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GROUPS OF GALAXIES IN THE *ROSAT* NORTH ECLIPTIC POLE SURVEY[1]

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ABSTRACT

We present the first measurement of the ensemble properties of X-ray–selected groups of galaxies. Their X-ray luminosity and temperature functions are a smooth extrapolation from rich clusters of galaxies. The X-ray–selected groups have a spiral fraction which is about a factor of 2 smaller than optically selected groups, possibly because the X-ray selection produces a more dynamically evolved sample. The binding masses of these groups and their contribution to the density of the universe is typical of those found from analyses of optically selected samples, but our estimates were derived from completely different selection criteria and mass measurements.

Subject headings: cosmology: theory — galaxies: statistics — surveys — X-rays: galaxies

1. INTRODUCTION

Most galaxies are in groups, which may imply that a substantial fraction of the mass of the universe is in groups. Certainly groups are far more common than rich clusters of galaxies and are more massive than individual galaxies. Thus studies of groups may produce insights into the mass density of the universe, one of the fundamental parameters in cosmology.

Unfortunately, it is difficult to find real groups; Ramella, Geller, & Huchra (1989) estimate from simulations that $\sim 30\%$ of their groups with fewer than five members are spurious, even when searching in complete redshift catalogs of galaxies. The best method used to date to construct group catalogs (or at least the one used most recently) is a percolation, or "friends of friends," algorithm applied to galaxy redshift surveys. Some of the more recent work constructing catalogs includes Hickson et al. (1993), Nolthenius (1993), Ramella et al. (1989), and Maia, da Costa, & Latham (1989). The median redshift of these catalogs is typically less than 0.03, while the median velocity dispersion of the groups is ~ 200 km s^{-1}. Prandoni, Iovino, & MacGillivray (1994) have produced the first catalog of groups selected entirely by machine.

In addition to the difficulty finding groups, the properties of those found seem to depend sensitively on the selection algorithm used to find them (Pisani et al. 1992). Some of the difficulties in determining the mean properties of groups result from the poor statistics associated with locating and studying objects which contain a small number of members. For example, it is very difficult to measure velocity dispersion and size if the group has only a few members. Another difficulty is that the redshift surveys are shallow enough that geometrical effects (such as walls and voids) are still important. As a result of these uncertainties, the parameter of most interest, the median mass-to-light ratio of groups, varies by more than a factor of 2 from one catalog to another. Combined with the various luminosity densities of the different catalogs, these mass-to-light ratios result in a range in Ω_0 of 0.05–0.3.

However, groups of galaxies are also X-ray emitters (Bahcall, Harris, & Rood 1984). The X-ray properties of groups are: bolometric luminosities up to a few 10^{43} h_{50}^{-1} ergs s^{-1} (where the Hubble constant is 50 h_{50} km s^{-1} Mpc^{-1}, which we use throughout this paper); temperatures of ~ 1 keV; and masses of a few 10^{13} h_{50}^{-1} $M_\odot$ (see Mulchaey et al. 1993; Ponman & Bertram 1993; David et al. 1994). Observations at X-ray wavelengths can overcome the difficulties with the present optical group surveys described above. The statistics of the measurement of any group property and the depth of the survey are only a function of the exposure time. In addition, since confining the hot X-ray–emitting gas requires a potential

[1] Results presented here are based in part on observations made with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona, and with the University of Hawaii 2.2 m telescope.

well, all X-ray–selected groups are real physical objects, not apparent associations seen only in projection.

All previous X-ray studies of groups have been of objects selected in other wave bands. The most extensively studied sample by far has been the Hickson compact groups, which were optically selected (Bahcall et al. 1984; Ponman & Bertram 1993; Ebeling, Voges, & Böhringer 1994; Böhringer 1994; Pildis, Bregman, & Evrard 1995; Saracco & Ciliegi 1995). The previous all-sky X-ray surveys, which could have been used to construct X-ray–selected group catalogs, have all been conducted in the 2–10 keV energy band and so are severely biased against finding the low-temperature groups. Thus the application of X-ray observations to the study of groups, and in particular the determination of their ensemble properties, has been quite limited. At present only about a dozen groups of galaxies are known to have a hot intergroup medium (the number is uncertain because some detections are quite weak and it is difficult to decide whether the emission is confined to only the galaxies).

The *ROSAT* All-Sky Survey (RASS), on the other hand, is optimal for finding groups. The RASS was carried out in the 0.1–2.4 keV energy band, and it has excellent sensitivity to low surface brightness objects. We are in the process of identifying all 629 of the RASS sources in an approximately 9° × 9° region around the north ecliptic pole (NEP) where the survey is the deepest. We report here the first determination of the ensemble properties of a statistically complete (but small) X-ray–selected sample of groups of galaxies. We find that groups fit on the extrapolation of the mass, temperature, and luminosity functions established for rich clusters.

2. GROUP SELECTION

We have searched a solid angle of 84.7 $\deg^2 = 0.0258$ sr around the NEP. The boundaries of the survey region are approximately: $259\overset{\circ}{.}10 \leq \alpha(2000) \leq 280\overset{\circ}{.}90$ for $61\overset{\circ}{.}8 \leq \delta(2000) \leq 64\overset{\circ}{.}8$; $257\overset{\circ}{.}75 \leq \alpha(2000) \leq 282\overset{\circ}{.}25$ for $64\overset{\circ}{.}8 \leq \delta(2000) \leq 67\overset{\circ}{.}8$; and $256\overset{\circ}{.}65 \leq \alpha(2000) \leq 283\overset{\circ}{.}35$ for $67\overset{\circ}{.}8 \leq \delta(2000) \leq 71\overset{\circ}{.}1$. Twenty-three group candidates were selected from the intersection of two sets (i.e., each group reported here had the properties of both). The first set comprised 98 RASS sources that were obviously extended (more than 2′ in at least one dimension), as judged by two of us independently. The second set comprised 49 RASS sources that has two or more galaxies (one of which with a major axis diameter greater than 18″) near the X-ray position. The optical plate material was *J* and *F* plates from the Palomar Schmidt, which were digitized by COSMOS. The surface brightness to which this galaxy angular diameter refers is undetermined at the moment, but it is not critical since this initial selection only produces a list of candidates. Images of the 23 candidates were examined at the telescope, and redshifts obtained for several objects in their fields. This procedure yielded a sample of eight groups with redshifts less than 0.04. The X-ray contours of these groups are overlaid on the E POSS print in Figures 1*a*–1*h* (Plates 1–8).

Although we have found groups with redshifts as great as 0.09 (Burg et al. 1992), the discussion in this paper will be restricted to those sources within a redshift of 0.04. We believe that we have found all groups with luminosities greater than $\sim 0.9 \times 10^{42}\, h_{50}^{-2}$ ergs s^{-1} in the survey region out to this limit and that this sample is therefore volume complete. The histogram of redshifts in Figure 2 is consistent with a constant space density, although there is some evidence of large-scale structure in the clump of groups near $z = 0.038$ which may be due to the northern extension of the Great Wall. We have used only the three groups with $z < 0.03$ in calculating space densities since the group properties of interest (see Table 3) are incomplete outside this limit. The volume in the survey region out to a redshift of 0.03 is $5.0 \times 10^4\, h_{50}^{-3}$ Mpc^3.

We are keenly aware of the limitations of our sample. First, the sample size is small. However, we are increasing the number of groups which are known to be X-ray–emitting by more than 50%. Further, we are measuring the ensemble properties in a region of parameter space where essentially nothing is known with a precision comparable to previous measurements for rich clusters. Even a measurement with 50% error bars is useful if the function being measured extends over 4 or 5 orders of magnitude (see Figs. 4 and 5). Second, although we believe that the sample is complete and are not severely biased by large-scale structure within our complete volume, we cannot prove it until all X-ray sources have been identified. An upper limit to any additional groups remaining may be obtained by noting that to date we have identified 27% of the 629 total sources. Adopting this value for our incompleteness, the number of groups would be increased by a factor of 3.7. This number is very conservative because we have biased our identification procedure to find groups; nevertheless, even incompleteness at this level would not substantially alter our conclusions.

3. OPTICAL OBSERVATIONS AND GALAXY DATA

Our spectroscopic observations were made with the low-resolution CCD spectrographs attached to the University of Hawaii 2.2 m telescope on Mauna Kea (MK) and the Multiple Mirror Telescope (MMT) on Mount Hopkins (MH). The data were acquired during a series of runs over the past several years. Since the galaxies observed were all rather bright, their redshift determinations were straightforward using standard data reduction procedures. Relative velocity errors were estimated to be ~ 300 km s^{-1} (MK) and ~ 50 km s^{-1} (MH). The positions and redshifts of the galaxies observed are given in

