X-ray Properties of Groups of Galaxies

John S. Mulchaey

*The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara St.,
Pasadena, CA 91101; e-mail: mulchaey@ociw.edu*

Key Words   intragroup medium, temperature, metallicity, masses, dark matter

■ **Abstract**   ROSAT observations indicate that approximately half of all nearby
groups of galaxies contain spatially extended X-ray emission. The radial extent of
the X-ray emission is typically 50–500 h_{100}^{-1} kpc or approximately 10–50% of the
virial radius of the group. Diffuse X-ray emission is generally restricted to groups
that contain at least one early-type galaxy. X-ray spectroscopy suggests the emission
mechanism is most likely a combination of thermal bremsstrahlung and line emission.
This interpretation requires that the entire volume of groups be filled with a hot, low-
density gas known as the intragroup medium. ROSAT and ASCA observations indicate
that the temperature of the diffuse gas in groups ranges from approximately 0.3 keV
to 2 keV. Higher temperature groups tend to follow the correlations found for rich
clusters between X-ray luminosity, temperature, and velocity dispersion. However,
groups with temperatures below approximately 1 keV appear to fall off the cluster
L_X-T relationship (and possibly the L_X-σ and σ-T cluster relationships, although
evidence for these latter departures is at the present time not very strong). Deviations
from the cluster L_X-T relationship are consistent with preheating of the intragroup
medium by an early generation of stars and supernovae.

There is now considerable evidence that most X-ray groups are real, physical sys-
tems and not chance superpositions or large-scale filaments viewed edge-on. Assuming
the intragroup gas is in hydrostatic equilibrium, X-ray observations can be used to es-
timate the masses of individual systems. ROSAT observations indicate that the typical
mass of an X-ray group is $\sim 10^{13}\,h_{100}^{-1}\,M_\odot$ out to the radius to which X-ray emission
is currently detected. The observed baryonic masses of groups are a small fraction of
the X-ray determined masses, which implies that groups are dominated by dark matter.
On scales of the virial radius, the dominant baryonic component in groups is likely the
intragroup medium.

1.   INTRODUCTION

Redshift surveys of the nearby universe indicate that most galaxies occur in small
groups (e.g. Holmberg 1950, Humason, Mayall & Sandage 1956, de Vaucouleurs
1965, Materne 1979, Huchra & Geller 1982, Geller & Huchra 1983, Tully 1987,
Nolthenius & White 1987). Despite diligent work in this area over the last two
decades, the nature of poor groups is still unclear. Dynamical studies of groups

289

are generally hampered by small number statistics: a typical group contains only a few luminous galaxies. For this reason, the dynamical properties of any individual group are always rather uncertain. In fact, many cataloged groups may not be real physical systems at all (e.g. Hernquist et al 1995, Frederic 1995, Ramella et al 1997), but rather chance superpositions or large-scale structure filaments viewed edge-on. Given the small number of luminous galaxies in a group, the prospects for uncovering the nature of these systems from studying the galaxies alone seem rather bleak.

The discovery that many groups are X-ray sources has provided considerable new insight into these important systems. X-ray observations indicate that about half of all poor groups are luminous X-ray sources. In many cases, the X-ray emission is extended, often beyond the optical extent of the group. X-ray spectroscopy suggests the emission mechanism is a combination of thermal bremsstrahlung and line emission from highly ionized trace elements. The spatial and spectral properties of the X-ray emission suggest the entire volume of groups is filled with hot, low-density gas. This gas component is referred to as the intragroup medium, in analogy to the diffuse X-ray emitting intracluster medium found in rich clusters (e.g. Forman & Jones 1982).

To first order, groups can be viewed as scaled-down versions of rich clusters. Many of the fundamental properties of groups, such as X-ray luminosity and temperature, are roughly what one expects for a "cluster" with a velocity dispersion of several hundred kilometers per second. However, some important physical differences exist between groups and clusters. The velocity dispersions of groups are comparable to the velocity dispersions of individual galaxies. Therefore, some processes such as galaxy-galaxy merging are much more prevalent in groups than in clusters. Other mechanisms that are important in the cluster environment, such as ram-pressure stripping and galaxy harassment, are not expected to be important in groups. The spectral nature of the X-ray emission is also somewhat different in groups than in clusters. At the typical temperature of the intracluster medium, almost all abundant elements are fully ionized, and the X-ray emission is dominated by a thermal bremsstrahlung continuum. At the lower temperatures of groups, most of the trace elements retain a few atomic electrons, and line emission dominates the observed X-ray spectrum. Thus, while the cluster analogy is a useful starting point, detailed studies of groups as a class are also important. Although no strict criterion exists for separating groups from poor clusters, for the context of this article I focus on systems with velocity dispersions less than about 500 km/s.

The idea that poor groups might contain diffuse hot gas dates back to the classic Kahn & Woltjer (1959) paper on the "timing mass" of the Local Group. Kahn & Woltjer (1959) found that the mass of the Local Group far exceeded the visible stellar mass and suggested the bulk of the missing mass was in the form of a warm, low-density plasma. Although it is now generally believed that the Local Group is dominated by dark matter, Kahn & Woltjer's estimates for the properties of the intragroup medium are remarkably similar to more recent estimates. More than a

decade after Kahn & Woltjer, the idea of diffuse gas in the Local Group and other groups was revisited by Oort (1970), Ruderman & Spiegel (1971), Hunt & Sciama (1972), and Silk & Tarter (1973).

The earliest claims for X-ray detections of groups came from the non-imaging X-ray telescopes Uhuru, Ariel 5, and HEAO 1 in the 1970s. Cooke et al (1978) produced a catalog (known as the 2A) of 105 bright X-ray sources from the Leicester Sky Survey Instrument on Ariel 5. Based on positional coincidences, Cooke et al (1978) suggested the identification of seven X-ray sources in the 2A catalog as groups of galaxies. Subsequent observations showed that several of these X-ray sources were variable, indicating they were actually active galaxies within the group (Ricker et al 1978, Ward et al 1978, Griffiths et al 1979). However, several of the remaining objects in Cooke et al (1978) were later shown to be poor clusters (Schwartz et al 1980).

X-ray studies of lower-mass systems received a major boost with the launch of the Einstein Observatory in November 1978. Einstein observations firmly established that some poor clusters with bright central galaxies (i.e. MKW and AWM clusters; Morgan et al 1975, Albert et al 1977) were X-ray sources (Kriss et al 1980, 1983, Burns et al 1981, Price et al 1991, Dell'Antonio et al 1994). The X-ray luminosities of these poor clusters range from several times 10^{41} ergs s^{-1} h$_{100}$$^{-2}$ up to several times 10^{43} ergs s^{-1} h$_{100}$$^{-2}$. The X-ray emission in these poor clusters was shown to be extended (out to radii as great as 0.5 h$_{100}$$^{-1}$ Mpc) with temperatures in the range T $\sim$1–5 keV. Although most of these systems are somewhat richer than the typical groups considered in this review, these Einstein observations clearly demonstrated that diffuse X-ray emission was not restricted to rich clusters.

