THE ASTROPHYSICAL JOURNAL, 238:L53–L58, 1980 June 1

HEAO 1 IDENTIFICATION OF THE X-RAY EMITTING POOR CLUSTER OF GALAXIES, AWM 7

D. A. SCHWARTZ,[1] M. DAVIS,[1,4] R. E. DOXSEY,[2] R. E. GRIFFITHS,[1] J. HUCHRA,[1]
M. D. JOHNSTON,[2] R. F. MUSHOTZKY,[3] J. SWANK,[3] AND J. TONRY[1]
Received 1979 November 20; accepted 1980 February 25

ABSTRACT

We identify the X-ray source 2A 0251+413 with the AWM 7 group of galaxies. The source is extended, with a FWHM of roughly 9′ if an isothermal sphere profile is assumed. The spectrum is best fitted by thermal bremsstrahlung at 4.0 ± 0.5 keV, with a significant Fe line emission of equivalent width 0.63 keV centered at 6.6 keV. This temperature is consistent with the measured dispersion velocity $\sigma_v = 600$ km s^{-1} of the central galaxies.

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

I. INTRODUCTION

We report the detection of an extended X-ray source in the poor cluster of galaxies containing the cD galaxy NGC 1129 (Albert, White, and Morgan 1977, hereafter AWM). Abell (1958) clusters and other rich clusters of galaxies are firmly identified as a class of X-ray source (see Jones and Forman 1978; McHardy 1978). It may thus be expected (e.g., Silk and Tarter 1973) that some groups of galaxies less rich than the minimum Abell richness class 0 will nevertheless accumulate enough hot gas to emit a detectable X-ray flux. Lugger (1978) noted several southern sky groups positionally associated with X-ray error boxes; however, either they could all be associated as well with clusters or else the refined 4U catalog positions (Forman *et al.* 1978) did not continue to support the identification. The 2A catalog (Cooke *et al.* 1978) notes seven positional coincidences of X-ray sources with groups. Three of these have subsequently been identified instead with active galaxies inside these groups (Ricker *et al.* 1978; Ward *et al.* 1978; Griffiths *et al.* 1979). The basic problem is that with the large and uncertain surface density of poor clusters, and the typical positional uncertainties $\gtrsim 0.1$ deg^2 of previous all-sky X-ray surveys, probabilistic arguments could not be made for the identifications.

We have used pointed observations of the *HEAO 1* satellite to locate the most probable of the *Ariel 5* associations, 2A 0251+413, which they suggest is identified with the galaxy NGC 1129 (Cooke *et al.* 1978). Utilizing the data from the scanning modulation collimator (MC) experiment (Schwartz *et al.* 1978*b;* Gursky *et al.* 1978), together with the total flux measured by the GSFC cosmic X-ray experiment (A-2)[5] (Rothschild *et al.* 1979), we show that the X-ray emission is extended over the size of the group as a whole, although we are unable to measure a detailed surface brightness profile. Spectral measurements with the A-2 experiment show that this is the source previously attributed to Abell 347/396 by Mushotzky *et al.* (1978), based on the third *Uhuru* catalog identification (Giacconi *et al.* 1974). It displays a spectrum typical of a cluster of galaxies and has X-ray properties consistent with optical and morphological correlations expected from the class of rich-cluster X-ray sources.

More recently, five other compact, poor clusters have been detected as X-ray sources (Schwartz *et al.* 1980; Jones *et al.* 1979; Kriss *et al.* 1980), with a variety of X-ray luminosities, and optical and radio morphologies.