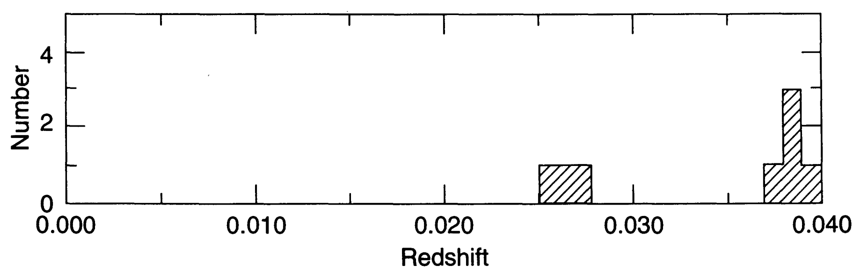

FIG. 2.—Histogram of redshifts for the groups reported in this paper

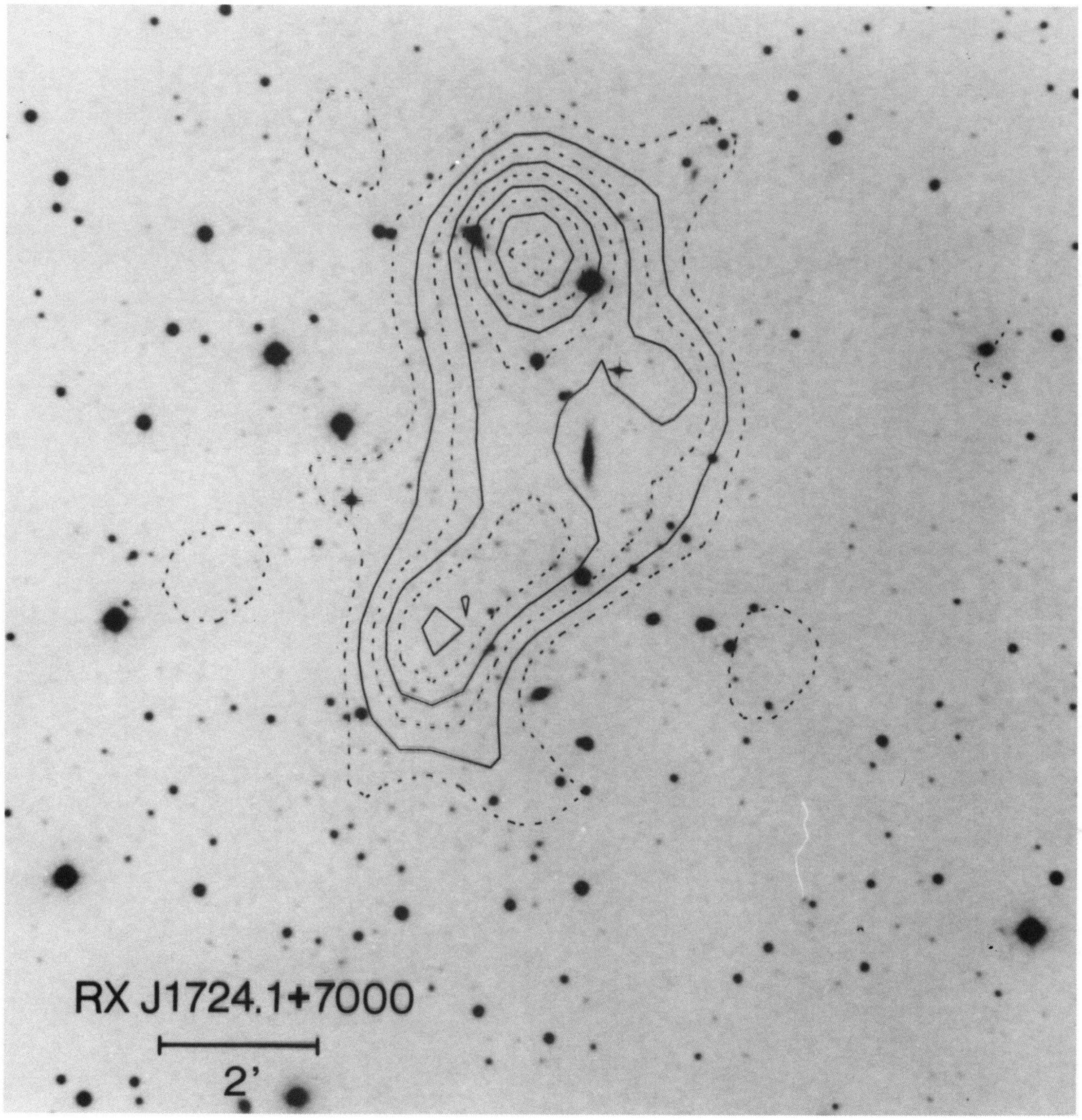

FIG. 1*a*

FIG. 1.—Contour plots of the X-ray surface brightness in channels 40–255, overlaid on the POSS E prints. North is up, east is to the left. The X-ray contours come from smoothing the data binned in 24" × 24" pixels with a Gaussian with FWHM = 85". The contours in units of counts s^{-1} $arcmin^{-2}$ are: (*a*) RX J1724.1+7000—0.00070, 0.00088, 0.0011, 0.0012, 0.0014, 0.0016, 0.0018, 0.0019, and 0.0021, including a background of 0.00036; (*b*) RX J1733.2+7045—0.00070, 0.00088, 0.0011, 0.0012, 0.0014, and 0.0016, including a background of 0.00037; (*c*) RX J1736.4+6804—0.00072, 0.0011, 0.0014, 0.0018, 0.0021, and 0.0025, including a background of 0.00043; (*d*) RX J1744.7+6633—0.00058, 0.00066, 0.00075, 0.00084, 0.00093, 0.0010, 0.0011, and 0.0012, including a background of 0.00040 (note that there is an 8% ± 2% contribution to the group flux from a foreground star which has a high surface brightness, so it appears prominent in the figure, but a low total flux); (*e*) RX J1751.2+6532—0.00079, 0.00097, 0.0012, 0.0014, and 0.0015, including a background of 0.00046; (*f*) RX J1755.8+6236—0.0012, 0.0018, 0.0023, 0.0028, 0.0034, 0.0039, 0.0044, 0.0049, 0.0055, 0.0060, 0.0065, 0.0071, and 0.0076, including a background of 0.00049; (*g*) RX J1756.5+6512—0.00074, 0.00091, 0.0011, 0.0013, 0.0015, 0.0016, 0.0018, and 0.0019, including a background of 0.00043; (*h*) RX J1833.6+6520: 0.00053, 0.00088, 0.0012, 0.0016, 0.0019, 0.0023, 0.0026, and 0.0030, including a background of 0.00044.

HENRY et al. (see 449, 423)

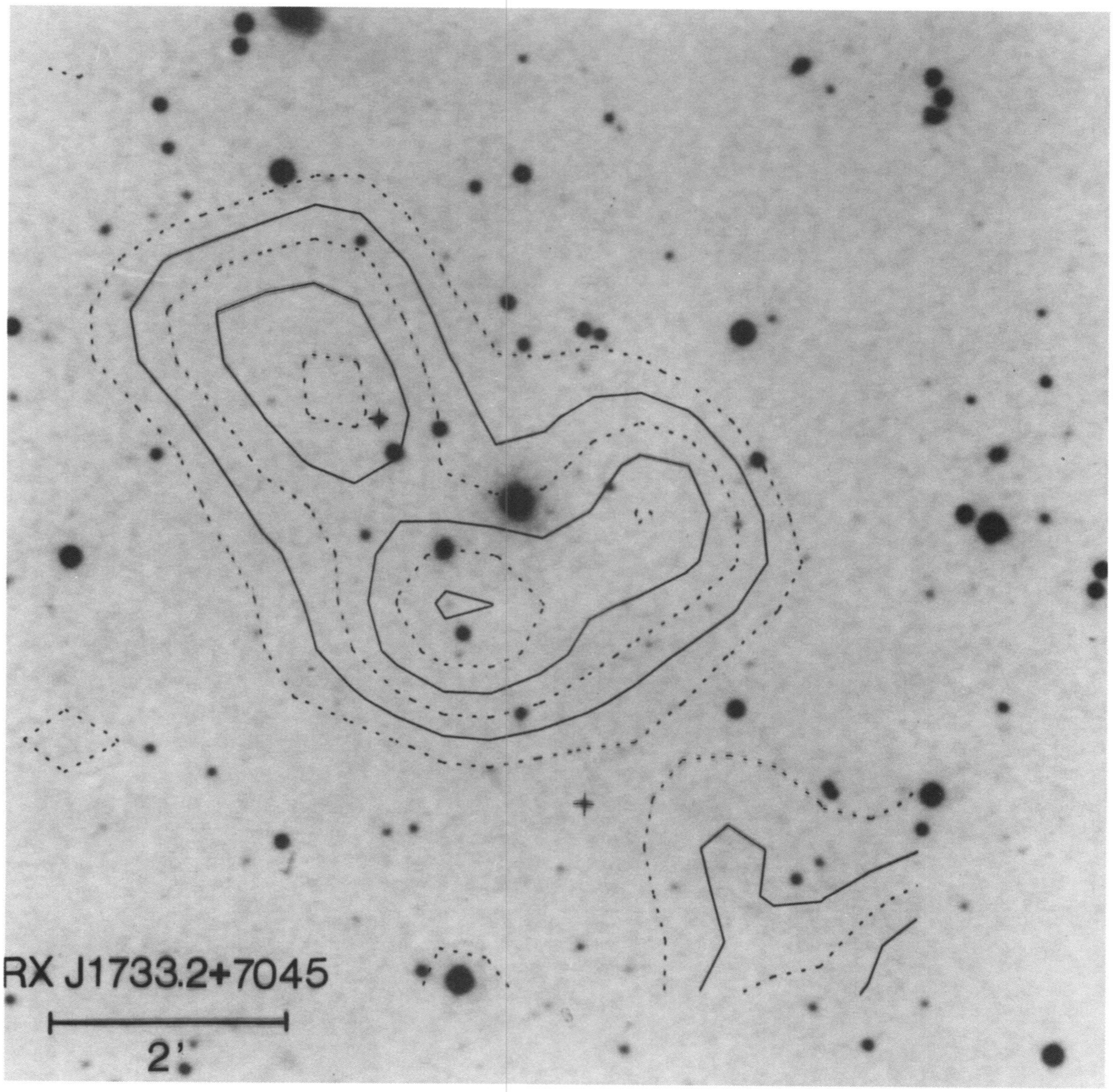

FIG. 1*b*

HENRY et al. (see 449, 423)