Several attempts were also made to study even poorer galaxy systems with Einstein. Biermann and collaborators detected extended emission in two nearby elliptical-dominated groups (Biermann et al 1982; Biermann & Kronberg 1983). In both cases, the X-ray emission was centered on the dominant galaxy. For the NGC 3607 group, Biermann et al (1982) concluded that the X-ray emission most likely originated from a hot, intergalactic gas because it was extended on scales larger than the galaxy. (Biermann et al estimate a Gaussian width for the X-ray emission of $4.7' \approx 13$ h$_{100}$$^{-1}$ kpc.) From a rough fit to the X-ray spectrum, a temperature of $\approx 5 \times 10^6$ K and an X-ray luminosity of 2×10^{40} h$_{100}$$^{-2}$ ergs s^{-1} was found. Following their discovery of X-ray emission in the NGC 3607 group, Biermann & Kronberg (1983) found a similar component in the NGC 5846 group. The Einstein Observatory was also used to study the X-ray properties of compact groups. Bahcall et al (1984) studied five compact groups, including four from Hickson's (1982) catalog. Three of the compact groups were detected with Einstein. The Einstein exposure times for these groups were very short, resulting in only $\sim$20–60 net counts in the X-ray detected cases. Bahcall et al (1984) noted that the X-ray luminosities of two of the groups were of order $\sim 10^{42}$ ergs s^{-1} h$_{100}$$^{-2}$, much higher than the X-ray emission expected from the member galaxies alone. The emission was also extended in these two groups, and in the case of Stephan's

Quintet, the shape of the X-ray spectrum was unlike that expected from individual galaxies. These X-ray properties led Bahcall et al (1984) to conclude that the X-ray emission likely originated in a hot intragroup gas in at least two of the five groups they studied. Thus, although it was not possible to unambiguously separate a diffuse component from galaxy emission with Einstein, there were strong indications that intragroup gas was likely present in some groups.

2.   X-RAY TELESCOPES

While there were hints from Einstein observations that some groups of galaxies might contain a hot intragroup medium, it was not until the 1990s that the presence of diffuse gas in groups was firmly established. Group studies were aided by the launch of two important X-ray telescopes, ROSAT (the ROentgen SATellite) and ASCA (Advanced Satellite for Cosmology and Astrophysics). Both of these telescopes were capable of simultaneous X-ray imaging and spectroscopy in the energy range appropriate for poor groups. In addition, the field of view for both telescopes was large enough that nearby groups could effectively be studied.

2.1   ROSAT

ROSAT consisted of two telescopes. The X-ray telescope (Aschenbach 1988) was sensitive to photons in the energy range of 0.1–2.4 keV, whereas the Wide Field Camera (Wells et al 1990) covered the energy range 0.070–0.188 keV. The relatively high luminosity of the X-ray background combined with the strong effects of absorption by the Galaxy limited the study of diffuse extragalactic gas with the Wide Field Camera. Therefore, this instrument was not useful for studies of groups and will not be discussed further. Two different kinds of detectors were used with the X-ray telescope: the Position Sensitive Proportional Counter (PSPC) and the High Resolution Imager (HRI). ROSAT was flown with two nearly identical PSPC detectors (Pfeffermann et al 1988). The low internal background, large field of view, and good sensitivity to soft X-rays made the PSPC detectors ideal for studying X-ray emission from groups. The PSPC detectors also had modest energy resolution, allowing the spectral properties of the X-ray emission to be studied. Although the ROSAT HRI provided higher spatial resolution than the PSPC detectors ($\sim 5''$ versus $\sim 25''$ for an on-axis source), the internal background of the HRI was high enough that the low surface brightness diffuse emission found in groups could in general not be studied with this instrument. Therefore, most ROSAT studies of groups were performed with the PSPC.

The ROSAT mission consisted of two main scientific phases. The first was a six-month, all-sky survey (Voges 1993) performed with one of the PSPC detectors (until that detector was destroyed during an accidental pointing at the Sun in January 1991). The mean exposure time for the all-sky survey was approximately 400 seconds. Following the completion of the survey, ROSAT was operated in

so-called "pointed mode"—that is, with longer pointings at individual targets. Typical exposure times during the pointed mode of the mission were in the range 5000 to 25,000 seconds, or roughly 10 to 50 times longer than the all-sky survey exposures. Although the pointed mode of the ROSAT mission lasted until early 1999, the second PSPC detector ran out of gas in late 1994, effectively ending studies of diffuse emission in groups.

2.2   ASCA

ASCA, a joint Japanese–United States effort, was launched in early 1993. ASCA consists of four identical grazing-incident X-ray telescopes each equipped with an imaging spectrometer (Tanaka et al 1994). The focal plane detectors are two CCD cameras (known as the Solid-State Imaging Spectrometers, or SIS; Gendreau 1995) and two gas scintillation imaging proportional counters (Gas Imaging Spectrometer, or GIS; Ohashi et al 1996). The SIS detectors have superior energy resolution, whereas the GIS detectors provide a larger field of view. The angular resolution of ASCA is considerably worse than that of ROSAT, with a half power diameter of approximately $3'$. However, ASCA's spectral resolution is much higher than that of the ROSAT PSPC ($E/\Delta E \sim 20$ for the SIS at 1.5 keV versus $E/\Delta E \sim 3$ for the PSPC), so this instrument has primarily played a role in the study of the spectral properties of the intragroup gas. Although the detectors aboard ASCA have undergone serious degradation, this mission is expected to remain operational until sometime in the year 2000.

3.   PROPERTIES OF THE INTRAGROUP MEDIUM

3.1   First ROSAT Results

The great potential of ROSAT for group studies was demonstrated in early papers by Mulchaey et al (1993) and Ponman & Bertram (1993). Each of these papers presented a detailed look at the X-ray properties of an individual group. Mulchaey et al (1993) studied the NGC 2300 group, a poor group dominated by an elliptical-spiral pair. The X-ray emission in the NGC 2300 group is not centered on any particular galaxy, but is instead offset from the elliptical galaxy NGC 2300 by several arcminutes. The X-ray emission can be traced to a radius of at least $\sim$150 h_{100}^{-1} kpc ($\sim 25''$). Ponman & Bertram (1993) studied Hickson Compact Group 62 (HCG 62). In this case, the X-ray emission is extended to a radius of at least 210 h_{100}^{-1} kpc ($\sim 18''$). Although the presence of intragroup gas had been suggested by earlier Einstein observations, these ROSAT PSPC results were the first to unambiguously separate a diffuse component related to the group from emission associated with individual galaxies. The intragroup medium interpretation was also supported by the ROSAT PSPC spectra, which are well-fit by a thermal model with a temperature of approximately 1.0 keV ($\sim 10^7$ K). The ROSAT PSPC spectrum of HCG 62 contained enough counts that Ponman & Bertram (1993)

could also derive a temperature profile for the gas. Ponman & Bertram (1993) found evidence for cooler gas near the center of the group, which they interpreted as evidence for a cooling flow. Many of the X-ray properties of the NGC 2300 group and HCG 62 are consistent with the idea of these systems being scaled-down versions of more massive clusters.

