X-RAY AND OPTICAL PROPERTIES OF GROUPS OF GALAXIES$^1$

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$^1$ Observations reported here were obtained at the F. L. Whipple Observatory and at the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.
ABSTRACT

We have measured 125 redshifts in 31 groups of galaxies observed with Einstein, and have compiled an additional 543 redshifts from the literature. There is a correlation between galaxy surface density and group velocity dispersion, with $\mu \propto \sigma^{1.6\pm0.6}$, but the scatter about this relation is large.

We examine the relationship between the group x-ray luminosity in the 0.3-3.5 keV band and the measured velocity dispersion. Richer groups follow the same relation as rich clusters (cf. Quintana & Melnick 1982) with $L_x \propto \sigma^{4.0\pm0.6}$, but the relation flattens for lower luminosity systems which have velocity dispersions below 300 km s$^{-1}$).

We suggest that the $L_x - \sigma$ relation arises from a combination of extended cluster emission and emission associated with individual galaxies. The x-ray emission for the richer groups is dominated by emission from the intragroup medium, as for the richer clusters; emission from the poorer clusters is dominated by less extended emission associated with the individual group galaxies.

1. INTRODUCTION

Groups of galaxies are one of the most common environments in the universe: most galaxies are members of groups or clusters (Soneira & Peebles, 1978, Ramella et al. 1989, hereafter RGH). Groups trace large-scale structure, and are the primary constituents of large-scale features like the Great Wall (Geller and Huchra 1989, Ramella et al 1990). The distribution of group velocity dispersions is a constraint on models for the formation of large-scale structure (eg. Ueda et al. 1993, Moore et al. 1992).

Catalogs of individual groups provide information about the mass-to-light ratios and evolution of systems of galaxies. Optical data alone can be used to test whether groups of galaxies are relaxed systems. For example, the work of Diaferio et al. (1993) suggests that they are dynamically young. X-ray data can provide a mass-to-light estimate for groups independent of the optical data (Kriss et al. 1983, hereafter KCC, Mulchaey et al. 1993), and the relation between the x-ray and optical properties can provide further clues to the history of the groups and their present state.

Although there have been several studies of the optical properties of groups (RGH, Hickson et al. 1982, Bahcall 1980, Beers et al. 1984, Huchra & Geller 1982, Diaferio et al 1993), and some analyses of the x-ray emission from groups (KCC, Price et al. 1991, hereafter PBDN, Mulchaey et al. 1993, Ponman & Bertram 1993), there has been no attempt to obtain complete optical data for a large set of
systems observed in x-rays.

Here we study a sample of 31 groups and poor clusters observed with the Einstein Observatory. We have collected 668 redshifts for galaxies in the group fields. We use the redshift, galaxy surface number density, and x-ray data to investigate the physical properties of groups. Throughout the paper, we assume \( H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

Section 2.1 contains a discussion of the observations. In section 2.2, we discuss the group selection criteria. Section 2.3 contains the results of the analysis of the optical data. Sections 3.1-3.5 deal with the x-ray data reduction. Finally, in section 4, we compare the optical and x-ray data.

2. OPTICAL DATA

2.1 Group Selection and Spectroscopy

Our sample includes 31 groups of galaxies observed with the Einstein satellite. Of these, 26 “groups” are in 23 fields observed by PBDN, and 5 were observed by KCC. The sample is not statistically complete; the groups were originally selected because they had been observed with the VLA (Burns et al. 1987), or because they contain a centrally dominant galaxy (MKW-AWM groups). A few other groups have been observed with the Einstein satellite. In some cases, we have omitted them from our analysis because we do not have complete redshift information. We omit other groups because they are too nearby to fit within the Einstein field.

For each of these groups, we obtained redshifts for galaxies with \( m_B \leq 15.7 \) within 1.5° of the x-ray pointing centers, corresponding to a radius of \( \sim 2.8 \) Mpc at the redshift of the farthest group (\( z \sim 0.04 \)), and \( \sim 0.4 \) Mpc for the nearest one (\( z \sim 0.005 \)). In all but the two nearest cases, this radius is larger than the typical size of groups objectively selected from a redshift survey (\( r_H \simeq 0.6 \) Mpc, cf. RGH). The angular scale is also slightly larger than the field of view of the Einstein satellite. We chose this angular scale rather than a physical scale because the groups were originally selected on the basis of their angular extent. We examine the group properties within the 1.5° field and within a fixed 0.7 Mpc circle around the x-ray centers. Table 1 lists the new heliocentric radial velocities (\( cz \)).