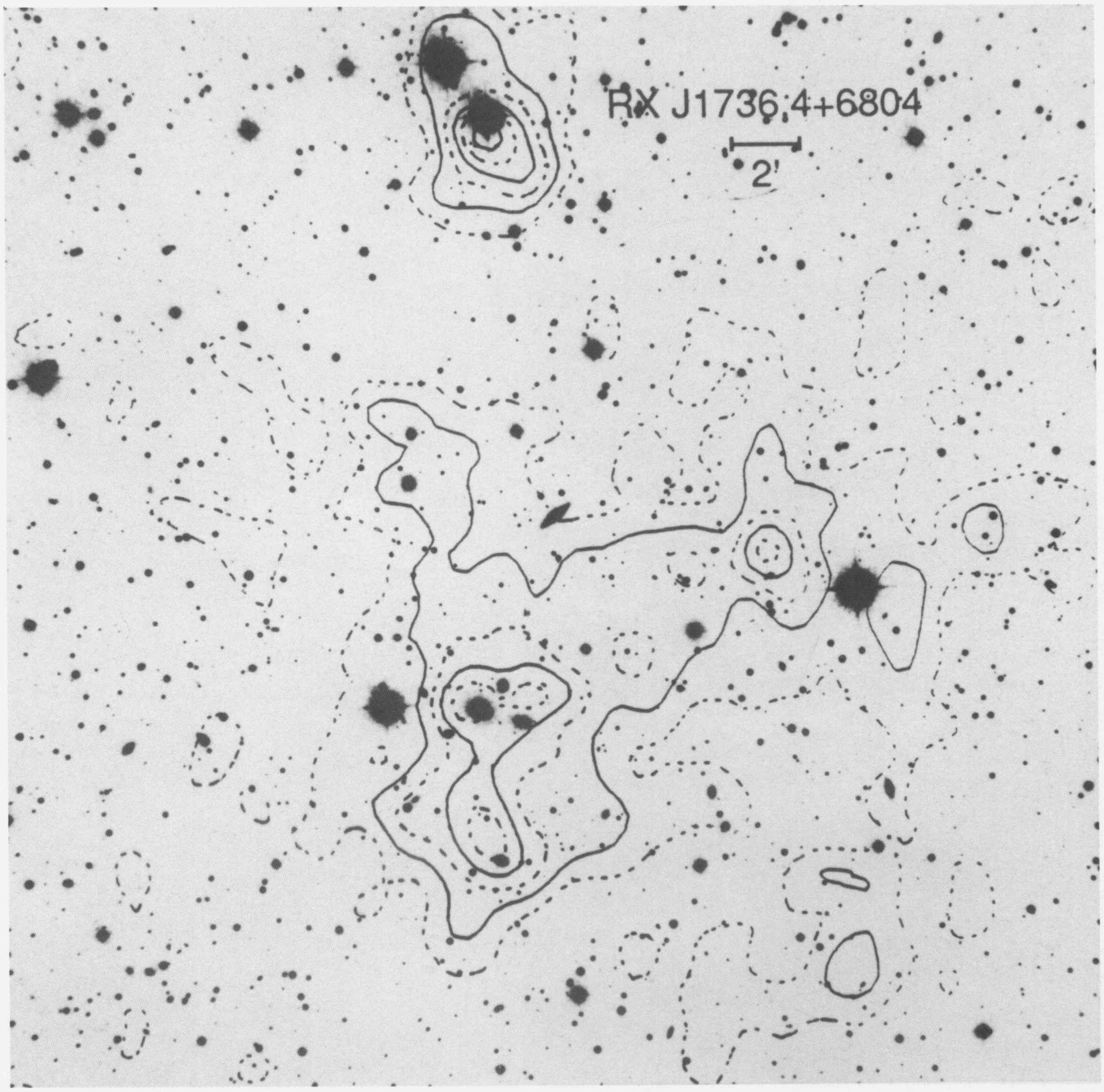

FIG. 1*c*

HENRY et al. (see 449, 423)

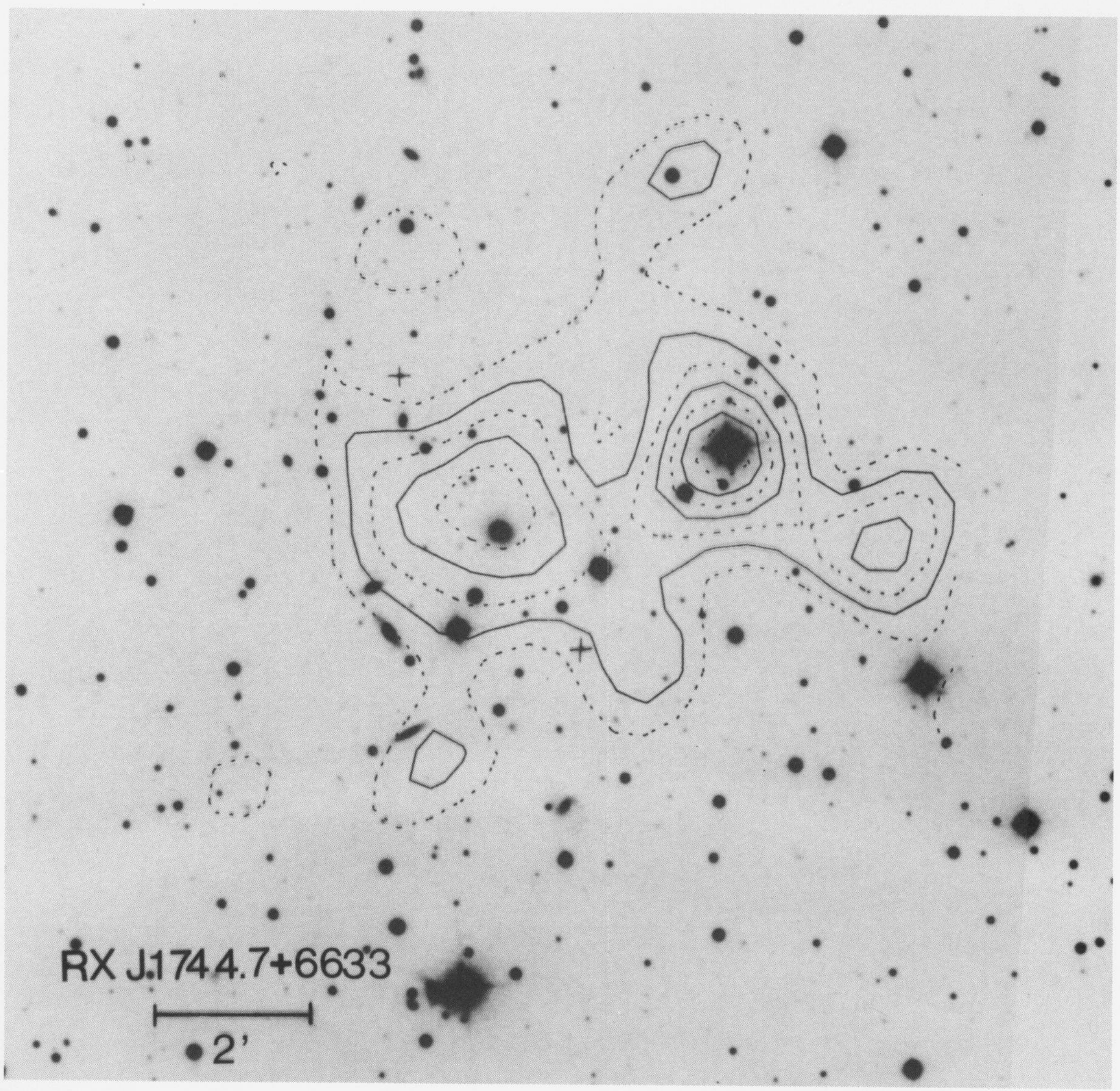

FIG. 1*d*

HENRY et al. (see 449, 423)

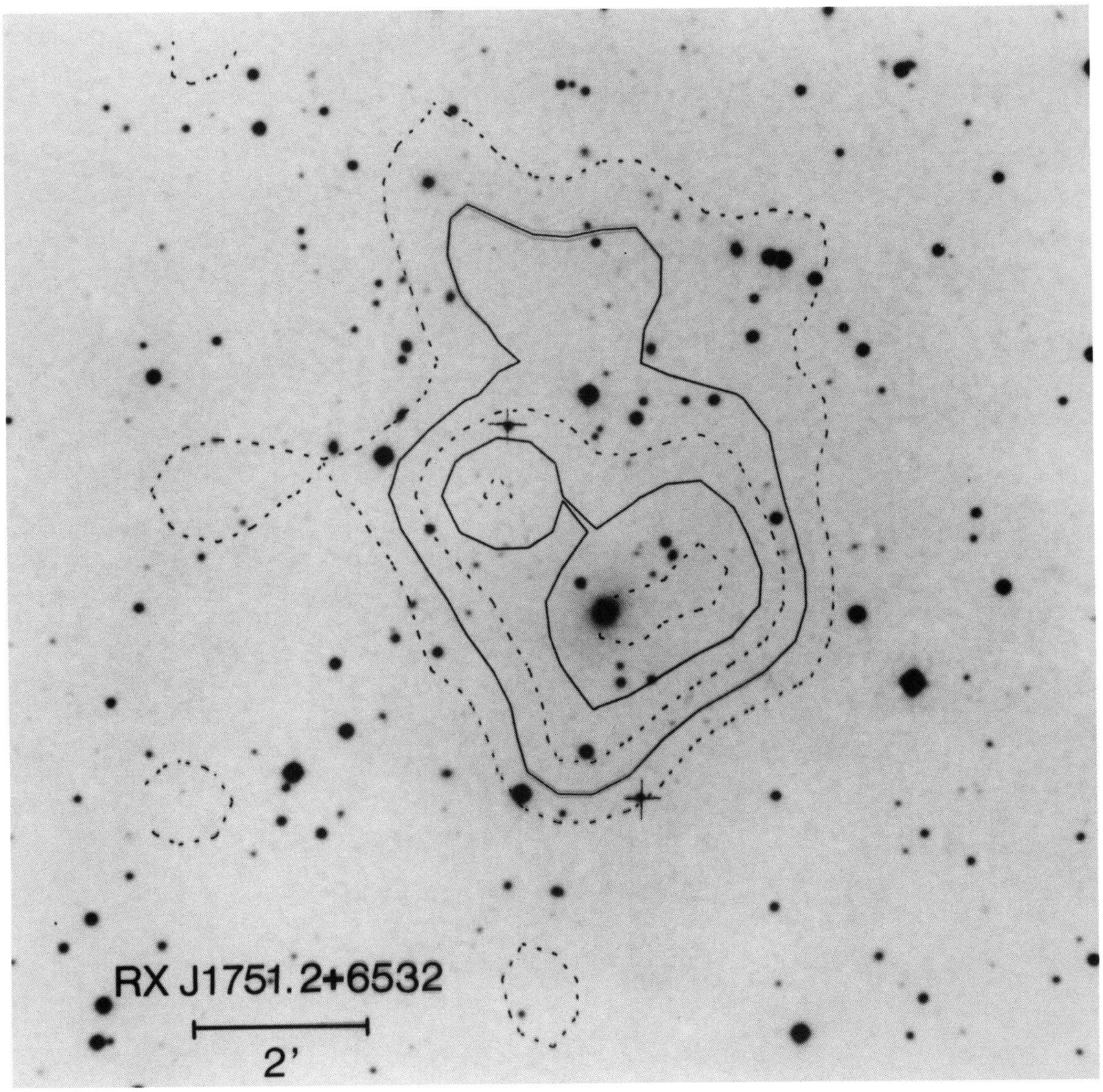

FIG. 1*e*

HENRY et al. (see 449, 423)