The early ROSAT observations of groups also provided some surprises. For both groups, the gas metallicity derived from the X-ray spectra was much lower than the value found for rich clusters ($\sim$6% solar for NGC 2300 and $\sim$15% solar for HCG 62, compared with $\sim$20–30% solar found for clusters; Fukazawa et al 1998). The X-ray data were also used to estimate the total masses of the groups. In each case, the mass of the group is approximately $10^{13}\,h_{100}{}^{-1}\,M_\odot$. Comparing the total mass as measured by the X-ray data with the total mass in observed baryons, Mulchaey et al (1993) and Ponman & Bertram (1993) concluded that the majority of mass in these groups is dark. In the case of the NGC 2300 group, Mulchaey et al (1993) estimated a baryon fraction that was low enough to be consistent with $\Omega = 1$ and the baryon fraction predicted by standard big bang nucleosynthesis. However, subsequent analysis of the ROSAT PSPC data suggests the true baryon fraction is higher in this group (David et al 1995, Pildis et al 1995, Davis et al 1996).

3.2   ROSAT Surveys of Groups

Unfortunately, the results of Mulchaey et al (1993) and Ponman & Bertram (1993) came late enough in the lifetime of the ROSAT PSPC that large systematic follow-up surveys of groups were not carried out with this instrument. However, the ROSAT PSPC observed many galaxies during its lifetime, and because most galaxies occur in groups, many groups were observed serendipitously. Furthermore, the field of view of the PSPC was large enough that many groups were also observed when the primary target was a star, an active galaxy, or a QSO. In the end, over 100 nearby groups were observed by the ROSAT PSPC during its lifetime, and most of our current understanding of the X-ray properties of groups comes from this dataset.

The existence of an excellent data archive has led to many X-ray surveys of groups using ROSAT PSPC data (Pildis et al 1995, David et al 1995, Doe et al 1995, Saracco & Ciliegi 1995, Mulchaey et al 1996a, Ponman et al 1996, Trinchieri et al 1997, Mulchaey & Zabludoff 1998, Helsdon & Ponman 2000; Mulchaey et al 2000). These surveys indicate that not all poor groups contain an X-ray—emitting intragroup medium. The exact fraction of groups that contain hot intragroup gas has been difficult to quantify because of biases in the sample selection. For example, many of the samples used in archival surveys contain groups that were a priori known to be bright X-ray sources or were likely to be bright X-ray sources based on morphological selection (such as a high fraction of early-type galaxies). These samples are almost certainly not representative of poor groups in general. Furthermore, the term "X-ray detected" has a variable meaning

in the literature; some authors use this term only when a diffuse, extended X-ray component (i.e. intragroup medium) is present, whereas others also include cases when emission is associated primarily with the individual galaxies.

There has been considerable interest in the Hickson Compact Groups (HCGs; Hickson 1982; for a review see Hickson 1997). The short crossing times implied for these systems has led some authors to suggest the HCGs are chance alignments of unrelated galaxies within looser systems (Mamon 1986, Walke & Mamon 1989), bound configurations within loose groups (Diaferio et al 1994, Governato et al 1996) or filaments viewed edge-on (Hernquist et al 1995). X-ray observations can potentially help distinguish between these various scenarios (Ostriker et al 1995; Diaferio et al 1995). Ebeling et al (1994) detected eleven HCGs in the ROSAT All-Sky Survey (RASS) data. For some of the detections, the X-ray emission was clearly extended and thus consistent with hot intragroup gas. However, in other cases the sensitivity of the RASS was not good enough to determine the nature of the X-ray emission. Still, Ebeling et al's sample was the first to suggest a correlation between the presence of X-ray emission and a high fraction of early-type galaxies in groups. Pildis et al (1995) and Saracco & Ciliegi (1995) each analyzed ROSAT pointed-mode observations of 12 HCGs (there was considerable overlap in these two samples). Both surveys found that approximately two-thirds of the HCGs were X-ray detected, although in many cases the X-ray emission could not be unambiguously attributed to intragroup gas. (Note also that many of the X-ray detections in these two surveys overlapped with Ebeling et al's earlier RASS detections.) A much more complete study of the HCGs was presented by Ponman et al (1996). This survey combined pointed ROSAT PSPC observations with ROSAT All-Sky Survey data to search for diffuse gas in 85 HCGs. These authors detected extended X-ray emission in ~26% (22 of 85 groups) of the systems studied and inferred that ~75% of the HCGs contain a hot intragroup medium (when one corrects for the detection limits of the observations). Although this is intriguing, some caution must be expressed regarding the Ponman et al (1996) results. Given the compactness of these groups, the nature of the X-ray emission in some of the detected HCGs is far from clear. For example, although Stephan's Quintet (HCG 92) is extended in the ROSAT PSPC data (Sulentic et al 1995), a higher-resolution ROSAT HRI image suggests that most of the extended emission is associated with a shock feature and not with a smooth intragroup gas component (Pietsch et al 1997). Thus, some of the detections in the Ponman et al (1996) survey may not be related to an intragroup medium at all.

Many of the problems inherent to the study of compact groups can be avoided with loose groups. Helsdon & Ponman (2000) studied a sample of 24 loose groups from the catalog of Nolthenius (1993) and found that half of the systems contain intragroup gas. Mulchaey et al (2000) detected diffuse gas in 27 of 57 groups selected from redshift surveys (including the Nolthenius catalog). Both of these studies relied on fairly deep ROSAT pointings and therefore are sensitive to gas down to low X-ray luminosities ($\sim 5 \times 10^{40}\ h_{100}^{-2}$ ergs s^{-1}). The majority of the groups in both Helsdon & Ponman (2000) and Mulchaey et al (2000)

were observed serendipitously with the ROSAT PSPC. Based on their velocity dispersions and morphological composition, these samples are fairly representative of groups in nearby redshift surveys. Therefore, these surveys suggest that ∼50% of nearby optically-selected groups contain a hot X-ray–emitting intragroup medium.