We measured redshifts of the group galaxies with the photon-counting Reticon systems (Latham 1982) on the Tillinghast Reflector (1.5 m) at the Whipple Observatory or with the blue channel of the MMT spectrograph. We obtain heliocentric radial velocities by cross-correlating object spectra against stellar and galaxy templates (Tonry & Davis 1979, Kurtz et al. 1992), or by fitting a gaussian function to emission lines. The cross-correlation errors are estimated from the width of the correlation peak and its height relative to the noise. If emission lines are present, we estimate the error from the dispersion of velocities determined from individ-
ual emission lines, weighted by the goodness of fit (Tonry & Davis 1979, Kurtz et al. 1992). The average calculated external error for our velocity measurements is $\sim 35 \text{ km s}^{-1}$; the actual external error should be only slightly larger (c.f. Lewis 1983). In all cases we quote heliocentric velocities in the form $v = cz$, where $z$ is the measured spectral redshift.

For each group, table 2 lists the position, mean radial velocity, and number of velocities for galaxies brighter than $m_b = 15.7$ in both the $1.5^\circ$ and $0.7$ Mpc samples. We derive these quantities from a total of 543 redshifts from the literature (Huchra et al. 1992) along with our 125 new measurements. Four of the groups, N56-388, N56-391, N56-394a, and MKW3, are not complete to $m_B = 15.5$; we omit these from the surface number density analysis, but we include them in our x-ray luminosity and velocity dispersion studies. In several cases, there are galaxies fainter than $m_B = 15.7$ with known redshifts in our fields. We include these galaxies in our calculation of the velocity dispersion.

Column 1 of table 2 lists the name of the group; columns 2-4 contain the right ascension of the group centers; columns 5 and 6 list the group center declination. Column 7 tabulates the mean recession velocity for each group and the uncertainty in the measurements derived from the individual measurement uncertainties and a statistical jack-knife procedure (Diaconis and Efron 1983). Columns 8 and 9 and columns 10 and 11 list the number of group members in the $1.5^\circ$ and $0.7$ Mpc samples, respectively. In each case, the first number represents the number of group galaxies known, the second is the number of galaxies with measured redshift and with $m_B \leq 15.7$. Column 12 gives the completeness limit for each group.

Figures 1a-1f show the spatial distribution of the galaxies on the sky, and the position of the 0.7 Mpc circle for all 31 groups. In Figures 1a-1f, the filled circles represent group members; the crosses and triangles represent foreground and background galaxies, respectively.

2.2 Group Membership

Once we have selected the group fields, we define the group “membership”. Objective group selection algorithms extract groups from large-scale surveys by making cuts in projected separation and velocity (RGH). However, one cannot “objectively” select the groups in this way a posteriori.

Our group fields were selected by other workers and do not represent a complete sample. In effect, a selection based on angular size has already been applied. We thus limit ourselves wherever possible to using the velocity separations as an additional membership criterion.

All groups except MKW2, N67-336a and N67-336b can be defined by a velocity cut alone, a consequence of the effective spatial cut made previously to select the group fields. We calculate the velocity dispersion of the central envelope of galaxies.
(defined as all galaxies differing by less than 200 km s\(^{-1}\) from another member). If the separation between an outlier and the nearest assigned member is less than 1.2\(\sigma\), we add the galaxy to the group list. This procedure is insensitive to the minimum \(\sigma\) criterion. We repeat the procedure for all the outliers. Although our procedure differs from the 3\(\sigma\) clipping procedure (Yahil & Vidal 1977), in practice the groups are well separated in redshift space, and the difference between our procedure and 3\(\sigma\) clipping is generally negligible. In only one case, S49-147, the velocity dispersion derived by our method differs from the 3\(\sigma\) clipping velocity dispersion by more than the error in the estimate: for S49-147, inclusion of the outliers as mandated by 3\(\sigma\) clipping yields a velocity dispersion \(\sigma = 422\) km s\(^{-1}\). This higher velocity dispersion is caused by symmetrically placed outliers in redshift space (see figure 2a). These outliers are significantly separated from the well-defined central peak; furthermore, all the outliers lie far from the core of the group (see figure 1a). The lower \(\sigma = 246\) km s\(^{-1}\) probably makes more sense.