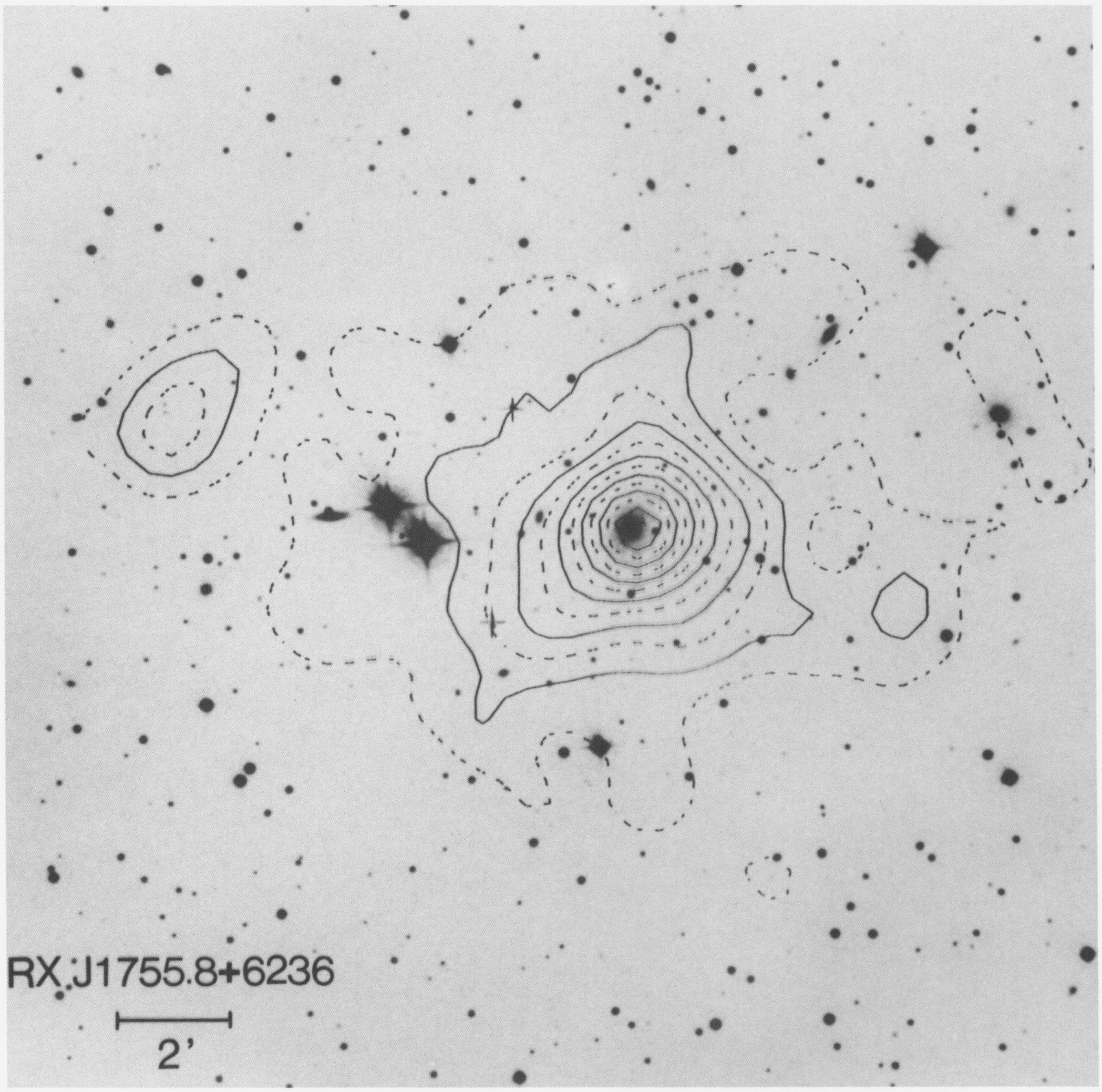

FIG. 1*f*

HENRY et al. (see 449, 423)

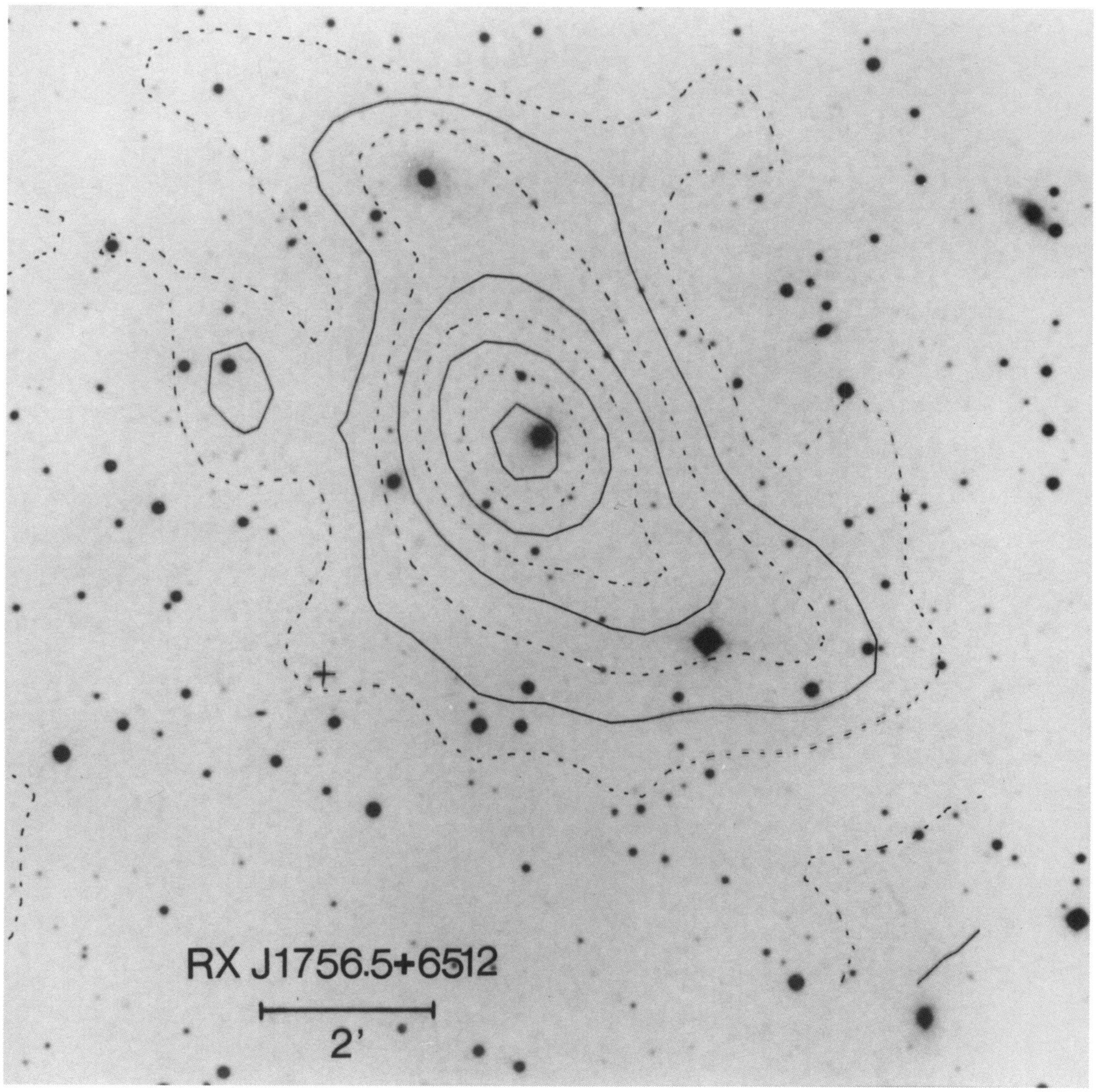

FIG. 1*g*

HENRY et al. (see 449, 423)