ROSAT All-Sky Survey (RASS) data have also played an important role in our understanding of the X-ray properties of groups. While the RASS observations are generally not very deep, the nearly complete coverage of the sky allows for larger samples to be studied than is possible with the pointed mode data alone. Henry et al (1995) used the RASS data in the region around the north ecliptic pole to define the first X-ray selected sample of poor groups. The survey by Henry et al (1995) was sensitive to all groups more luminous than ∼2.3×10^{41} h_{100}^{-2} ergs s^{-1}. Although their sample was rather small (8 groups), Henry et al (1995) were able to show that X-ray–selected groups lie on the smooth extrapolation of the cluster X-ray luminosity and temperature functions. The X-ray selected groups also have lower spiral fractions than typical optically- selected groups, which may suggest that X-ray selection produces a more dynamically evolved sample of groups (Henry et al 1995).

The RASS data have also been used to study optically-selected group samples. Burns and collaborators have devoted considerable effort into studying the X-ray properties of the WBL poor clusters and groups (White et al 1999), which were selected by galaxy surface density. One of the more important results from these studies is the derivation of the first X-ray luminosity function for an optically selected sample of groups and poor clusters (Burns et al 1996). The luminosity function derived by Burns et al (1996) is a smooth extrapolation of the rich cluster X-ray luminosity function and is consistent with the luminosity function Henry et al (1995) derived from their X-ray–selected sample of groups. Follow-up work on some of the brighter sources in the WBL catalog indicates that many of these objects are more massive than typical groups with gas temperatures of 2–3 keV (Hwang et al 1999). These systems are important because they represent the transition objects between poor groups and rich clusters.

Mahdavi et al (1997, 2000) used the RASS database to study the X-ray properties of a large sample of groups selected from the CfA redshift survey (Ramella et al 1995). After accounting for selection effects, Mahdavi et al (2000) estimate that ∼40% of the groups are extended X-ray sources. From these detections, the authors derive a relationship between X-ray luminosity and velocity dispersion that is much shallower than is found for rich clusters (see Section 4.2). They suggest that this result is consistent with the X-ray emission in low velocity dispersion groups being dominated by intragroup gas bound to the member galaxies as opposed to the overall group potential. Unfortunately, the RASS observations of groups typically contain very few counts, so detailed spatial studies of the emission are not possible with this dataset. A much deeper X-ray survey of an optically-selected group sample like the one used in Mahdavi et al (2000) would be very useful and should be a priority for future X-ray missions.

## 3.3   Spatial Properties of the Intragroup Medium

3.3.1 X-Ray Morphologies   The morphology of the X-ray emission can provide important clues into the nature of the hot gas. There is a considerable range in the observed X-ray morphologies of groups. X-ray luminous ($L_X > 10^{42} h_{100}^{-2} erg\, s^{-1}$) groups tend to have somewhat regular morphologies (see Figure 1). The total extent of the X-ray emission in these cases is often beyond the optical extent of the group as defined by the galaxies. The peak of the X-ray emission is usually coincident with a luminous elliptical or S0 galaxy, which tends to be the most optically luminous group member (Ebeling et al 1994, Mulchaey et al 1996a, Mulchaey & Zabludoff 1998). The position of the brightest galaxy is also indistinguishable from the center of the group potential, as defined by the mean velocity and projected spatial centroid of the group galaxies (Zabludoff & Mulchaey 1998). Therefore, the brightest elliptical galaxy lies near the dynamical center of the group. There is also a tendency for the diffuse X-ray emission to roughly align with the optical light of the galaxy in many cases (Mulchaey et al 1996a, Mulchaey & Zabludoff 1998). These morphological characteristics are similar to those found for rich clusters containing cD galaxies (e.g. Rhee et al 1992, Sarazin et al 1995, Allen et al 1995).

At lower luminosities, more irregular X-ray morphologies are often found (see Figure 2). In these cases, the X-ray emission is not centered on one particular galaxy, but rather is distributed around several galaxies. Low X-ray luminosity groups also tend to have lower gas temperatures. Dell'Antonio et al (1994) and Mahdavi et al (1997) suggested that the change in X-ray morphologies at low X-ray luminosities indicates a change in the nature of the X-ray emission. They proposed a "mixed-emission" scenario where the observed diffuse X-ray emission originates from both a global group potential and from intragroup gas in the potentials of individual galaxies. In this model, the latter component becomes dominant in low-velocity dispersion systems. This model is consistent with the fact that the X-ray emission is distributed near the luminous galaxies in many of the low-luminosity systems. Another possible source of diffuse X-ray emission in the low-luminosity systems might be gas that is shock-heated to X-ray temperatures by galaxy collisions and encounters within the group environment. This appears to be the case in HCG 92, where the diffuse X-ray emission comes predominantly from an intergalactic feature also detected in radio continuum maps (Pietsch et al 1997). Given that many of the groups with irregular X-ray morphologies are currently experiencing strong galaxy-galaxy interactions (e.g. HCG 16, HCG 90), shocks may be important in many cases. Regardless of the exact origin of the gas, the clumpy X-ray morphologies suggest that the X-ray gas may not be virialized in these cases.