II. LOCATION AND SIZE OF 2A 0251+413

The MC experiment has two collimator systems: MC1 has 30″ FWHM with transmission bands repeating every 4′; MC2 has 2′ FWHM with 16′ periodicity. Figure 1 shows the X-ray locations allowed by MC2 in the vicinity of 2A 0251+413. Although the MC experiment produces multiple locations (of which only portions of six lines are shown), there is a most probable location at AWM 7 (circle in Fig. 1) consistent with the NRL *HEAO 1* Large Area Sky Survey (LASS), the *HEAO 1* A-2, and the *Ariel 5* (Cooke *et al.* 1978) positions. Our examination of the individual *Uhuru* lines of position suggests that most of them are also consistent with this location (C. Jones, private communication 1979). The source MX 0255+41 (Markert *et al.* 1976, 1979) is reported as variable and almost twice as strong as the 4U and *HEAO 1* A-2 fluxes, and therefore must be distinct from the extended source which we report here. The occurrence of such a variable source is not unlikely at this galactic latitude, $b = -15.^\circ6$. Because a variable source must be pointlike, we can place a 3 σ upper limit of 0.8 UFU[6] to MX

[1] Harvard-Smithsonian Center for Astrophysics.

[2] M.I.T. Center for Space Research.

[3] Goddard Space Flight Center.

[4] Alfred P. Sloan Fellow.

[5] The *HEAO 1* A-2 experiment is a collaboration led by E. Boldt (GSFC) and G. Garmire (CIT) with collaborators at CIT, GSFC, UCB, and JPL.

[6] 1 UFU = 1.7×10^{-11} ergs cm^{-2} s^{-1}, 2–6 keV; ~1.6 μJy at 3.6 keV.

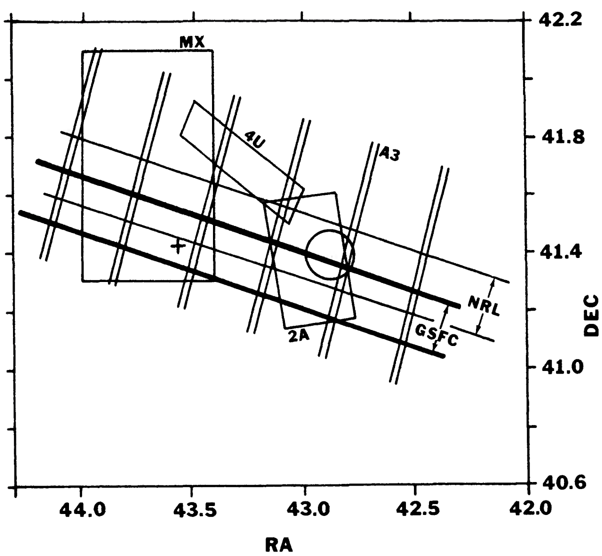

FIG. 1.—Locations of 2A 0251+413 as determined by 4U = *Uhuru* (Forman *et al.* 1978), 2A = *Ariel 5* SSI (Cooke *et al.* 1978), MX = *OSO 7* (Market *et al.* 1976), NRL = *HEAO 1* Large Area Sky Survey experiment, GSFC = *HEAO 1* A-2 experiment, A3 = portions of only a few of the multiple locations from the MC2 (2′ FWHM) collimator. The circle indicates the position of AWM 7, and the plus sign the position of the cluster A396. AWM 7 is the unique identification agreeing with all previous data except (possibly) the MX location (see text).

0255+41, based on the MC1 data. Even if there were many ($\lesssim 6$) point sources in the field of view, a limit ≤ 1 UFU would apply to each of them, since the 30″ FWHM is 8 times smaller than the collimator periodicity. Therefore, even if we ignored both the *Ariel 5* catalog which has yielded ~80 identifications out of 107 sources, and the 4U catalog, *HEAO 1* data alone would *require an extended source*, which could only be the AWM 7/NGC 1129 group or else the distance class 5, richness 0 cluster A396. The latter identification would imply the extreme parameters $L_x \sim 8 \times 10^{45}$ ergs s^{-1} (2–10 keV), a core radius of about 1.5 Mpc, and an unidentified X-ray line between 7.3 and 7.9 keV emitted energy. The last argument is sufficient to reject A396 for the bulk of the measured X-rays. The presence of one or two additional weak sources in the field of view will not affect the results on AWM 7 presented here.