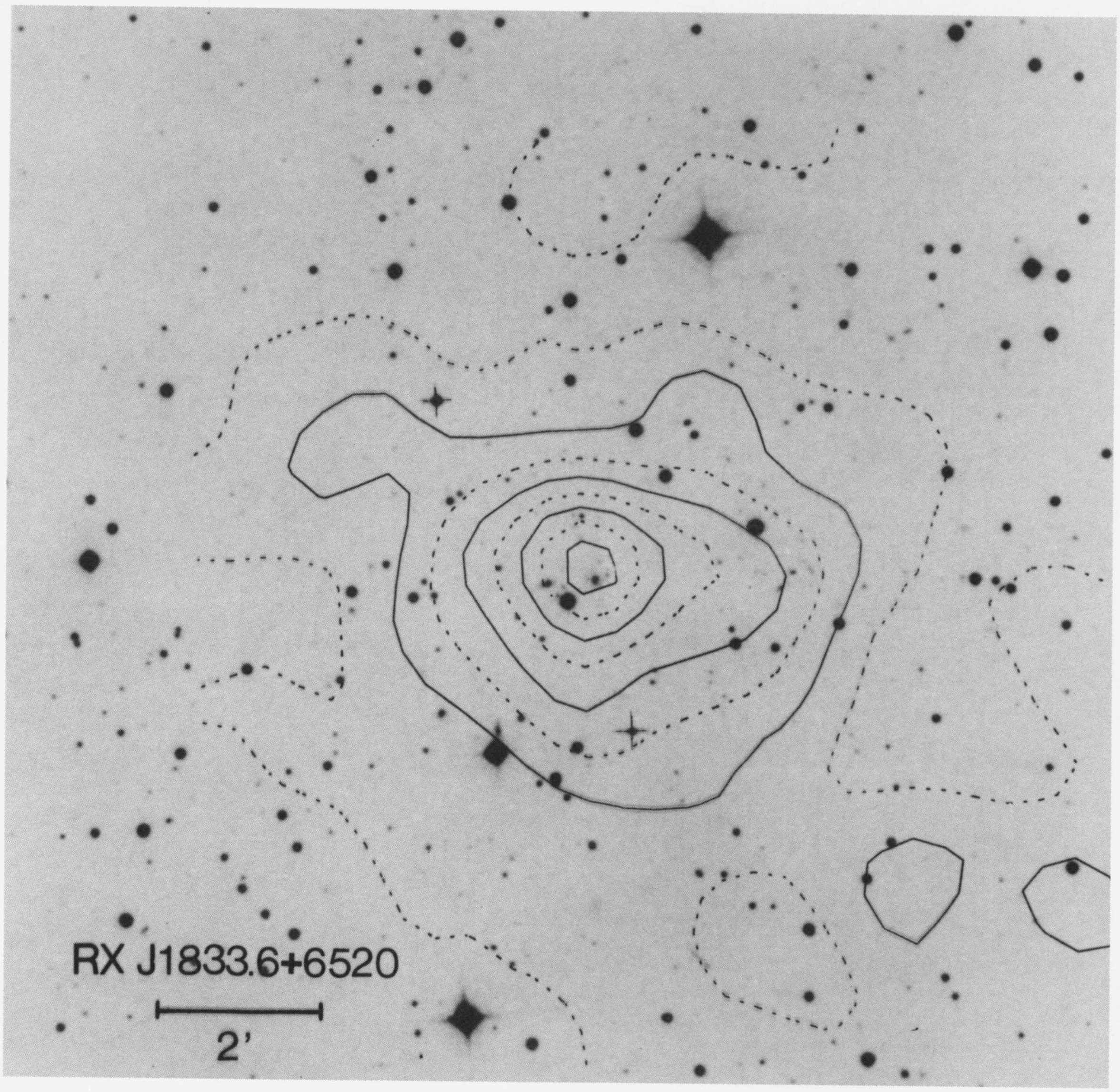

FIG. 1*h*

HENRY et al. (see 449, 423)

Table 1, along with the Zwicky magnitude $B(0)$ when available and our type classification for all spectroscopically confirmed group members. Using the more precise MH measurements, we have calculated velocity dispersions for the three groups with at least four redshift measurements, and the results are also given in Table 1.

The optical images of the groups in Figure 1 appear to show a low spiral fraction. We have quantified this impression by classifying the galaxies in two samples as either E/S0 or spiral Hubble types. The first sample comprised all the Zwicky galaxies within the X-ray detect radius (defined in § 4.1). We have limited ourselves to the Zwicky catalog in order to have a magnitude-limited sample. These data are given in Table 2. The spiral fraction, f_{sp}, of this sample is 0.31 ± 0.12, where the error is calculated from the binominal distribution. The second sample comprised all galaxies in Table 1 that are members of their respective groups. This second sample includes all but one of the Zwicky galaxies (because we did not have a redshift for it) and contains 29 galaxies. For this sample we find f_{sp} is 0.34 ± 0.09.

These spiral fractions are indeed quite low compared to those of optically selected groups. For example, considering only groups with 10 or fewer members, the spiral fraction for CfA groups is 0.67 ± 0.02 (Geller & Huchra 1983), for Southern Sky Redshift Survey (SSRS) groups it is 0.76 ± 0.02 (Maia et al. 1989), and for Southern Sky compact groups (SCGs) it is 0.66 ± 0.03 (Prandoni et al. 1994).

Several other interesting quantities may be calculated from the number of Zwicky galaxies in these groups, $N(>L_{th})$, above Zwicky's limiting magnitude of $B(0) = 15.7$. This number is

TABLE 1

Redshifts and Positions of Galaxies

α(2000)	δ(2000)	z	B(0)	Notes
		RX J1724.1+7000		
$17^h24^m02^s.1$	+69°58′01″......	0.0387	...	Sp
		RX J1733.2+7045		
17 33 12.4	+70 46 29	0.0408	15.6	E/S0
17 33 19.8	+70 46 05	0.0372	...	E/S0
		RX J1736.4+6804 = ZwC 1745.6+6703 (σ = 288 km s^{-1})		
17 34 19.5	+68 01 01	0.0263	15.6	Sp
17 34 56.1	+68 07 34	0.0291	...	MK Spec E/S0
17 34 56.1	+68 06 29	0.0244	...	MK Spec E/S0
17 35 16.9	+68 00 54	0.0254	...	Sp
17 35 22.4	+68 05 48	0.0256	15.5	E/S0
17 36 07.4	+68 09 12	0.0265	15.5	NGC 6419 Sp
17 36 08.1	+68 05 23	0.0245	...	E/S0
17 36 15.1	+68 03 00	0.0271	15.5	NGC 6420 E/S0
17 36 21.5	+68 04 06	0.0263	...	E/S0
17 36 23.0	+67 58 57	0.0245	...	MK Spec E/S0
17 36 28.6	+68 03 22	0.0256	15.1	NGC 6422 E/S0
17 36 54.8	+68 10 09	0.0242	15.6	NGC 6423 E/S0
		RX J1744.7+6633		
17 44 49.0	+66 33 53	0.039	15.7	E/S0
17 45 03.8	+66 32 36	0.035	...	Sp
		RX J1751.2+6532		
17 50 59.7	+65 32 29	0.0382	...	E/S0
17 51 07.5	+65 31 50	0.0389	15.4	NGC 6505 E/S0
		RX J1755.8+6236 = ZwC 1754.9+6230 (σ = 387 km s^{-1})		
17 54 49	+62 38 36	0.0279	14.8	NGC 6512 E/S0
17 55 13	+62 39 38	0.0253	15.7	NGC 6516 Sp
17 55 48.6	+62 36 44	0.0275	14.3	NGC 6521 E/S0
17 56 31	+62 36 44	0.0257	15.5	Sp
		RX J1756.5+6512 (σ = 195 km s^{-1})		
17 55 34.3	+65 15 22	0.0265	...	MCG +11-22-12 Sp
17 55 44.3	+65 05 52	0.0873	...	
17 55 50.0	+65 19 28	0.0378	...	
17 56 01.2	+65 20 24	0.0278	...	E/S0
17 56 28.8	+65 12 36	0.0263	15.6	E/S0
17 56 42.6	+65 15 34	0.0269	15.6	MCG +11-22-15 Sp
17 56 45.2	+65 12 01	0.0275	...	E/S0
		RX J1833.6+6520		
18 33 48.9	+65 21 37	0.0382	...	Sp

TABLE 2

SUMMED PROPERTIES OF THE ZWICKY GALAXIES WITHIN THE X-RAY DETECT RADIUS

RX J (1)	z (2)	$N(>L_{\rm th})$ (3)	E/S0 (4)	Sp (5)	$N(>L_{\rm th})/E_1(L_{\rm th}/L^*)$ (6)	L_B^T [a] (7)	$M_{\rm gal}$ [b] (8)	$L_{\rm x,gal}$ [c] (9)
1736.4+6804......	0.0258	6	4	2	14.8	6.4	3.8	3.0
1755.8+6236......	0.0266	5	3	2	13.4	5.8	3.4	2.7
1756.5+6512......	0.0270	2	1	1	5.6	2.4	1.4	1.1
1744.7+6633......	0.0370	1	1	0	8.1	3.5	2.1	1.6
1751.2+6532......	0.0386	1	1	0	9.6	4.1	2.5	1.9
1733.2+7045......	0.0390	1	1	0	10.1	4.4	2.6	2.0

[a] $10^{11}\ h_{50}^{-2}\ L_\odot$.
[b] $10^{12}\ h_{50}^{-1}\ M_\odot$.
[c] $10^{41}\ h_{50}^{-2}$ ergs s^{-1} in the 0.2–4.0 keV band.

used to normalize the galaxy luminosity function in order to include those galaxies fainter than the limiting magnitude. We use a Schechter function fit to the data of de Lapparent, Geller, & Huchra (1989) which gives a $M^*_{B(0)} = -20.7 \pm 0.1 + 5 \log h_{50}$ and an $\alpha = -1.1 \pm 0.1$. We will set α equal to -1, which is consistent with the observations and which will make the integrals simpler. The Zwicky magnitudes must also be corrected to total magnitudes by $B^T(0) = B(0) - 0.4$. Integrating the galaxy luminosity function to obtain the total group luminosity from the galaxies gives $L_B^T = L^{T*}\ N(>L_{\rm th})/E_1(L_{\rm th}/L^*)$, where E_1 is the exponential integral (Abramowitz & Stegun 1965, eq. [6.5.15]), L^* is the luminosity corresponding to $M^*_{B(0)}$, L^{T*} is the total luminosity corresponding to $M^*_{B(0)} - 0.4$, and L_B^T is the total luminosity of the group in the B band. The mass of the group in galaxies is then $M_{\rm gal} = L^{T*}\ (M/L)_{\rm gal}\ N(>L_{\rm th})/E_1(L_{\rm th}/L^*)$, where $(M/L)_{\rm gal}$ is the ratio of mass to blue luminosity of a galaxy, which equals $5.95 \pm 0.25\ h_{50}\ M_\odot/L_\odot$ (van der Marel 1991). This mass-to-light ratio applies to the region of the galaxy that contains stars; that is, it is the mass in stars. The ratio is substantially higher for the larger volumes sampled by neutral hydrogen or hot X-ray gas. Finally, the X-ray luminosity of the galaxies alone, $L_{\rm x,gal}$, is obtained by integrating along the galaxy luminosity function the relation between L_B^T and $L_{\rm x,gal}$ given by Fabbiano, Kim, & Trinchieri (1992): $L_{\rm x,gal} = \Lambda[L_B^T]^\lambda$, where (Λ, λ) are $(3.16 \times 10^{21}, 1.8)$ for E/S0 and $(2.00 \times 10^{29}, 1.0)$ for spirals, L_B^T is in units of solar luminosities, and $L_{\rm x,gal}$ is in the 0.2–4.0 keV band (i.e., a wider band than ours). The result is

$$\{(1 - f_{\rm sp})\Lambda(e)/\lambda(e)[L^{T*}]^{\lambda(e)} + f_{\rm sp}\,\Lambda(s)/\lambda(s)[L^{T*}]^{\lambda(s)}\} \times N(>L_{\rm th})/E_1(L_{\rm th}/L^*)\ .$$