3.3.2 Spatial Extent   To estimate the extent of the hot gas, the usual method is to construct an azimuthally-averaged surface brightness profile and determine at what radial distance the emission approaches the background value. For most rich
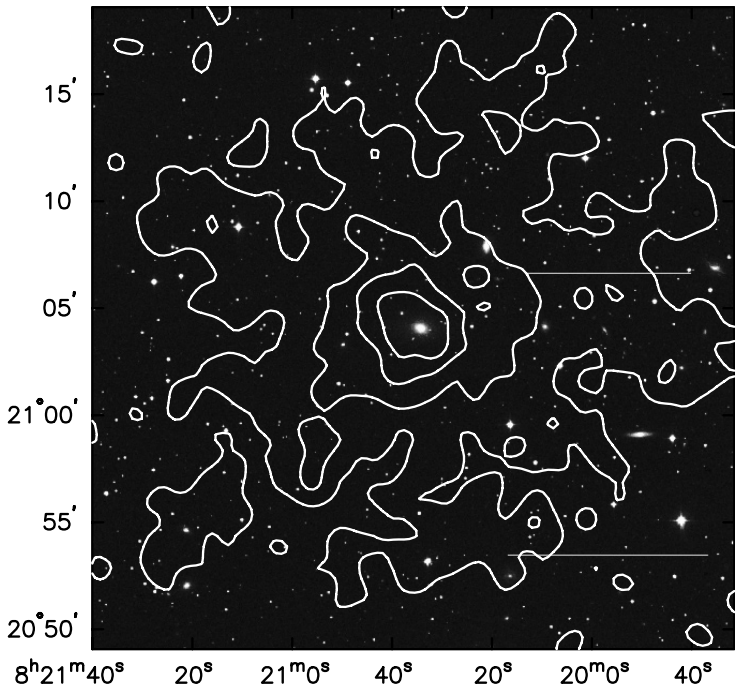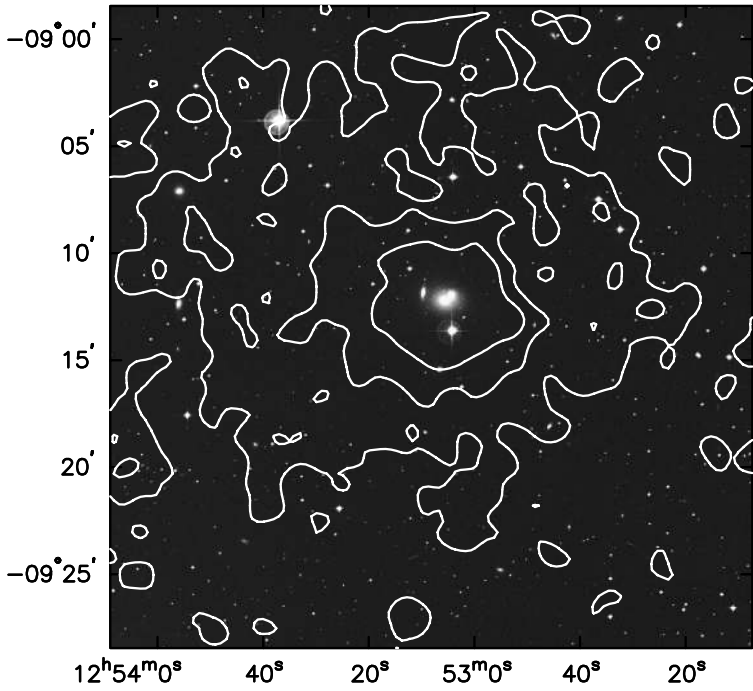
Figure 1 Contour map of the diffuse X-ray emission as traced by the ROSAT PSPC in HCG 62 (*top*) and the NGC 2563 group (*bottom*) overlayed on the STScI Digitized Sky Survey. The X-ray data have been smoothed with a Gaussian profile of width 30″. The coordinate scale is for epoch J2000.
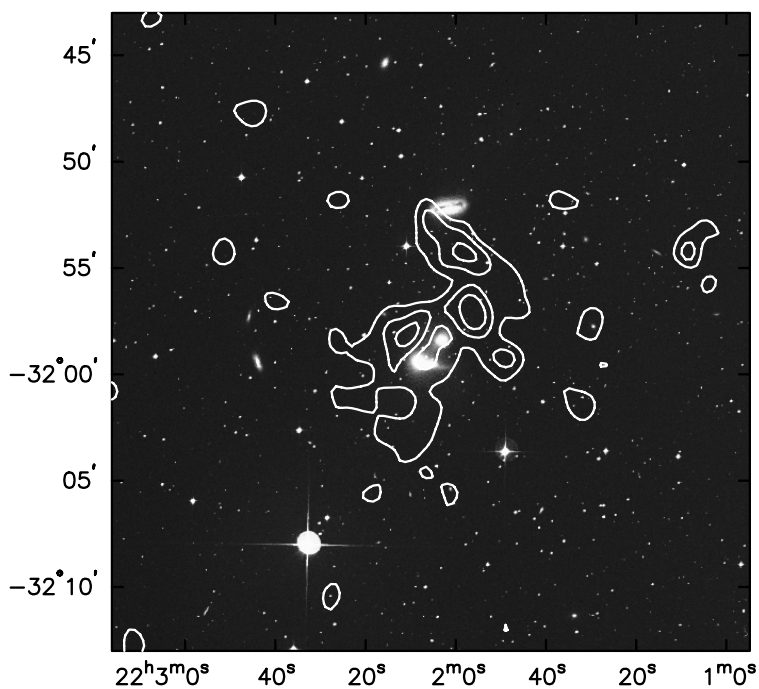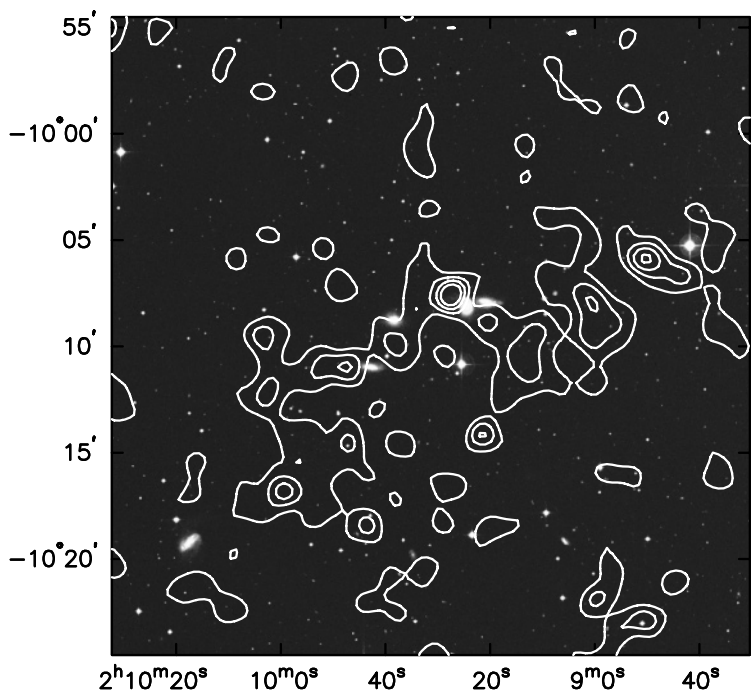
Figure 2 Contour map of the diffuse X-ray emission as traced by the ROSAT PSPC in HCG 16 (*top*) and HCG 90 (*bottom*) overlayed on the STScI Digitized Sky Survey. The X-ray data have been smoothed with a Gaussian profile of width 30″. The coordinate scale is for epoch J2000.
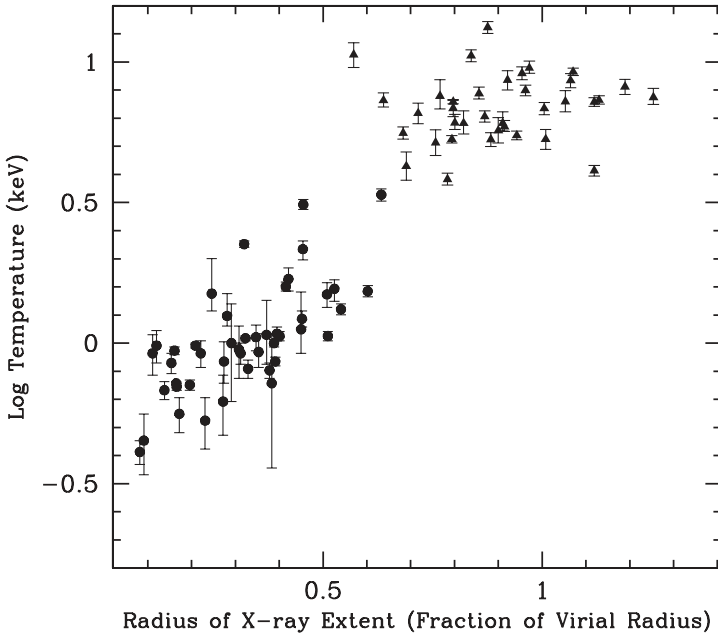
Figure 3 Total radius of X-ray extent plotted as a fraction of the virial radius of each system versus the logarithm of the temperature for a sample of groups (circles) and rich clusters (triangles). The groups were taken from Mulchaey et al (1996a), Hwang et al (1999) and Helsdon & Ponman (2000). The clusters plotted are a redshift-selected subset of the clusters in White (2000). The virial radius for each system was calculated assuming $r_{virial}(T) = 1.85 \, (T/10 \, \text{keV})^{0.5} \, (1+z)^{-1.5} \, h_{100}^{-1}$ Mpc (Evrard et al 1996).