The MC2 position shown in Figure 1 is based on pointed data from 1978 August 28 and 29. Analysis of pointed data is described by Dower *et al.* (1980). Using only data when pointed at AWM 7, our automatic software assumes that the total mean counting rate is background, and searches for an excess point source. We obtain a 2.9 σ (above background) signal equivalent to ~0.7 ± 0.3 UFU flux, using 1–5.4 keV data. MC1 gives a 1.1 σ signal. We estimate the size by comparing the apparent 0.7 UFU flux to the true flux of 5.6 ± 0.3 UFU, obtained by the A-2 experiment during the same pointed observations. If we assume that the spatial profile is a Gaussian shape, then simulations of the MC response indicate a FWHM of 12′ to produce the observed demodulation of the flux observed by A-2. We estimate a formal 90% confidence range of greater than 9′, considering statistics and the estimated 20% calibration uncertainty between the A-2 and MC experiments.

Figure 2 shows the MC2 raw data, folded modulo the 16′ period and plotted in phase bins of 64″. The dashed line shows an independent estimate of the MC2 non–X-ray background, obtained in the off-source portions of the "ping-pong" pointing, with the superposed response predicted for the total flux, observed by A-2, as if it were a point source. Dower *et al.* (1980) describe the method of estimating the non–X-ray background in some detail. Briefly, we correlate the change in the counting rate of our X-ray data channel with changes in the counting rates of events rejected by the pulse shape discriminators (PSD), when the experiment pointed 6° to the west. This correlation is very linear over the restricted range of PSD rates for which we superpose data. We then use the measured PSD rates when pointed at AWM 7 to estimate the non–X-ray background shown in Figure 2. The excess of the measured histogram over this expected non–X-ray background is about 6 σ (above background) and represents roughly 4.8 ± 1 UFU, depending on the exact spatial profile. (We do not have sufficient precision to measure the detailed surface brightness profile.) The positions of the five brightest galaxies (see Fig. 3) noted by AWM are marked in Figure 2. Upper

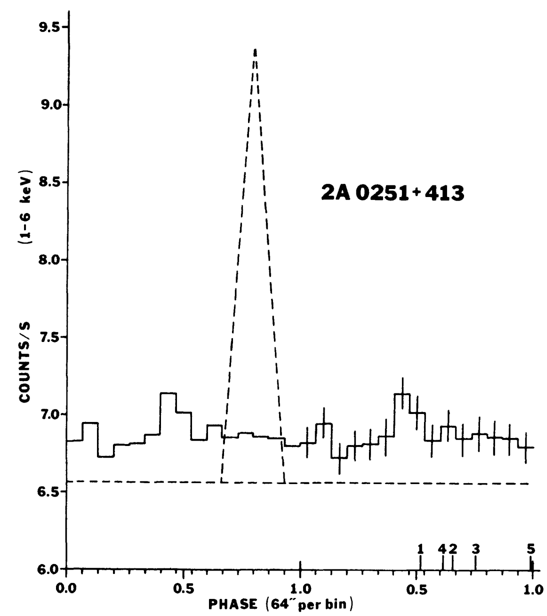

FIG. 2.—Data from the two lowest-energy channels (1–5.4 keV) of MC2 plotted vs. phase of the 16′ collimator period. The dashed triangle is the predicted response (plotted at an arbitrary phase) to a point source of the strength measured with the A-2 experiment. This proves that 2A 0251+413 is extended. The dashed horizontal line is an estimate of non–X-ray background obtained from portions of the orbit when *HEAO 1* pointed about 6° to the west. The estimated statistical uncertainty of this level is 0.044 counts s^{-1}. The numbers 1–5 indicate the center of the galaxies in the finding chart of AWM. The zero phase is arbitrary so that, e. g., emission 0.25 phase left of NGC 1129 could be either 4′ west or 12′ east of this galaxy.