Inserting the numbers we find

$$L_B^T = 4.31 \times 10^{10}\ h_{50}^{-2}\ L_\odot\ N(>L_{\rm th})/E_1(L_{\rm th}/L^*)\ ,$$

$$M_{\rm gal} = 2.56 \times 10^{11}\ h_{50}^{-1}\ M_\odot\ N(>L_{\rm th})/E_1(L_{\rm th}/L^*)\ ,$$

$$L_{\rm x,gal} = 2.00 \times 10^{40}\ h_{50}^{-2}\ {\rm ergs\ s^{-1}}\ N(>L_{\rm th})/E_1(L_{\rm th}/L^*)\ .$$

These quantities are collected in Table 2 for the groups that contain at least one Zwicky galaxy. Clearly, it is only for those objects with $z < 0.03$, where there is more than one Zwicky galaxy in the group, that we can claim any precision in the measurement. Even so, the dispersion in the calculated quantities among the five groups is not large, and in any case we only use properties averaged over all groups in what follows.

4. X-RAY OBSERVATIONS

4.1. *X-Ray Spatial Observations*

We have determined the net counting rate within the smallest radius (termed $R_{\rm Det}$ in Table 3) beyond which there is no

TABLE 3

GROUP PROPERTIES

RX J (1)	α(2000) (2)	δ(2000) (3)	z (4)	$N_{\rm H}$ [a] (5)	Exposure [b] (6)	Net Counts [c] (7)	Flux [d] (8)	Luminosity [e] (9)	kT [f] (10)	β (11)	$M(<0.4\ h^{-1}$ Mpc) [g] (12)	$R_{\rm Det}$ [h] (13)
1724.1+7000...	17ʰ24ᵐ11ˢ2	+70°00′17″	0.0387	4.08	2953	104.0 ± 14.4	3.31	2.12	0.95 ± 0.20	...	...	0.38
1733.2+7045...	17 33 17.0	+70 45 33	0.0390	3.83	2735	50.4 ± 10.0	1.73	1.13	...	...	...	0.27
1736.4+6804...	17 36 27.7	+68 04 31	0.0258	4.37	5707	988.7 ± 53.4	16.45	4.68	$1.12^{+0.40}_{-0.20}$	$0.35^{+0.14}_{-0.04}$	$1.7^{+1.0}_{-0.4}$	0.59
1744.7+6633...	17 44 47.7	+66 33 52	0.0370	3.89	9891	127.2 ± 24.1	1.21	0.71	...	...	...	0.39
1751.2+6532...	17 51 12.5	+65 32 49	0.0386	3.88	8672	305.8 ± 27.5	3.31	2.12	$1.25^{+0.25}_{-0.10}$	$0.72^{+0.53}_{-0.19}$	$4.0^{+3.0}_{-1.1}$	0.40
1755.8+6236...	17 55 48.5	+62 36 38	0.0266	3.39	4560	808.3 ± 35.4	16.66	5.07	$1.50^{+0.50}_{-0.20}$	0.51 ± 0.12	$5.2^{+4.3}_{-1.7}$	0.37
1756.5+6512...	17 56 31.5	+65 12 57	0.0270	3.66	11175	661.3 ± 41.4	5.56	1.74	0.80 ± 0.05	$0.40^{+0.05}_{-0.03}$	$1.4^{+0.2}_{-0.1}$	0.42
1833.6+6520...	18 33 40.5	+65 20 48	0.0.382	2.79	4575	149.2 ± 15.8	3.07	1.92	0.92 ± 0.10	...	...	0.27

NOTE.—All errors are at the 68% confidence level.
[a] 10^{20} cm^{-2}.
[b] Seconds.
[c] In channels 40–255.
[d] 10^{-13} ergs cm^{-2} s^{-1} in the 0.5–2.0 keV band.
[e] $10^{42}\ h_{50}^{-2}$ ergs s^{-1} in the 0.5–2.0 keV band.
[f] keV.
[g] $10^{13}\ h_{50}^{-1}\ M_\odot$.
[h] h_{50}^{-1} Mpc.

longer a statistically significant increase in the integrated count rate. This radius is typically 6′. We used a factor of 1 count s^{-1} in pulse-height channels 40–255 = 9.4×10^{-12} ergs cm^{-2} s^{-1} in the 0.5–2.0 keV band in order to convert from counting rate to flux. This factor is appropriate to a thermal spectrum with a 1 keV temperature and the range of hydrogen column densities encompassed by our groups.

The luminosity that we measure cannot be due solely to the integrated luminosities of the individual group galaxies. Although the X-ray surface brightness may be termed patchy, in most cases the X-ray peaks are not centered on bright galaxies, as may be seen in Figure 1. More quantitatively, the measured X-ray luminosities in Table 3 may be compared to those expected from the galaxies given in Table 2. This calculation is conservative because not all of these galaxies have redshift measurements, so they may not be group members, and the calculated X-ray emission from the galaxies is in a wider band than are our measurements, so the galaxies will appear more luminous. We find that the expected summed X-ray luminosity from the galaxies is a factor of approximately 10 lower than the measured group luminosity. Price et al. (1991) also find that galaxies contribute a similar small fraction of the total X-ray emission of poor clusters of galaxies.

We have fitted the standard β-model to the azimuthally averaged X-ray surface brightness for the four groups with sufficient counts to constrain the model parameters. Three of these groups are approximately circularly symmetric, but RX J1736.4+6804 is not. The β-model parameters for this group will just give an indication of its average properties. In the β-model the surface brightness is assumed to follow $I(\theta) = I_0(1 + \theta/\theta_c)^{-3\beta+1/2}$, where θ_c is the core radius. We found that our data do not strongly constrain the core radius, which is to be expected given our measured resolution of 1′.8 FWHM and the core radii measured in pointed *ROSAT* observations of even closer groups (Ponman & Bertram 1993; David et al. 1994; Pildis et al. 1995). This situation is unfortunate because it precludes the measurement of the hot gas density. It is possible to constrain the value of β, which we give in Table 3, along with the 68% confidence errors for one interesting parameter. The objects that have no values of β in Table 3 had too few counts to constrain either β or the core radius. Figures 3*a*–3*d* show the fits.

There are two points that can be made about these fits. First, the weighted average value of β is 0.40. This value is lower than the canonical 0.67 found for rich clusters (Jones & Forman 1984). Such a lower value of β for groups has already been noted by Böhringer (1994), and it is found in pointed PSPC data for the groups HCG 62 (0.38, Ponman & Bertram 1993; 0.51 ± 0.02, Pildis et al. 1995), HCG 68 (0.61 ± 0.04; Pildis et al. 1995), HCG 97 (0.48 ± 0.01; Pildis et al. 1995), NGC 2300 (0.40 ± 0.06, Mushotzky 1993; 0.32 ± 0.02, Pildis et al. 1995), and NGC 5044 (0.53 ± 0.02, David et al. 1993). Second, the surface brightness distribution for RX J1755.8+6236 shown in Figure 3*c* has the enhanced central value compared to the β-model which is characteristic of a central cooling flow. The temperature measurements discussed in the next section and our observations of [O III], [N II], and Hα in emission in the optical spectrum of NGC 6521, the central group galaxy, support this conclusion. If we were able to determine the hot gas density in this object, then we could place limits on the central merger rate since any region which is cooling must have been undisturbed for a cooling time. Such a constraint might be interesting with respect to the merger instability of groups discussed at the end of § 4.3, but it will have to wait for better data.

4.2. *X-Ray Temperature Observations*

We fit Raymond-Smith thermal models with the abundances of the heavy elements fixed at 0.3 to the pulse-height spectra of the groups. We verified that the best-fitting temperature did not change for abundances in the range 0.1–1. Temperatures around 1 keV were consistent with the data; see Table 4. For three groups there were enough counts that it was possible to divide the data into an inner circle and an outer annulus and still have reasonably small error bars. These latter fits showed that the groups were isothermal, as has been seen in the longer pointed observations of other groups referred to previously, except for RX J1755.8+6236, which exhibited a cooler inner circle as was expected from its surface brightness.

4.3. *Mass Measurements*

It is not possible to determine the hot gas mass from our data because of our inability to determine the X-ray core radius. Fortunately, it is possible to measure the total confining mass within a radius that is large compared to the X-ray core radius. Long pointed observations of groups show that the temperatures are essentially isothermal (Ponman & Bertram 1993; David et al. 1993; Böhringer 1994). If the X-ray gas is isothermal, spherically symmetric, and in hydrostatic equilibrium, then the mass confining it measured within a radius r, which is much larger than the gas core radius, is given by $M(<r) = 3\beta kTr/G\mu m_p$, where μ is the mean molecular weight (0.6) and m_p is the proton mass. Note that the mass increases linearly with radius. Figure 1 shows that the assumption of spherical symmetry is reasonable for all groups for which we have measured the mass, except for RX J1736.4+6804. The mass we determine for this group will be in error, probably by a factor of order unity, but detailed numerical calculations are required to determine the size of this error.