Even in cases where there are two groups superimposed on the sky, our procedure is robust provided that the redshift separation between the groups is large enough (cf. N56-394a and N56-394b.) For the two cases where there are overlapping groups – MKW2 and MKW2s, and N67-336a and N67-336b – we use the galaxy positions to make the membership assignments (we do not include MKW2S in our group sample because we lack complete redshift data for it). Because it is virtually impossible to assign the galaxies in the overlap region, we consider only the cores of the groups, defined as circles of 0.45 Mpc about the optical centers of the subclumps (corresponding to the density peaks and listed in table 3). Although this procedure greatly reduces the number of redshifts available for analysis, it reduces the risk of contamination from the neighboring group.

Figures 2a-2f show the radial velocity distributions for galaxies in our 1.5° fields; the group members appear as hatched histograms. Table 4 lists the derived velocity dispersions (corrected for “redshift inflation” in accordance with Danese et al. 1980) of our systems for both the 1.5° (columns 2 and 3) and 0.7 Mpc samples (column 4 and 5). In each case, we calculate the velocity dispersion first using all the available redshifts and then using only those of galaxies brighter than \(m_B = 15.7\). Column 6 lists the group surface number density parameter \(\mu\) (see section 2.3).

With the exception of N45-389, the derived velocity dispersions are generally quite stable, despite the large variations in the number of galaxies in the different samples for a particular group. In the case of N45-389, the difference in the velocity dispersion between the samples might be attributable to an outer envelope of galaxies infalling onto a tightly bound, low velocity dispersion, central core. In other cases where the velocity dispersion varies significantly – N56-369, N56-394b and MKW6a – the number of galaxies used to determine the dispersion is small (3 or 4 galaxies). In these cases the velocity estimates in table 3 are underestimates by as much as a factor of 2, and the 1-D velocity dispersion we compute is a biased estimator of the 3-D velocity dispersion (Diaferio et al. 1993). Fortunately, this bias in the computed velocity dispersions for groups with few redshift measurements affects only a few of the groups, and thus does not affect the conclusions of this
study.

### 2.3 Correlation of Velocity Dispersion and Surface Density

Because our groups were selected according to their angular size, the physical scale of the groups is a function of distance. The procedure for group selection makes it difficult to define a group “radius” a posteriori. We do not yet have sufficient photometric data to determine luminosity functions for the groups. Because of the difficulty of uniformly determining a spatial scale and the uncertainty in the optical luminosity of the groups, derived mass-to-light ratios are indeterminate. We therefore focus on the velocity dispersion and surface density which we can derive from our data.

Although the value for \( N_{gal} \) in table 2 is related to the “richness” of the groups, a proper estimate of the surface number density of bright galaxies in these groups requires a correction for the range in the group redshifts. We need to normalize all the groups to same distance. We count group members brighter than \( m_B = 15.7 \) within the 0.7 Mpc circle (smaller than the 1 Mpc circle chosen by Zabludoff et al. (1993)). We normalize to a fixed distance by assuming that all the groups have the same Schechter luminosity function. We choose a Schechter luminosity function with \( \alpha = -1.2 \) and \( M_* = -19.15 \), and normalize our distances to 130 Mpc. This choice agrees with the normalization of Zabludoff et al. (1993). Where we are not complete to \( m_B = 15.7 \), we extrapolate from the number of galaxies brighter than \( m_B = 15.5 \). To compare our data with Zabludoff et al. (1993), we normalize by the mean ratio of the number of group members within 1.0 Mpc and 0.7 Mpc, \( n(1\text{Mpc})/n(0.7\text{Mpc}) = r \); we use groups where we have a complete survey to 1 Mpc and \( m_B = 15.7 \). This ratio, \( r \), is 1.42. The number densities are not corrected to account for Galactic obscuration.