clusters, the central surface brightness of the intracluster medium is several orders of magnitude higher than the surface brightness of the X-ray background. Not surprisingly, the central surface brightness of less massive systems like groups tends to be much lower. In fact, in many of the X-ray weakest groups, the central surface brightness of the intragroup gas is just a few times higher than that of the background. Therefore, the measured extent of the X-ray emission in groups is usually much less than that of rich clusters. When comparing groups and clusters, it is useful to normalize the radial extent of the X-ray gas by the mass of the system. Figure 3 plots X-ray extent normalized by the virial radius (R_{virial}) of each system versus temperature for a sample of groups and clusters. Figure 3 indicates that many rich clusters are currently detected to approximately R_{virial}, whereas groups are typically detected to a small fraction of R_{virial}. In some cases, the group X-ray extents are less than 10% of the virial radius. There is also a strong correlation between the radius of detection in virial units and the temperature of the gas in groups: cool groups are detected to a smaller fraction of their virial radius than hot groups. This correlation is important because it suggests that a

smaller fraction of the gas mass, and thus, X-ray luminosity, is detected in low temperature systems. Therefore, it is very important to account for this effect when one compares X-ray properties of systems spanning a large range in temperature (i.e. mass). Unfortunately, this has generally not been done in the literature.

3.3.3 The Beta Model

3.3.3 The Beta Model   Traditionally, a hydrostatic isothermal model has been used to describe the surface brightness profiles of rich clusters (e.g. Jones & Forman 1984). By analogy to the richer systems, this model is usually adopted for poor groups. The hydrostatic isothermal model assumes that both the hot gas and the galaxies are in hydrostatic equilibrium and isothermal. These assumptions appear to be valid for groups with regular X-ray morphologies, but are likely incorrect for groups with irregular X-ray morphologies (although this model is often applied even in these cases). With King's (1962) analytic approximation to the isothermal sphere, the X-ray surface brightness at a projected radius R is given by:

$$S(R) = S_o \left(1 + (R/r_c)^2\right)^{-3\beta+0.5}$$

where r_c is the core radius of the gas distribution. This model is often referred to as the standard beta model in the literature. The parameter β is the ratio of the specific energy in galaxies to the specific energy in the hot gas:

$$\beta \equiv \mu m_p \sigma^2 / kT_{gas}$$

where μ is the mean molecular weight, m_p is the mass of the proton, σ is the one-dimensional velocity dispersion, and T_{gas} is the temperature of the intragroup medium. For high-temperature systems such as clusters, the X-ray emissivity is fairly independent of temperature over the energy range observed by ROSAT ($\sim$0.1–2 keV). Therefore, the gas density profile can be derived from the surface brightness profile even if the gas temperature varies somewhat within the cluster. However, at the temperatures more typical of groups, the X-ray emissivity is a strong function of temperature. Thus, to invert the observed surface brightness profiles of groups to a gas density profile, the gas must be fairly isothermal.

Based on fits to ROSAT PSPC data, most authors have derived β values of around $\sim$0.5 for groups (Ponman & Bertram 1993, David et al 1994, Pildis et al 1995, Henry et al 1995, Davis et al 1995, David et al 1995, Doe et al 1995, Mulchaey et al 1996a). This number is somewhat lower than the typical value found for clusters (e.g. $\sim$0.64; Mohr et al 1999). However, simulations of clusters indicate that the β value derived from a surface brightness profile depends strongly on the range of radii used in the fit (Navarro et al 1995, Bartelmann & Steinmetz 1996). In particular, β values derived on scales much less than the virial radius tend to be systematically low. As most groups are currently detected to a much

smaller fraction of the virial radius than rich clusters, a direct comparison between group and cluster β values may not be particularly meaningful.

Although the hydrostatic isothermal model has almost universally been used for groups, in most cases it provides a poor fit to the data. In general, the central regions of groups exhibit an excess of emission above the extrapolation of the beta model to small radii. This steepening of the profile is often accompanied by a drop in the gas temperature, which has led some authors to suggest that the central deviations are related to a cooling flow (Ponman & Bertram 1993, David et al 1994, Helsdon & Ponman 2000). Alternatively, the excess flux could be emission associated with the central elliptical galaxy (Doe et al 1995, Ikebe et al 1996, Trinchieri et al 1997, Mulchaey & Zabludoff 1998).

Mulchaey & Zabludoff (1998) have shown that the surface brightness profiles in many groups can be adequately fit using two separate beta models. Although the various parameters are not well-constrained with the two-component models, Mulchaey & Zabludoff (1998) found a systematic trend for the β values to be larger with this model than in the case of a single beta model. Similar behavior has been found for rich clusters of galaxies (Ikebe et al 1996, Mohr et al 1999). Mohr et al (1999) suggest that the effect is a consequence of the strong coupling between the core radius (r_c) and β in the fitting procedure; a beta model with a large core radius and high β value can produce a profile similar to that of a beta model where both parameters are lower. Therefore, the presence of a central excess drives the core radius (and thus β) to lower values in the single beta model fits. While Helsdon & Ponman (2000) verified the need for multiple components in groups, they did not derive systematically higher β values. The likely explanation is that the argument in Mohr et al (1999) applies exclusively to systems where the extended component (i.e. the group/cluster gas) dominates the central component. In many of the lower-luminosity systems in Helsdon & Ponman's sample, however, the central component is dominant.