We can estimate the mass of four of the groups since β and kT are known for them. We choose a radius of 0.4 h_{50}^{-1} Mpc within which to measure the confining mass since our data extend that far. The masses calculated according to these assumptions are given in Table 3. These masses are in the range of those found from the previously referenced pointed observations of groups within the same radius ([1.8–2.4] $\times 10^{13}$ h_{50}^{-1} $M_\odot$).

TABLE 4

GROUP TEMPERATURE MEASUREMENTS

RX J	Radius	kT (keV)	χ^2_ν
1724.1+7000......	0′.0–5′.6	0.95 ± 0.20	0.90
1736.4+6804......	0.0–6.0	$1.2^{+0.4}_{-0.2}$	0.41
	6.0–13.2	$1.1^{+0.4}_{-0.2}$	0.61
	0.0–13.2	$1.1^{+0.4}_{-0.2}$	0.27
1751.2+6532......	0.0–6.0	$1.3^{+0.3}_{-0.1}$	1.16
1755.8+6236......	0.0–4.0	1.0 ± 0.1	0.84
	4.0–8.0	$2.3^{+1.8}_{-0.5}$	1.23
	0.0–8.0	$1.5^{+0.5}_{-0.2}$	0.94
1756.5+6512......	0.0–4.2	$0.72^{+0.10}_{-0.05}$	0.68
	4.2–8.4	$0.89^{+0.05}_{-0.10}$	1.35
	0.0–8.4	0.80 ± 0.05	1.04
1833.6+6520......	0.0–4.0	0.92 ± 0.10	0.79

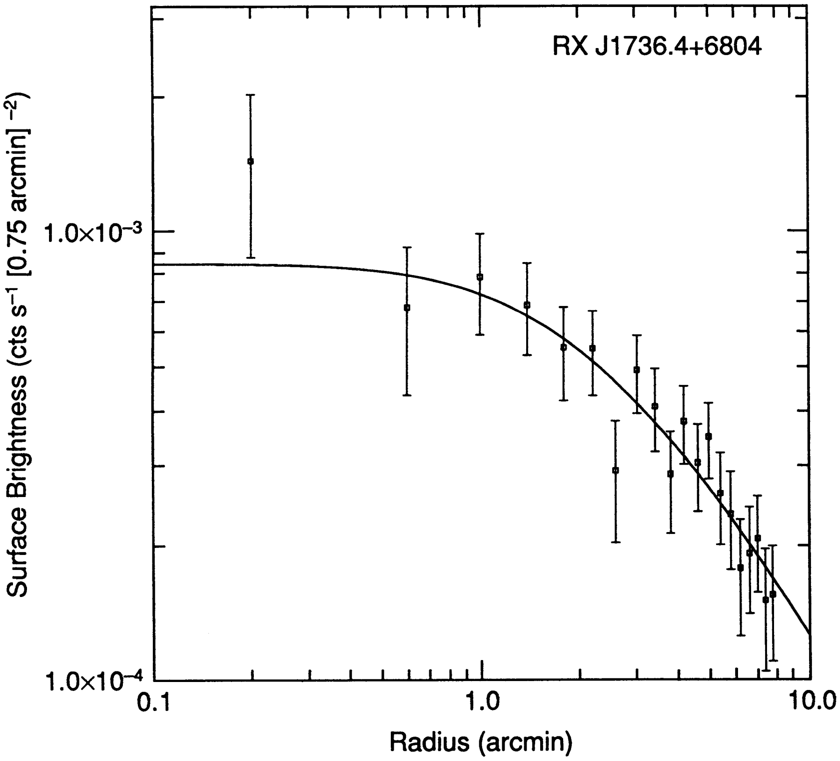

FIG. 3*a*

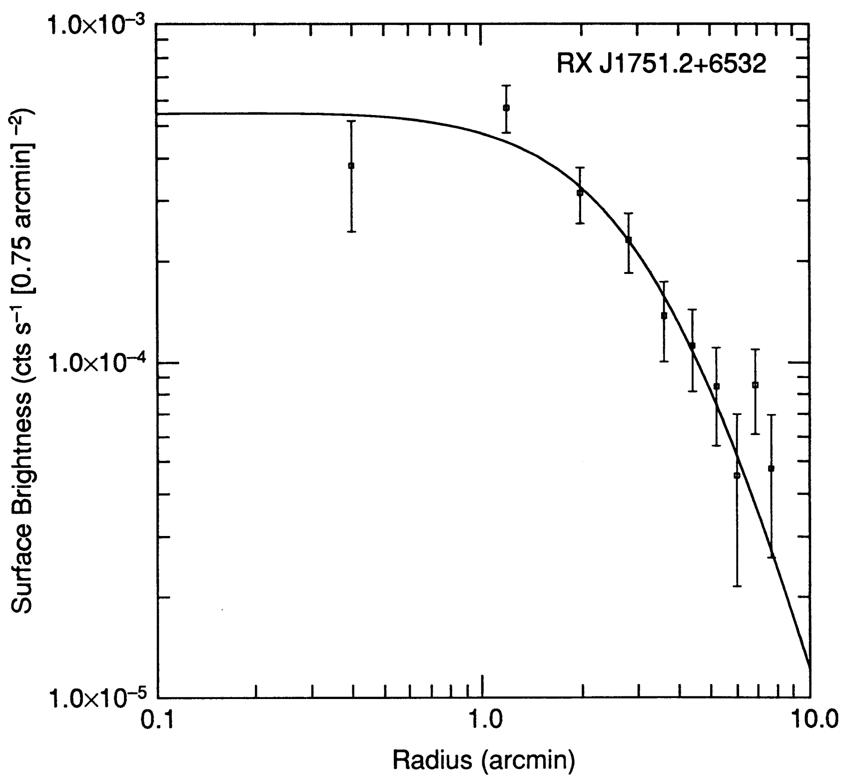

FIG. 3*b*

FIG. 3.—The β-model fits to the azimuthally averaged surface brightnesses of four groups. For RX J1756.5 + 6512, the open squares are for a point source.

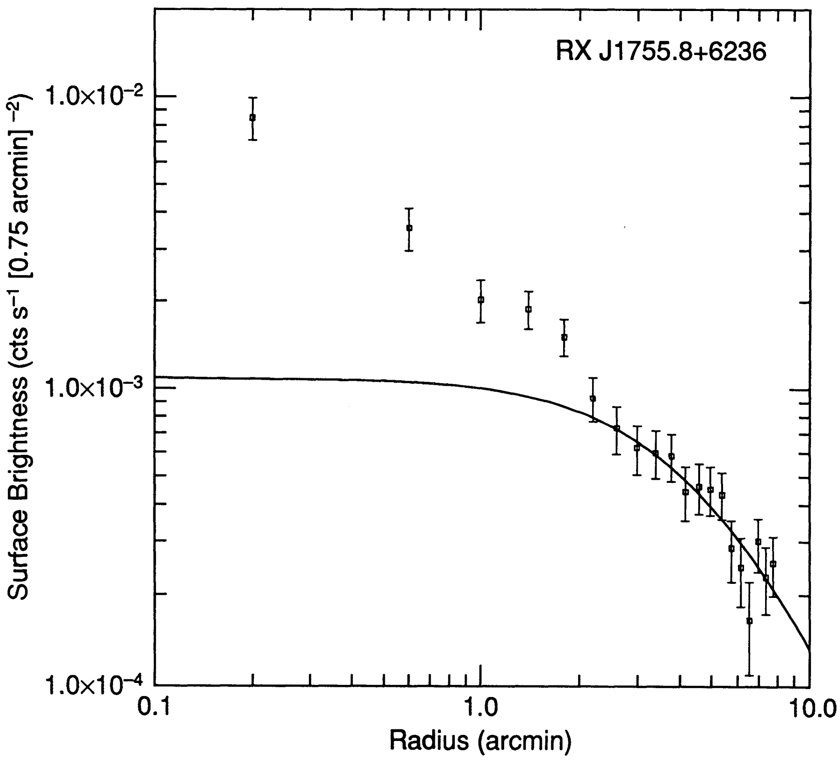
RX J1755.8+6236
Surface Brightness (cts s^{-1} [0.75 arcmin] $^{-2}$)
1.0×10^{-2}
1.0×10^{-3}
1.0×10^{-4}
0.1
1.0
10.0
Radius (arcmin)

FIG. 3*c*

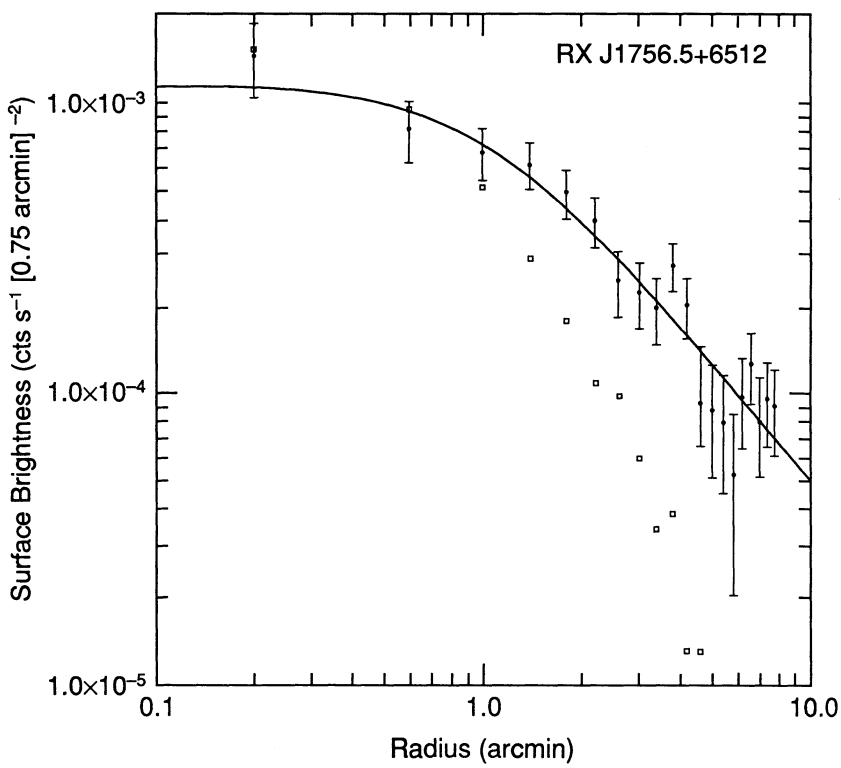
RX J1756.5+6512
Surface Brightness (cts s^{-1} [0.75 arcmin] $^{-2}$)
1.0×10^{-3}
1.0×10^{-4}
1.0×10^{-5}
0.1
1.0
10.0
Radius (arcmin)