Figure 3 shows the relationship between the normalized surface density and \( \sigma \) for our groups and for the clusters of Zabludoff et al. (1993). The velocity dispersion is derived using all group galaxies, including those with \( m_B > 15.7 \) (column 3, table 4). The correlation between the surface density of galaxies and velocity dispersion extends across the entire observed range of velocity dispersions \((50 \text{ km s}^{-1} \leq \sigma \leq 1200 \text{ km s}^{-1})\). The best fit relation is

\[
\log(\mu) = -4.3(\pm 1.6) + 1.6(\pm 0.6)\log(\sigma),
\]

with a Q value (Press et al 1993) of 0.25 (Here Q is the probability that the chi-square value of the fit would occur by chance). The fit is quite a bit more robust when we exclude the poor cluster AWM7. AWM7 is the group most affected by galactic absorption, and therefore we probably underestimate the surface density of AWM7 relative to the other groups. Correcting for this effect would improve the fit.
Simple models of groups can account for the observed correlation. For an isothermal sphere, the integrated surface mass density inside a fixed radius follows the relation $\mu \propto \sigma^2$. For a King model, the relation is slightly flatter because the velocity dispersion drops outside the core of the system. A reasonable approximation to a King model gives $\mu \propto \sigma^{1.8-1.9}$. For our sample of poor clusters, the observed slope ($1.6 \pm 0.6$) is certainly consistent with these estimates from simple models.

3. THE X-RAY DATA

3.1 Observations

The 31 “groups” in our sample were observed with the Einstein Observatory Imaging Proportional Counter (IPC). A total of 32 fields were observed, with observation times varying from 400 seconds to 23000 seconds. For a few of the shorter observations, we derive only upper limits for the luminosity, but many of the groups are detected (PBDN, KCC).

We calculate the x-ray luminosities from the Einstein images using the counts in the 0.3-3.5 keV range, which corresponds to Pulse Height Invariant (PI) bins 3-10. We use the optical positions of the group galaxies to check that the x-ray emission is actually associated with the group. To provide the best possible signal-to-noise ratio, we compute the luminosities only in the region where there is a detectable excess over background determined from the radial x-ray surface brightness profile. We thus obtain isophotal luminosities for the groups, rather than fixed-aperture luminosities. This procedure might underestimate the total x-ray luminosity of some of the groups, particularly those with short observation times.

Table 4 lists the x-ray parameters for the observed groups. The second column lists the galactic HI column density (in cm$^{-2}$) in the direction of the groups, derived from the Burstein & Heiles (1983) maps. Column 3 gives the area (in square arcminutes) used in the flux determination. Column 4 gives the mean group redshift. Column 5 gives the background-subtracted counts measured for each group. Column 6 lists the effective exposure time for the Einstein observation. The derived temperature for each group is in column 7. Finally, Columns 8 and 9 tabulate the x-ray luminosities for each group in units of $10^{42}h^{-1}$ ergs s$^{-1}$ for two assumed group temperatures, 1 keV and the temperature derived from the $L_x - T$ relation (Edge & Stewart 1991), respectively.

In general, the groups have x-ray luminosities $\lesssim 10^{42}h^{-1}$ ergs s$^{-1}$. Thus, with very few exceptions, the extraction of the group x-ray emission from the data is quite complex. In many cases, we expect the x-ray maps to be dominated by emission from the individual galaxies. At the distances typical of the poor clusters in the sample (60-90 Mpc), almost all the galaxies have (optical) angular sizes less than an arcminute. The typical resolution for the Einstein IPC is $\sim 1.5\arcmin$. Although the
largest galaxies in the nearer groups will be slightly extended when observed with the Einstein IPC, most of the galaxies under consideration are considerably smaller than the IPC resolution; as a first approximation, we model them as point sources.

3.2 Creating a Point Response Function

Many groups show x-ray emission strongly clumped at locations corresponding to the positions of bright galaxies. A natural interpretation for this phenomenon is that the x-ray emission is just the integrated emission from individual sources inside the galaxies themselves, or possibly from hot gas associated with the interstellar medium of the galaxies (Fabbiano et al. 1992). As a first step in identifying the contribution of individual galaxies to the X-ray emission from the poor clusters, we model the emission from individual galaxies.

The Einstein IPC has a complicated point response function, which depends on both the photon energy and the instrument gain. To simulate these point sources, we follow Mauche (1983): we model the IPC as a convolution of an energy-dependent mirror response function and a (gaussian) voltage gain setting-dependent detector response. For each typical value of the IPC gain setting, we then can create a point response function dependent on the energy spectrum of the incoming x-rays. In order to estimate the effects of the detector response, we use the raw pulse-height channel (PH) data rather than the PI binning.