1980ApJ...238L..53S

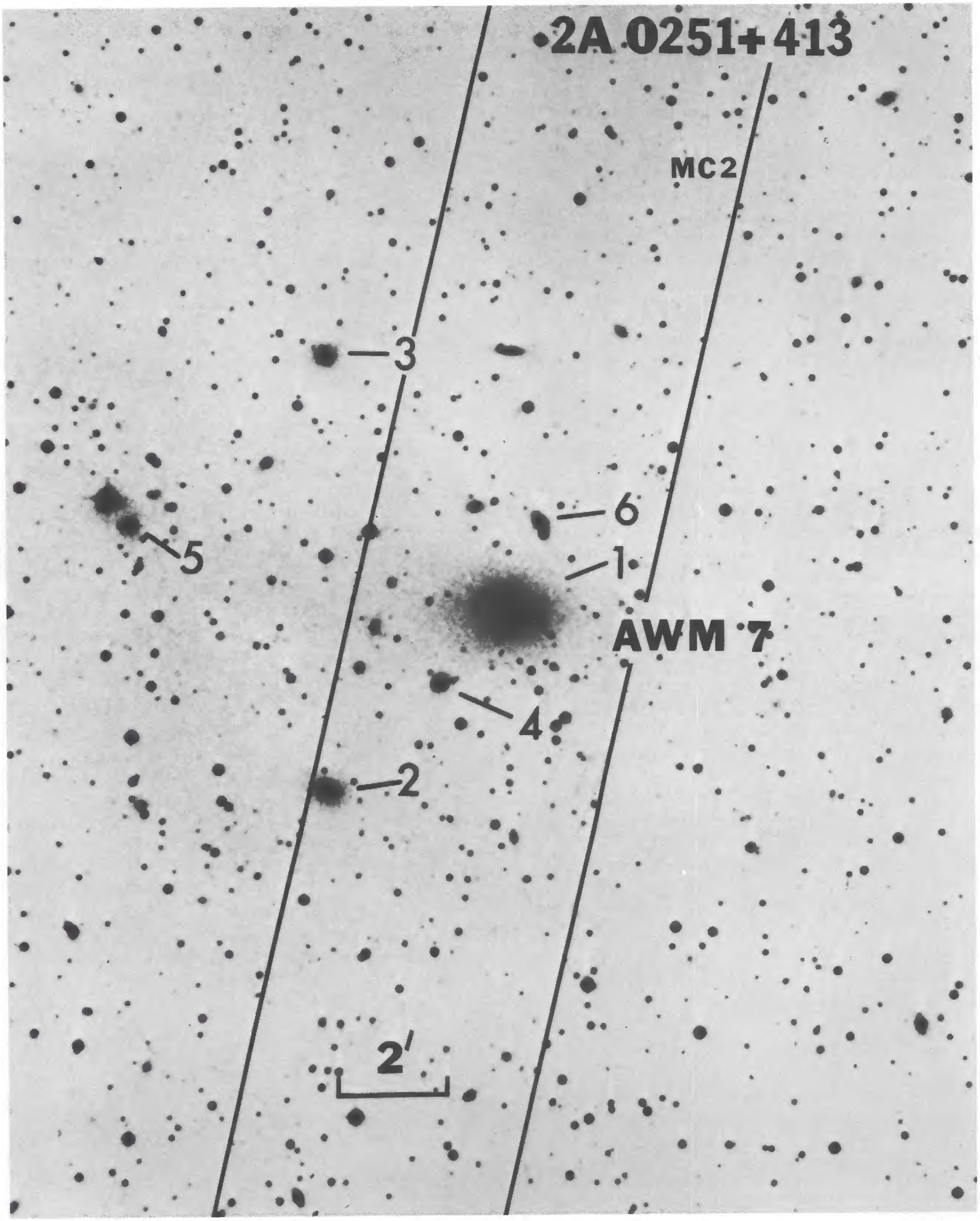

FIG. 3.—MC2 location uncertainty (see text) plotted on the finding chart of AWM 7