FIG. 3*d*

It should be noted that this outer radius is approximately one-half of the virialized radius for objects of the masses we find; that is, the virialized radius is about 0.8 h_{50}^{-1} Mpc. This value is nearly the same as the analogous quantity used to determine masses using optical measurements and the virial theorem, the harmonic radius, which has a median value of 1.0 h_{50}^{-1} Mpc (Ramella et al. 1989). These considerations imply that the total masses of these groups (i.e., that within the virialized radius) will be a factor of approximately 2 larger than what we report here. Given an average velocity dispersion of $\sim$300 km s^{-1}, the virial crossing time for this virialized radius is $\sim$0.13 of the Hubble time, independent of the Hubble constant. Thus these groups, in fact, have had sufficient time to virialize within this larger radius according to the discussion in the Appendix of Nolthenius & White (1987). The gas in the groups probably has virialized; whether the galaxies have is a matter of debate. *N*-body calculations (Diaferio et al. 1993 and references therein) indicate that galaxies in groups are unstable to mergers. That is, the galaxies do not virialize; they merge instead because their orbital velocities are comparable to their internal velocities.

5. DISTRIBUTION FUNCTIONS

The properties of groups and clusters of galaxies can serve as important constraints on cosmological models (e.g., Henry & Arnaud 1991; Moore, Frenk, & White 1993; Zabludoff et al. 1993). Using our sample of X-ray–selected groups, we can extend the luminosity, temperature, and mass functions determined for X-ray clusters into regions of these parameters where essentially nothing is known. The statistical accuracy of our new point for groups is comparable to those obtained for clusters. For any of the three observables Y, the distribution function $n(Y_{\rm av}) = 3/(5.0 \times 10^4\ h_{50}^{-3}\ {\rm Mpc}^3\ \Delta Y)$, where $Y_{\rm av}$ is the average value of Y and ΔY is the total range of Y.

We find that

$$n(3.8 \times 10^{42}\ h_{50}^{-2}\ {\rm ergs\ s^{-1}}) = 1.8^{+1.7}_{-1.0} \times 10^{-3}\ h_{50}^{3}\ {\rm Mpc}^{-3}\ (10^{44}\ h_{50}^{-2}\ {\rm ergs\ s^{-1}})^{-1}$$

$$n(1.4\ {\rm keV}) = 4.0^{+3.9}_{-2.3} \times 10^{-5}\ h_{50}^{3}\ {\rm Mpc}^{-3}\ {\rm keV}^{-1}\ ,$$

$$n(2.8 \times 10^{13}\ h_{50}^{-1}\ M_\odot) = 1.6^{+1.5}_{-0.9} \times 10^{-5}\ h_{50}^{3}\ {\rm Mpc}^{-3}\ (10^{13}\ h_{50}^{-1}\ M_\odot)^{-1}\ .$$

The first two of these are compared to the distribution functions of richer clusters (Henry & Arnaud 1991; Henry et al. 1992, who reported luminosities in the band closest to that used in this paper) in Figures 4 and 5. The group data lie on a smooth extrapolation of the cluster functions.

It is also of interest to compare the mass function with other such determinations. In order to make this comparison, all masses must be determined within the same radii. The simplest method would be to increase our measured masses by a factor of 2 in order to measure a total mass, defined to be that within the virialization radius. We compare our mass function with that from Bahcall & Cen (1993), who converted a luminosity function to a mass function using a mass-to-light ratio. After changing the integral mass function of Bahcall & Cen to a differential function, we find a value of

$$n(5.6 \times 10^{13}\ h_{50}^{-1}\ M_\odot) = 5.7 \pm 1.0 \times 10^{-6}\ h_{50}^{3}\ {\rm Mpc}^{-3}\ (10^{13}\ h_{50}^{-1}\ M_\odot)^{-1}\ ,$$

which agrees within the errors with our value.

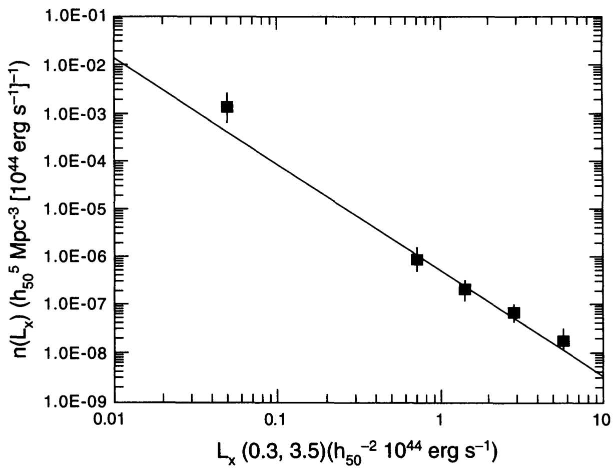

FIG. 4.—Luminosity function of groups and clusters of galaxies. The data reported here give the lowest luminosity point, which has been converted to the 0.3–3.5 keV band for comparison with previous measurements. The straight line is from the Henry et al. (1992) fit only to the high-luminosity data (including the constraint that there were no objects detected with luminosities above the last point).

6. DISCUSSION

We find that the ensemble X-ray properties of groups are consistent with simply scaled-down versions of their richer cousins, clusters of galaxies. This point has been made previously by comparing the optical properties of complete optically selected samples (Ramella et al. 1989) and the X-ray properties of individual objects selected in the optical (Price et al. 1991). Our work extends this conclusion to the X-ray properties deduced from a complete X-ray–selected sample.

The groups reported here have a higher fraction of elliptical galaxies than does the average optically selected group. Ebeling et al. (1994) and Pildis et al. (1995) report that X-ray–luminous Hickson compact groups also have a low spiral fraction. This trend may be related to the need for a deep potential well in order to confine the hot gas. Such a well may only occur after the group has evolved into a compact form, converting its spiral galaxies into ellipticals through mergers, as is indicated

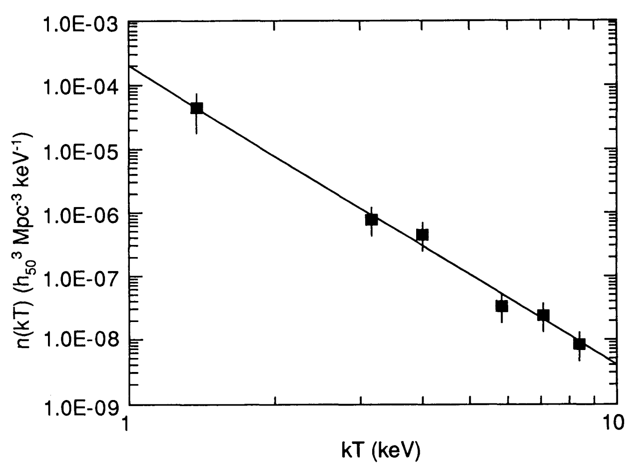

FIG. 5.—Temperature function of groups and clusters of galaxies. The data reported here give the lowest temperature point. The straight line is the Henry & Arnaud (1991) fit to only the five highest temperature data points.

by N-body calculations (Barnes 1989). RX J1755.8+6236 may be an object near the endpoint of this process.

It is of interest to determine quantities related to the mass of the groups since mass is one of the fundamental parameters, yet in the past this has been difficult to measure, particularly for groups. Our selection criteria and method of mass determination are completely different from any used previously, so it is particularly interesting to compare our results with those determined from optically selected samples. The first quantity we determine, mainly for historical reasons, is the average ratio of mass to blue light. There are four groups that have both their mass and optical luminosity determined; see column (12) of Table 3 and column (7) of Table 2. We have increased the mass of RX J1736.4+6804 by 50% since all optical luminosities in Table 2 are those within the detect radius (0.6 h_{50}^{-1} Mpc in this case), but the masses are within 0.4 h_{50}^{-1} Mpc. The unweighted average ratio of mass to blue light is 60 h_{50} $M_{\odot}/L_{\odot}$. This value is in the range of previous determinations, although it is on the low end (cf. 74 h_{50} $M_{\odot}/L_{\odot}$ by Nolthenius 1993, or 83 h_{50} $M_{\odot}/L_{\odot}$ by Ramella et al. 1989). The apparent mass density of the three groups within a redshift of 0.03 corresponds to a $\Omega_{\rm groups}$ of $\sim$0.05, when the factor-of-2 increase of the mass out to the viral radius is applied. This value is also on the low end of that obtained by optical determinations. However, as we have noted previously, our X-ray–selected groups have very low spiral fractions. In fact, only 21% $\pm$ 3% of CfA groups and 20% $\pm$ 4% of SSRS groups have spiral fractions less than or equal to that of our groups. If the masses of the spiral rich groups are comparable to the X-ray–selected ones, then the density of all groups corresponds to an Ω_0 of $\sim$0.25. In either case, our data indicate that the universe is far from closed unless most of its mass is distributed rather uniformly.

It is clear that X-ray observations of groups of galaxies using *ROSAT* will greatly increase our understanding of their structure and evolution. Measurements of group properties are now no longer limited by the small number statistics of the few galaxies in them. Rather the precision of a measurement is now primarily limited by observation time. We expect that there will be advances similar to those made when clusters were first intensively observed in X-rays. The most urgent task now is to greatly enlarge the sample size.

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