Helsdon & Ponman (2000) also compared the β values of groups and rich clusters and found a trend for β to decrease as the temperature of the system decreases. A similar trend had previously been found in samples of poor and rich clusters (e.g. David et al 1990, White 1991, Bird et al 1995, Mohr & Evrard 1997, Arnaud & Evrard 1999). Mohr et al (1999) reexamined the effect in clusters and found that it disappears when the surface brightness profiles are properly modeled using the two-component beta models. This explanation does not appear to work for poor groups, however, because Helsdon & Ponman (2000) used two-component beta models in their study. The lower β values in groups may be an indication that non-gravitational heating has played a more important role in low-mass systems (David et al 1995, Knight & Ponman 1997, Horner et al 1999, Helsdon & Ponman 2000). However, as noted above, simulations indicate that the derived β value depends strongly on the radii over which the surface brightness fit is performed. Thus, given the strong correlation between system temperature and X-ray extent (Figure 3), conclusions about how β varies with temperature (i.e. mass) may be premature.

3.4   Spectral Properties

X-ray spectral studies of groups have followed the techniques previously used for other diffuse X-ray sources such as elliptical galaxies and rich clusters. The observed data from X-ray instruments such as ROSAT or ASCA do not give the actual spectrum of the source but a convolution of the source spectrum with the instrument response. In general, it is not possible to uniquely invert the convolution and obtain the input spectrum. The usual solution is to adopt a model spectrum with a few adjustable parameters and to find the best fit to the observed data. By analogy to rich clusters, it has generally been assumed that the dominant emission mechanism in groups is thermal emission from diffuse, low-density gas. Many authors have calculated the spectrum emitted by a hot, optically thin plasma. The most popular models are that of Raymond & Smith (1977) and Mewe and collaborators (the so-called MEKAL model; Mewe et al 1985, Kaastra & Mewe 1993, Liedahl et al 1995). For simplicity, single-temperature (i.e. isothermal) models are usually assumed. The free parameters of interest in the isothermal plasma models include the gas temperature and metal abundance. For very hot systems, such as rich clusters, the X-ray emission in the isothermal model is dominated by the free-free continuum from hydrogen and helium. For the temperatures more typical of groups ($\sim 10^7$ K), much of the flux is found in line emission and bound-free continuum.

3.4.1 Gas Temperature   In general, isothermal plasma models provide good fits to the ROSAT PSPC spectra of groups. The derived gas temperatures are in the range $\sim$0.3–1.8 keV (see Figure 3), which is roughly what is expected given the range of observed velocity dispersions for groups (e.g. Ponman et al 1996, Mulchaey et al 1996a, Mulchaey & Zabludoff 1998, Helsdon & Ponman 2000). There is generally good agreement in the literature on the temperature of the gas; multiple authors have derived temperature values within 10% of each other, even when temperatures were derived over vastly different physical apertures (e.g. Mulchaey et al 1996a). The temperatures derived from the different plasma models (i.e. Raymond-Smith, MekaL) are also fairly consistent with each other (e.g. Mulchaey & Zabludoff 1998). Furthermore, there is very good agreement between gas temperatures determined by the ROSAT PSPC and ASCA for systems with temperatures less than about 2 keV. For higher-temperature gas (i.e. clusters), the ROSAT data appear to underestimate the true gas temperature by approximately 30% (Hwang et al 1999). All these observations suggest that the derived temperatures for the intragroup medium are fairly robust.

For some of the groups observed by ROSAT, it is possible to measure temperature profiles for the hot gas (Ponman & Bertram 1993, David et al 1994, Doe et al 1995, Davis et al 1996, Trinchieri et al 1997, Mulchaey & Zabludoff 1998, Helsdon & Ponman 2000, Buote 2000b). These profiles suggest that the gas is not strictly isothermal, but rather follows a somewhat universal form: the gas temperature is at a minimum at the center of the group, rises to a temperature

maximum in the inner $\sim$50–75 h_{100}^{-1} kpc, and drops gradually at large radii. The temperature minimum in the inner regions of the group is coincident with the sharp rise in the X-ray surface brightness profile. This behavior is consistent with that expected from a "cooling flow" (cf Fabian 1994). The temperature drop at larger radii is often based on lower-quality spectra, and in most cases is not statistically significant. Even if this latter effect is present, the gas temperature at large radii is usually within 10–15% of the temperature maximum. Therefore, isothermality is not a bad assumption over most of the group, as long as the central regions are excluded. However, when global gas temperatures are quoted for groups in the literature, the central regions are almost always included. Because the central regions dominate the total counts in the spectrum, the temperatures found in the literature may underestimate the global temperatures in many cases.

3.4.2 β_{spec} Although most authors have estimated the ratio of specific energy of the galaxies to the specific energy of the gas (i.e. the β parameter) from surface brightness profiles (see Section 3.3.3), β can in principle be determined by directly measuring σ and T_{gas}. Unfortunately, because σ is usually derived from only a few velocity measurements, this method is often not very robust. Detailed membership studies have been made for a few X-ray groups (i.e. Ledlow et al 1996, Zabludoff & Mulchaey 1998, Mahdavi et al 1999), and in these cases the velocity dispersion estimates are more reliable. Using such estimates, Mulchaey & Zabludoff (1998) found $\beta_{spec} \sim$1 for most of the groups in their sample. Helsdon & Ponman (2000) found a similarly high value for β_{spec} for groups with temperatures of $\sim$1 keV, but noted a trend for β_{spec} to decrease in the lower-temperature systems. However, almost all of the low-temperture groups in the Helsdon & Ponman (2000) sample have velocity dispersions determined from a small number of galaxies. Thus, while the current data suggest a trend for β_{spec} to decrease as the temperature of the group decreases, detailed spectroscopy of cool groups will be required to verify this result.

The $\beta \sim$1 values derived for hot groups from the direct measurement of temperature and velocity dispersion (β_{spec}) are significantly higher than the values of β often derived from surface brightness profile fits (β_{fit}). This so-called β-discrepancy problem has been discussed extensively for rich clusters (e.g. Mushotzky 1984, Sarazin 1986, Edge & Stewart 1991, Bahcall & Lubin 1994). Based on simulations, Navarro et al (1995) concluded that β_{fit} is biased low in galaxy clusters because of the limited radial range used in the X-ray profiles. This explanation may also explain the discrepancy found for groups, which are typically detected to a much smaller fraction of the virial radius than their rich cluster counterparts. Therefore, the β-discrepancy in groups may be an indication that the current derived β_{fit} values underestimate the true β values in many cases.

3.4.3 Gas Metallicity   In addition to measuring gas temperatures, ROSAT PSPC and ASCA observations of groups have been used to estimate the metal content

of the intragroup medium. As noted earlier, X-ray spectra of groups are dominated by emission line features. The strongest emission lines are produced when an electron in a highly ionized atom is collisionally excited to a higher level and then radiatively decays to a lower level. The most important features in the X-ray spectra of groups include the K-shell (n = 1) transitions of carbon through sulfur and the L-shell (n = 2) transitions of silicon through iron. Particularly important is the Fe L-shell complex in the spectral range $\sim$0.7–2.0 keV (Liedahl et al 1995). The wealth of line features in the soft X-ray band potentially provides powerful diagnostics of the physical conditions of the gas, including the excitation mechanism and the elemental abundance (Mewe 1991, Liedahl et al 1990).