Because early and late type galaxies have substantially different x-ray spectra, we construct two representative “point sources” per gain setting– one for a spiral galaxy, the other for an elliptical. We use representative x-ray spectra from Fabbiano et al. (1992). Given the energy band and the IPC gain setting, we convolve a gaussian of specific width (Harnden et al. 1984) with an Einstein HRI monochromatic test exposure. After convolving the maps for each channel, we construct a weighted sum of the resulting maps to obtain a model point response function. We also construct model point sources for AGN with known spectra (Wilkes & Elvis 1987) in order to test the validity of the procedure. The resulting image fits the spatial distribution of point sources quite well (figure 4).

The variations in the point spread functions for different spectra are not very large. Typically, the width of the profile varies by $\lesssim 5\%$ FWHM. Variations in gain are a more serious problem. The high voltage gain setting influences the point spread function by changing the correspondence between photon energies and pulse height channel. If we consider the same energy range for all the maps, then we need to consider different pulse-height channels. This problem is especially serious at the low energy end of the x-ray spectrum, because the difference in FWHM between the channel 2 and channel 3 IPC response is $\sim 25\%$. Figure 5 shows the difference in the radial profiles for identical point sources observed with gains of 12, 14, 16, 18. We use these radial profiles to determine whether there is extended x-ray emission associated with the galaxies in the groups.
### 3.3 X-ray Image Reduction

To reduce the full x-ray images, we first subtract a standard background file, scaled according to the count rate in the image away from strong sources. We then multiply by a flat field map to correct for the variation in detector response across the image. We construct an error image from the data assuming Poisson noise and an uncertainty of 25% in the background level determination. Finally, to aid in the identification of low surface brightness features, we smooth the image (and the error map) with a 1.5′ gaussian. We use the unsmoothed images in all the analyses.

Because the Einstein IPC fields often contain sources not associated with the groups, we compare the x-ray map with the observed galaxy distribution to identify the emission associated with the group. We then determine the number of counts associated with the group by summing the emission from the selected regions of the unsmoothed background-subtracted maps.

### 3.4 Group Profiles, Poor vs. Rich Systems

It is interesting to contrast the morphological appearance of high and low density and velocity dispersion groups. For example, figures 6 and 7 compare the profiles for a high velocity dispersion (N67-335==MKW4) and a low velocity dispersion group (MKW10). In both cases, there is a single bright source associated with the group. In MKW10 ($\sigma = 165$ km s$^{-1}$), however, the radial profile of the source is only slightly extended; the excess over the point source profile (the dotted line in figure 6) accounts for only $\sim$12 % of the total emission. In contrast, N67-335 ($\sigma = 476$ km s$^{-1}$) is clearly extended. Here the excess over the point source profile is more than a factor of five. The surface number density of N67-335 ($\mu = 0.748$) is more than twice that of MKW10 ($\mu = 0.305$), as expected from the $\mu - \sigma$ relation.

There is an easily discernible trend in the qualitative nature of x-ray surface brightness distributions for groups: groups with a higher velocity dispersion (and a higher surface density of galaxies) have more extended emission, often centered on the dominant optical galaxy. These systems also tend to have smoother, more regular x-ray surface-brightness contours (AWM4, figure 8), than the less luminous, lower velocity dispersion systems (e.g. S34-111 and S49-138, figures 9, 10). For the lowest velocity dispersion systems ($\sigma \lesssim 200$ km s$^{-1}$), the emission appears to be concentrated almost exclusively around a few bright ($m_B \leq 15.7$) galaxies; the x-ray morphology of these groups is in accordance with our model for the nature of the group emission (see section 3.5).

The x-ray emission for low $\sigma$ groups is roughly consistent with that expected from the individual galaxies. As a check on this model, we added up the best (highest signal-to-noise) observations of groups made with high voltage gain settings of 16 and 18 (N79-286, N67-336a, N56-381, S49-138, and MKW1s). We stack the images to superimpose the center of emission, or, in the case where there seem
to be distinct sources (e.g. S49-138), the centers of emission. Figure 11 plots the radial profile of this “summed image” compared to the point source profile for the same gain. The profile is only slightly extended, showing an excess of $\sim 10\%$ over the point source. Some of this emission can be attributed to the presence of other point sources in the vicinity. In addition, uncertainties in centroiding the superimposed images could account for some of the excess. We estimate that positional uncertainties contribute an uncertainty of $\sim 3\%$ in the point source fit.

3.5 X-Ray Counts-to-Flux Conversion and Temperatures

Because the energy bins are very broad, the x-ray counts-to-flux conversion depends on the input energy spectrum, and thus on the temperature of the groups. Temperatures for the poor clusters have not been well measured, but ROSAT observations (Ramella 1993) indicate that the temperatures are $\sim 1$ KeV.