limits to point sources at these galaxies are 1.2, 0.5, 0.8, 0.5, and 0.6 UFU (2 σ), respectively. This totals only 3.6 UFU and therefore does not supply the total X-ray flux of the group. It is possible that extended sources at the position of several galaxies supply all the X-rays; however, in this case the strengths and sizes would have to be quite similar to simulate the smooth profile shown in Figure 2.

To define the centroid of the X-ray emission, we fitted the data of Figure 2 to an isothermal sphere profile folded through the collimator response. For one "interesting" degree of freedom (see Avni 1976; Lampton, Margon, and Bowyer 1976) the 90% confidence location width is 4′, as shown in Figure 3. For an arbitrary source centroid, we can only determine, to 90% confidence for two interesting parameters, a lower limit isothermal core radius of 5′. However, if we assume that NGC 1129 is the X-ray centroid, then the one parameter isothermal core radius is in the range 5′–12′.

III. SPECTRUM

Figure 4 shows the X-ray photon spectrum in the 2–10 keV band from the A-2 xenon detector, derived by correcting the counting rate data to the best-fit thermal bremsstrahlung shape of 3.95 ± 0.45 keV. The fit requires an iron line feature at an emitted energy 6.7 keV of 0.63 ± 0.19 keV equivalent width, where the errors are for 90% combined confidence for three interesting parameters. The spectral model fits the data with a chi-square of 16.2 for 10 degrees of freedom. No low-energy absorption is detected, with an upper limit of $N_H < 7 \times 10^{21}$ H atoms per cm^2. This spectrum is consistent with, but more precise than, that of the *OSO 8* measurement of 2A 0251+413 (Mushotzky *et al.* 1978) which was attributed to Abell 347/396 based on the third *Uhuru* catalog (Giacconi *et al.* 1974). The fact that the inferred iron abundance is the same as that in rich clusters (Mushotzky *et al.* 1978) proves that the X-ray emitting gas in this group has undergone a similar evolution.

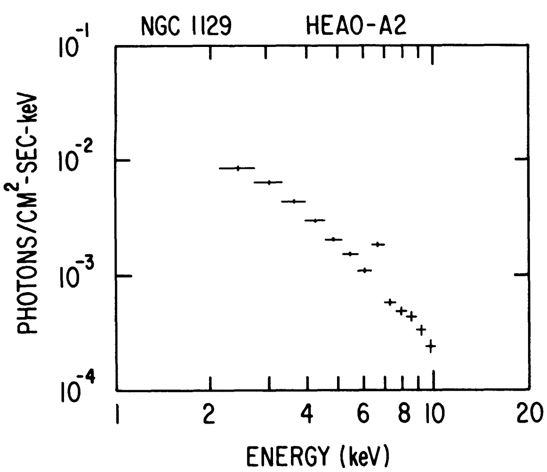

FIG. 4.—Photon spectrum of AWM 7 from the A-2 xenon detector. The correction from counts to photons assumes the best-fit thermal bremsstrahlung spectrum (with Gaunt factor) of kT = 3.95 keV.

IV. OPTICAL IDENTIFICATION AND DISCUSSION

Because of the large angular extent of the X-ray source we rule out identification with any stellar-appearing object. The position then requires identification with the group 7 of AWM. The X-ray location is superposed on their finding chart of the group in Figure 3. AWM noted this weak clustering because it contained a possible cD galaxy, NGC 1129 (number 1 in Fig. 3). Stauffer and Spinrad (1980) confirm the cD classification.

