references therein), then their presence is a direct indication of the original high central density of the cluster, and poor groups dominated by a cD galaxy would more likely be X-ray emitters. Since cannibalism proceeds faster in poor clusters of the same original density as rich clusters owing to the shorter crossing time, it is possible that in some MKW and AWM clusters the meal is almost finished. The poorer supply of initial galaxies could explain the diminution of the parameters of the cD galaxies in poor clusters compared with those in rich ones (Oemler 1976; Bahcall 1977*a;* van den Bergh 1977, and Schild and Davis 1979).

We are grateful to N. Roos for the suggestion of MKW 3s and AWM 4 as likely objects for X-ray study and to the staff at the Harvard-Smithsonian Center for Astrophysics for their aid with the data processing and reduction. For help with the optical observations we thank M. Johns, C. Price, and W. A. Hiltner of the University of Michigan. We also acknowledge the contributions of S. van den Bergh. Finally, we thank M. DiCiaccio for her preparation of the manuscript. This work was sponsored by NASA contract NAS8-30752.

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Note added in proof.—Subsequent HRI observations place the centroid of the X-ray emission from MKW 3s at $15^h19^m24\overset{s}{.}7$ and 7°53′05″ (1950), within 10″ of the nucleus of NGC 5920.

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