We calculate the counts-to-flux conversion in two ways. First, we assume all the groups have a temperature of 1 KeV. In a second approach, we extrapolate the $L_x - T$ relation for rich clusters (Edge & Stewart, 1991) to lower luminosities and use the relation to derive a temperature and a luminosity for each group iteratively. This second procedure leads to luminosities which are up to 40% lower at the low luminosity end than the first approach. Some of the poor clusters at the high velocity dispersion end of our sample do have published X-ray temperatures (KCC, Schwartz et al. 1980). To treat all our groups consistently, we use the temperature estimates from the Edge & Stewart relation instead of the measured temperatures. These two approaches agree in all cases to within the published error bars (KCC).

For completeness, Table 5 includes fluxes determined from both approaches; columns 8 and 9 give the x-ray luminosities in the 0.3-3.5 KeV band: column 8 tabulates the luminosity assuming group temperatures of 1 KeV, and column 9 contains the luminosities assuming the derived temperatures (listed in column 7). The difference between these two values is an indication of the systematic uncertainties in the x-ray luminosity measurements.

In figure 12, we plot the x-ray group luminosities (assuming $T=1$ KeV) against the velocity dispersions; for comparison, we also include luminosities and velocity dispersions for some rich clusters (Zabludoff et al. 1993, Struble & Rood 1987). X-ray luminosity and velocity dispersion are obviously correlated. We find

$$\log(L_x) \sim 31.81(\pm 1.67) + 4.0(\pm 0.6) \log(\sigma)$$

(2)

using our groups alone. This result is consistent with the relation derived for rich clusters (Quintana et al. 1982). If we assume the temperatures derived from the $L_x - T$ relation for our groups, we find $L_x(T_g) \propto \sigma^{4.2\pm 0.7}$, not significantly different from (2). However, if we only consider the groups which show emission associated
with individual sources (those with $L_x \leq 1.5 \times 10^{42} h^{-1}$ erg s$^{-1}$), we find a shallower slope, $L_x \propto \sigma^{2.7 \pm 1.3}$, albeit with greater scatter. This flattening occurs regardless of the $L_x - T$ relation assumed.

Because we only calculate luminosities within regions where the emission is stronger than the background, the luminosities we calculate are lower limits: typically we would not detect a diffuse component with $L_x \lesssim 1 - 4 \times 10^{40}$ ergs s$^{-1}$. However, any additional emission only accentuates the deviation of the poor groups from the $L_x - \sigma$ relation defined by the richer systems.

4. DISCUSSION

4.1 $L_x - \sigma$: Observation and Theoretical Considerations

The standard explanation for the observed relation between the x-ray luminosity and the velocity dispersion of rich systems of galaxies is that both quantities depend on the mass of the cluster. Thermal emission from the intracluster gas yields an x-ray luminosity proportional to the square of the gas density. For a constant mass-to-light ratio, the x-ray luminosity is then proportional to the square of the mass of the cluster. If the cluster is a relaxed system, the velocity dispersion is roughly proportional to the square root of the mass. Thus, $L_x \propto \sigma^4$, consistent with the observed slope derived from our group sample ($50 \text{ km s}^{-1} \lesssim \sigma \lesssim 800 \text{ km s}^{-1}$) (figure 12), and the slope previously derived for clusters.

Figure 12 shows that although the rich (high dispersion) groups follow the $L_x - \sigma$ relation defined by clusters quite closely, there appears to be a flattening of the relation for velocity dispersions $\lesssim 300 \text{ km s}^{-1}$. A simple model shows that the increasing relative contribution of the integrated emission from individual galaxies should cause a shallower slope for these lower $\sigma$ systems.

For both spiral and elliptical galaxies there is a correlation between the x-ray and optical luminosity (Fabbiano et al. 1992):

$$L_x(\text{elliptical}) = 3.16 \times 10^{21} L_B^{1.8}$$

and

$$L_x(\text{spiral}) = 2.00 \times 10^{29} L_B^{1.0}$$

where $L_x$ is in erg s$^{-1}$ and $L_B$ is in solar luminosities. There is a large scatter (almost an order of magnitude!) around these relations. If the group luminosity
function is a Schechter luminosity function, the total x-ray luminosity from the group is

\[ L_x(tot) = r \mu_o \int_{X_{min}}^{\infty} x^{-\alpha} e^{-x} (f_{sp} L_x(spi, x) + (1 - f_{sp}) L_x(ell, x)) \]  

where \( x = L/L^* \), \( r \) is the correction factor from section 2.3, and \( \mu_o \) is a fiducial surface number density. The lower limit of integration is \( X_{min} = L_{min}/L^* \) and \( L_{min} \) is the minimum galaxy luminosity (which we take to be \( M_B = -13 \)).