Optical data were obtained for several of the group members using the CFA Photon Counting Reticon™ (Davis and Latham 1979) on the Mount Hopkins 60″ (1.5 m) telescope. Table 1 lists the velocities and internal velocity dispersions and the Zwicky catalog magnitudes for the galaxies observed, using the analysis technique described by Tonry and Davis (1979). The galactocentric velocity of NGC 1129 is 5433 km s^{-1}. The mean, luminosity-weighted cluster velocity is 5250 km s^{-1}. This places the AWM cluster in the Perseus supercluster (Tifft, Hillsman, and Corrado 1975; Tifft and Gregory 1978; Jôeveer and Einasto 1978).

The luminosity-weighted line of sight velocity dispersion is $\sigma_v = 600 \pm 50$ km s^{-1}, in excellent agreement with the value noted by Stauffer and Spinrad (1980), but much lower than the value of 884 km s^{-1} given by Hintzen and Scott (1979). For the X-ray temperature kT = 4.0 keV, our dispersion agrees with a prediction of σ_v = 600 km s^{-1} obtained by scaling from the Coma cluster, and falls within the scatter of σ_v versus kT for Abell clusters plotted by Mushotzky *et al.* (1978, Fig. 5).

The measured internal velocity dispersion for NGC 1129 is 272 km s^{-1}, significantly lower than the core dispersion of 375 km s^{-1} found by Dressler (1979) for the cD galaxy in the rich cluster Abell 2029. However, the absolute blue magnitude of NGC 1129 derived from its Zwicky magnitude of 14.6, a galactic absorption correction of 0.20 csc b^{II} = 0.74, and a Hubble constant

TABLE 1

GALAXIES IN THE AWM 7 CLUSTER

Galaxy	Galactocentric Radial Velocity[a] V, (km s^{-1})	Zwicky Magnitude m_p	Internal Velocity Dispersion σ_v (km s^{-1})
1 = NGC1129.....	5433±20	14.6	272±20
1A[b]..............	5216±24	(16.0)	219±28
2..................	4615±26	14.8	197±30
3 = I265..........	5456±28	15.7	196±35
4 = NGC1131.....	5508±23	15.6	240±23
5..................	4351±29	(16.0)	127±50
6 = NGC1130.....	6322±22	15.6	185±40

[a] Corrected by 300 sin l cos b.

[b] Located SW of galaxy 1, inside its envelope.

of 50 km s^{-1} Mpc^{-1}, is -21.2. This places it almost exactly on the $L_B \propto \sigma^4$ line of Faber and Jackson (1976), which is standardized on the $B(0)$-Zwicky magnitude scale (Huchra 1976). Stauffer and Spinrad (1980) derive a *total* magnitude (rather than isophotal) for the cD galaxy of $m = 13.2$, which gives $M_B = -22.6$. The internal velocity dispersion of several members is sufficiently high that there could be X-rays with a detectable $kT \sim 1.5$ keV if there is gas associated with the individual galaxies. We will schedule observations with the high-resolution imager of the *Einstein* Observatory to investigate this.

The 2–6 keV luminosity is 1.3×10^{44} ergs s^{-1}, which implies a bolometric luminosity of $4.4 \pm 0.6 \times 10^{44}$ ergs s^{-1} for the 4 keV thermal source. Using the assumed isothermal sphere model we estimate a core radius of 290 kpc and central density of 4×10^{-3} particles per cm^3. Although we are not performing a sensitive measurement of the surface brightness profile, these numbers do not change greatly for any smooth distribution of the gas (see Schwarz *et al.* 1979).