Our measured surface number density is

\[ \mu = \mu_o \int_{X_o}^{\infty} x^{-\alpha} e^{-x} dx \]  

where \( X_o = L_o/L^* \) and \( L_o \) is the luminosity corresponding to our limiting magnitude of \( m_B = 15.7 \) at a distance of 130 Mpc (\( M_o = -20.19 \)). We can then write (3) in terms of \( \mu \):

\[ L_x(tot) = r \mu \left( \frac{\int x^{-\alpha} e^{-x} (f_{sp} L_x(spi, x) + (1 - f_{sp}) L_x(ell, x))}{\int x^{-\alpha} e^{-x} dx} \right). \]  

This expression can be integrated numerically given \( \alpha = -1.2 \) and \( L^* = 3.5 \times 10^9 L_\odot \) (see section 2.3). To solve for \( L_x \) we need a value for the spiral fraction \( f_{sp} \): we use a rough median value for the spiral fraction observed in our groups \( f_{spi} = 0.66 \). The range of spiral fractions in our groups introduces an extra uncertainty in the \( L_x - \mu \) relation. Calculations show that varying \( f_{sp} \) from 0.4 to 0.9 introduces a factor of 3 variation in the normalization of the \( L_x - \mu \) relation.

In order to relate this theoretical prediction to a model of the \( L_x - \sigma \) relation, we first fix the normalization of the \( \mu - \sigma \) relation using our observed correlation (equation (1)). Thus for groups where the galaxy contribution is dominant, we expect \( L_x \sim 4.5 \times 10^{36} \sigma^{1.6} \) ergs s\(^{-1}\). The dotted lines in figure 11 show the range of luminosities expected as a function of \( \sigma \), taking into account the observed scatter in the \( L_x - L_{opt} \) relation for galaxies, and the uncertainty in spiral fraction. The flattening of the \( L_x - \sigma \) relation for our groups occurs just where emission from individual galaxies should become important—at \( \sigma \sim 300 \) km s\(^{-1}\).

We construct our heuristic model by comparing the group data with that for rich clusters at high \( \sigma \), and with x-ray properties of individual galaxies at low \( \sigma \). In this picture, groups of galaxies should show intermediate properties, with a transition between “galaxy-dominated” and “intra-cluster medium dominated” properties occurring at \( \sigma \sim 300 \) km s\(^{-1}\). It is still a challenge to understand what (if any) underlying physics determines this transition.
5. CONCLUSIONS

We have collected a uniform data set, consisting of velocity dispersions, surface number densities, and x-ray luminosities for 31 groups of galaxies. We find a relation between the surface galaxy number density and velocity dispersion, \( \mu \propto \sigma^{1.6 \pm 0.6} \). For comparison, for an isothermal sphere the relation is \( \mu \propto \sigma^{2} \), and for a King model \( \mu \propto \sigma^{1.8 \pm 1.9} \).

The x-ray luminosity - velocity dispersion relation for rich clusters continues to poorer systems as well, with \( L_x \propto \sigma^{4.0 \pm 0.6} \). For the groups with \( \sigma \lesssim 300 \, \text{km} \, \text{s}^{-1} \), however, there is a significant flattening in the relation: \( L_x \propto \sigma^{2.7 \pm 0.3} \). We suggest that this change in slope represents the transition between “ICM dominated” and “galaxy” dominated systems. This model is consistent with the x-ray morphology of the groups; for \( \sigma \geq 300 \, \text{km} \, \text{s}^{-1} \) the groups have smooth, extended x-ray surface brightness profiles. For \( \sigma \lesssim 300 \, \text{km} \, \text{s}^{-1} \) the group emission is consistent with a collection of “point sources” associated with the individual galaxies in the groups. Unfortunately, the x-ray data available for the poor groups is not sufficient to determine whether the intracluster medium of these groups is less abundant, or is just too cool and/or diffuse to be seen. Longer observations with imaging x-ray telescopes such as ROSAT or AXAF should allow us to answer this question. Because we only calculate luminosities in regions where the emission is greater than the background, we might be underestimating the luminosity of our faintest groups. However, this only increases the flattening of the \( L_x - \sigma \) relation, because the error does not depend on the group luminosity.