The isothermal sphere model implies a core mass of 5×10^{13} $M_\odot$ to bind the 4 keV gas, although this number is indeed sensitive to the X-ray profile (Fabricant, Lecar, and Gorenstein 1980). From the observed velocities and magnitudes we can derive an estimate of the dynamical (virial) mass from the standard relations:

$$\text{mean harmonic radius} = r_H = \frac{\pi}{2}\frac{\bar{V}}{H_0} \times \left[L_c(L_c - \bar{L}) \left(\sum_{i \neq j} \frac{L_i L_j}{\theta_{ij}} \right)^{-1} \right], \tag{1}$$

$$\text{line of sight velocity dispersion} = \sigma_v^2 = [\Sigma\, L_i(V_i - \bar{V})^2]/(L_c - \bar{L}), \tag{2}$$

$$\text{cluster mass} = M_c = \frac{3\sigma_v^2 r_H}{G} \tag{3}$$

where

$$L_c = \Sigma\, L_i \quad \text{and} \quad \bar{L} = L_c/N .$$

L_i is the luminosity of the ith galaxy, $\bar{V}$ is the luminosity-weighted mean cluster velocity, θ_{ij} is the angular separation between the ith and jth galaxies, and the factor of 3 in equation (3) is to remove the three-dimensional projection effect in the velocity dispersion. Depending on the adopted magnitude for NGC 1129 itself, the derived mean harmonic radius is between 190 and 250 kpc, in good agreement with the X-ray core radius, and the derived cluster mass is between 3 and 5×10^{13} $M_\odot$—sufficient to bind the gas. Using the total luminosity for NGC 1129 measured by Stauffer and Spinrad and correcting the cluster luminosity for missing faint galaxies by the Schechter function (Schechter 1976), we find the cluster mass to light ratio to be $\sim$200 in solar units. We also estimate the mass of hot gas to be 10^{13} $M_\odot$, and therefore a non-negligible contribution to the cluster mass. This is a very high ratio of gas to virial mass, and might be reduced if some X-ray emission is clumped around the individual galaxies.

The distinction of this group as the first poor cluster to be established as an X-ray emitter (Schwartz *et al.* 1978*a*) is in accordance with the correlations of higher X-ray luminosity to high central galaxy surface density or to low spiral fraction (Bahcall 1977*a*, *b*). With 10–20 bright galaxies within a 0.5 Mpc circle, this object is also consistent with the central galaxy density versus kT and emission integral versus kT correlations (Figs. 6 and 7 of Mushotzky *et al.* 1978) for rich clusters.

We are grateful to the Data Reduction and Analysis Support Team, M. Conroy, M. Garcia, E. Ralph, and W. Roberts for assistance in the reduction of data and preparation of figures. We thank Dr. H. Friedman for permission to use the *HEAO 1* Large Area Sky Survey (LASS) data to reduce the location uncertainty. This work was supported in part by the National Aeronautics and Space Administration under contracts NAS 8-30543 and NAS 8-27972, and by NSF grant AST 78-24856.

REFERENCES

Abell, G. 1958, *Ap. J. Suppl.*, **3**, 221.
Albert, C. E., White, R. A., and Morgan, W. W. 1977, *Ap. J.*, **211**, 309.
Avni, Y. 1976, *Ap. J.*, **210**, 642.
Bahcall, N. A. 1977*a*, *Ap. J.* (*Letters*), **217**, L77.
———. 1977*b*, *Ap. J.* (*Letters*), **218**, L93.
Cooke, B. A., *et al.* 1978, *M.N.R.A.S.*, **182**, 489.
Davis, M., and Latham, D. 1979, *SPIE Proceedings, Instrumentation in Astronomy III*, **172**, 71.
Dressler, A. 1979, *Ap. J.*, **231**, 659.
Dower, R. G., Griffiths, R. E., Bradt, H. V., Doxsey, R. E., and Johnston, M. D. 1980, *Ap. J.*, **235**, 355.
Fabricant, D., Lecar, M., and Gorenstein, P. 1980, *Highlights of Astronomy*, in press.
Faber, S., and Jackson, R. 1976, *Ap. J.*, **204**, 668.
Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., and Giacconi, R. 1978, *Ap. J. Suppl.*, **38**, 357.
Giacconi, R., *et al.* 1974, *Ap. J. Suppl.*, **27**, 37.
Griffiths, R. E., Doxsey, R. E., Johnston, M. D., Schwartz, D. A., Schwarz, J., and Blades, J. C. 1979, *Ap. J.* (*Letters*), **230**, L21.
Gursky, H., *et al.* 1978, *Ap. J.*, **223**, 973.
Hintzen, P., and Scott, J. 1979, *Ap. J.* (*Letters*), **232**, L145.
Huchra, J. 1976, *A.J.*, **81**, 952.
Jôeveer, M., and Einasto, J. 1978, in *IAU Symposium No. 79, The Large Scale Structure of the Universe*, ed. M. S. Longair and J. Einasto, (Dordrecht: Reidel), p. 241.
Jones, C., and Forman, W. 1978, *Ap. J.*, **224**, 1.
Jones, C., Mandel, E., Schwarz, J., Forman, W., Murray, S. S., and Harnden, F. R., Jr. 1979, *Ap. J.* (*Letters*), **234**, L21.
Kriss, G. A., Canizares, C. R., McClintock, J. E., and Feigelson, E. D. 1980, *Ap. J.* (*Letters*), **235**, L61.
Lampton, M., Margon, B., and Bowyer, S. 1976, *Ap. J.*, **208**, 177.
Lugger, P. M. 1978, *Ap. J.*, **221**, 745.
Markert, T. H., Canizares, C. R., Clark, G. W., Li, F. K., Northridge, P. L., Sprott, G. F., and Wargo, G. F. 1976, *Ap. J.*, **206**, 265.
Markert, T. H., *et al.* 1979, *Ap. J. Suppl.*, **39**, 573.
McHardy, I. 1978, *M.N.R.A.S.*, **184**, 783.
Mushotzky, R. F., Serlemitsos, P. J., Smith, B. W., Boldt, E. A., and Holt, S. S. 1978, *Ap. J.*, **225**, 21.
Ricker, G., Doxsey, R. E., Dower, R. G., Jernigan, J. G., Delvaille, J. P., MacAlpine, G. M., and Hjellming, R. M. 1978, *Nature*, **271**, 35.

Rothschild, R., *et al.* 1979, *Space Sci. Instr.*, **4**, 269.
Schechter, P. 1976, *Ap. J.*, **203**, 297.
Schwartz, D. A., Bradt, H. V., Doxsey, R. E., Fabbiano, G., Griffiths, R. E., and Johnston, M. D. 1978*a*, *Bull. AAS*, **10**, 628.
Schwartz, D., Schwarz, J., Gursky, H., Bradt, H., and Doxsey, R. 1978*b*, *Proc. AIAA 16th Aerospace Sciences Conf.*, 78–34.
Schwartz, D., Schwarz, J., and Tucker, W. 1980, *Ap. J.* (*Letters*), **238**, L59.
Schwarz, J., *et al.* 1979, *Ap. J.* (*Letters*), **231**, L105.
Silk, J., and Tarter, J. 1973, *Ap. J.*, **183**, 387.
Stauffer, J., and Spinrad, H. 1980, *Ap. J.*, **235**, 347.
Tifft, W. G., and Gregory, S. A. 1978, in *IAU Symposium No. 79, The Large Scale Structure of the Universe*, ed. M. S. Longair and J. Einasto (Dordrecht: Reidel), p. 267.
Tifft, W. G., Hilsman, K. A., and Corrado, L. C. 1975, *Ap. J.*, **199**, 16.
Tonry, J., and Davis, M. 1979, *A.J.*, **84**, 1511.
Ward, M. J., Wilson, A. S., Penston, M. V., Elvis, M., Maccaccaro, T., and Tritton, K. P. 1978, *Ap. J.*, **223**, 788.

M. Davis, R. E. Griffiths, J. Huchra, D. A. Schwartz, and J. Tonry: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

R. E. Doxsey and M. D. Johnston: Center for Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

R. F. Mushotzky and J. Swank: Goddard Space Flight Center, Greenbelt, MD 20771