It would be interesting to investigate whether there are other quantities which show differences between high velocity dispersion and low velocity dispersion systems. For example, studies of the baryon content of the Coma cluster (White et al. 1993) suggest that the baryon fraction in clusters is substantially higher than expected from primordial nucleosynthesis limits. Blumenthal et al. (1984) have suggested that richer MKW/AWM groups also have higher baryon fractions. However, Mulchaey et al. (1993) have found a much lower baryon fraction for at least one poorer group. It would be useful to extend this calculation to smaller systems by acquiring accurate photometric data to improve estimates of mass-to-light ratios. Detailed photometric studies along with redshifts for even fainter members would yield information about the baryon fraction in groups, a potentially important constraint on models of galaxy and structure formation (White et al. 1993).

We thank Massimo Ramella, Antonaldo Diaferio, Joe Mohr and Ann Zabludoff for helpful and stimulating discussions. We thank M. Ramella for providing information about ROSAT observations in advance of publication. We thank S. Tokarz for help with the data reduction. We thank the anonymous referee for useful criticism and suggestions. This research funded in part by NASA grant NAGW-201, and by the Smithsonian Institution.
Figure Captions

Figures 1a-f: The positions of galaxies in the 1.5° fields; group members are denoted by filled circles, foreground galaxies by crosses, and background galaxies by open triangles. The large circles indicate regions with in 0.7 Mpc of the x-ray center.

Figures 2a-f: Velocity histograms for the 1.5° group fields. The hatched histogram represents the group members, the open histogram shows the interlopers (or, in the case of N67-336a, N67-336b and MKW2, the galaxies not in the core of the group).

Figure 3: A plot of the surface density of galaxies (section 2.3) versus velocity dispersion for the groups in our sample (filled circles) and rich clusters from the Zabludoff et al. (1993) sample (stars).

Figure 4: A comparison of the radial profile of 3C273 as observed by Einstein with the model profile for a AGN-spectrum point source.

Figure 5: A comparison of model point-source profiles for an elliptical galaxy measured at 4 different gain values: 18 (dashed dotted line), 16 (large dashed line), 14 (short dashed line) and 12 (solid line). The radius is in units of 8-arcsecond pixels.

Figure 6: Radial profile for the x-ray emission from the group MKW10 (squares) and a point source model (elliptical) normalized to match at a radius of 24 arcseconds. The error bars are 1-σ errors. The excess above the point source model at larger radii accounts for ∼12% of the total flux.

Figure 7: Radial profile for the emission from the group N67-335 (=MKW4) and for a point source model normalized as in figure 6.

Figure 8: A contour plot of the Einstein x-ray map for the group AWM4. The contour levels represent 8, 15, 30, 60, and 90 percent of the peak intensity, respectively. The crosses represent the optical positions of $m_{B(0)} \leq 15.7$ galaxies in the group field; the $x$ marks the position of the cD galaxy.

Figure 9: A contour plot of the Einstein x-ray map for the group S34-111. The contour levels represent 30, 60 and 90 percent of the peak intensity. The clump of
emission centered around pixel (250,100) is associated with a background galaxy.

Figure 10: A contour plot of the Einstein x-ray map for the group S49-138. The contour levels represent 15, 30, 60 and 90 percent of the peak intensity. The emission appears to be concentrated around the three central galaxies.

Figure 11: radial profile of the combined x-ray emission for lower dispersion groups ($\sigma \lesssim 200$ km s$^{-1}$) in our study.

Figure 12: A plot of the x-ray luminosity (for $T_g = 1$ Kev) versus velocity dispersion $\sigma$ for our groups (filled circles), rich clusters from figure 3 (filled stars) and other clusters from Rood & Struble (1987) (open stars). The five-pointed stars show Rosat observations of groups by Mulchaey et al. (1993) and Ponman & Bertram (1993). The dotted and solid lines outline the range of luminosities expected from the integrated emission from individual galaxies assuming $\mu = 3.5 \times 10^{38} \sigma^{1.6}$, and $\mu = 3.6 \times 10^{34} \sigma^{1.6}$, respectively.
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