Unfortunately, the X-ray telescopes flown to date have not had high enough spectral resolution to resolve individual line complexes. Still, many attempts have been made to estimate the elemental abundance of the gas. For groups, this method primarily measures the iron abundance in the gas, because lines from this element dominate the spectra. Spectral fits to both ROSAT and ASCA data suggest that the metallicity of the intragroup medium varies significantly from group to group; some systems are very metal-poor ($\sim$10–20% solar), whereas others are more enriched ($\sim$50–60% solar; Mulchaey et al 1993; Ponman & Bertram 1993; David et al 1994; Davis et al 1995; Saracco & Ciliegi 1995; Davis et al 1996; Ponman et al 1996; Mulchaey et al 1996a; Fukazawa et al 1996, 1998; Mulchaey & Zabludoff 1998; Davis et al 1999; Finoguenov & Ponman 1999; Hwang et al 1999; Helsdon & Ponman 2000). The low metallicities measured in some groups are surprising because the ratio of stellar mass to gas mass is higher in groups than in clusters. Consequently, one would naively expect the metallicities of the gas to be higher in groups than in rich clusters.

Several potential problems have been noted with the low metallicity measurements for the intragroup medium. Ishimaru & Arimoto (1997) pointed out that most X-ray studies have adopted the old photospheric value for the solar Fe abundance (Fe/H $\sim 4.68 \times 10^{-5}$), whereas the commonly accepted "meteoritic" value is significantly lower (Fe/H $\sim 3.24 \times 10^{-5}$). (Note that more recent estimates of the photospheric Fe abundance in the sun are consistent with the meteoritic value; see McWilliam 1997.) Thus, essentially all the Fe measurements in the X-ray literature should be increased by a factor of $\sim$1.44 to renormalize to the meteoritic value. This is particularly important when comparing the X-ray metallicities to chemical-evolution models, which usually adopt the meteoritic Fe solar abundance. The ability of ROSAT data to properly measure the gas abundance has also been questioned. Bauer & Bregman (1996) measured metallicities with the ROSAT PSPC for stars with known metallicities close to the solar value, and found the ROSAT metallicities were typically a factor of five lower than the optical measurements. Bauer & Bregman (1996) suggested several possible explanations for the discrepancy, including instrumental calibration uncertainties, problems with the plasma codes and possible differences in the photospheric and coronal

abundances of stars. Instrumental uncertainties with the ROSAT PSPC are unlikely to be the major source of the problem because ASCA spectroscopy of groups also indicates low gas metallicities (Fukazawa et al 1996, 1998; Davis et al 1999; Finoguenov & Ponman 1999; Hwang et al 1999). The possibility that the plasma models are inaccurate or incomplete has been a major concern. While abundance measurements for rich clusters are derived primarily from the well-understood Fe K-α line, group measurements rely on the much more complicated Fe L-shell physics. Problems with the plasma models were in fact identified by early ASCA observations of cooling flow clusters (Fabian et al 1994). Liedahl et al's (1995) revision to the standard MEKA thermal emission model likely accounts for the largest problems in the earlier plasma codes. However, fits to ASCA spectra of groups with the revised model still require very low metal abundances. Hwang et al (1997) have shown that for clusters with sufficient Fe L and Fe K emission (i.e. clusters with temperatures in the range $\sim$2–4 keV), the metallicities derived from the Fe L line complex are consistent with the values derived from the better understood Fe K complex (see also Arimoto et al's 1997 analysis of the Virgo cluster). Unfortunately, it is not clear that the reliability of the Fe L diagnostics implied from $\sim$2–4 keV poor clusters necessarily extends down to lower temperature groups, since other Fe lines dominate the spectrum below $\sim$1 keV (Arimoto et al 1997). Therefore, some problems with the plasma models may still exist.

Another potentially important problem is that the usually assumed isothermal model may be inappropriate for groups (Trinchieri et al 1997; Buote 1999, 2000a). There is clear evidence for temperature gradients in groups, particularly in the inner $\sim$50 h_{100}^{-1} kpc. In fact, the surface brightness profiles of ROSAT PSPC data suggest the presence of at least two distinct components in groups (Mulchaey & Zabludoff 1998). Mixing of multiple-temperature components is particularly an issue for ASCA data because separating out the central component from more extended emission is not possible with the ASCA point spread function. Buote (1999, 2000a) has studied this problem in detail for both elliptical galaxies and groups, and finds that in general single-temperature models provide poor fits to the ASCA spectra. By adopting a two-temperature model, one can obtain better fits, and the metallicities derived are substantially higher. For a sample of 12 groups, Buote (2000a) derives an average metallicity of $Z = 0.29 \pm 0.12 \, Z_\odot$ for the isothermal model and $Z = 0.75 \pm 0.24 \, Z_\odot$ for the two-temperature model (a single metallicity is assumed for the gas in these models). Buote (2000a) also finds that a multiphase cooling flow model provides a good description of the data. This model also requires higher metallicities ($Z = 0.65 \pm 0.17 \, Z_\odot$). Buote (2000a) finds a trend for the metallicities to be lowest in those groups for which the largest extraction apertures were used. This result is consistent with metallicity gradients in groups (see also Buote 2000c). Alternatively, it may simply reflect that the relative contribution of the "group" gas component increases as one adopts a larger aperture. In fact, given the results of the ROSAT surface brightness profile

fits, emission from the central elliptical galaxy may dominate the flux in the typical ASCA aperture and thus likely dominates the metallicity measurement. Therefore, the ASCA measurements may not be providing an accurate gauge of the global metal content of the group gas. Regardless, the work of Buote (1999, 2000a) is an important reminder that the properties derived from X-ray spectroscopy are very sensitive to the choice of the input model.

Matsushita et al (2000) also considered multi-temperature models for a large sample of early-type galaxies observed with ASCA. In contrast to Buote (1999, 2000a), Matsushita et al (2000) concluded that the poor spectral fits to ASCA data were not caused by incorrect modeling of multi-temperature emission. Furthermore, the multi-temperature models used by Matsushita et al (2000) produced relatively small increases in the overall abundance in many cases. Matsushita et al (2000) suggested that the strong coupling between the abundance of the so-called α-elements (i.e. O, Ne, Mg, Si, S) and the abundance of Fe hampers a unique determination of the overall metallicity. By fixing the abundance of the α-elements, Matsushita et al (2000) found that the derived metallicities are approximately solar. Although Matsushita et al (2000) restricted their analysis to early-type galaxies, these results may be applicable to groups, which have X-ray properties very similar to those of X-ray luminous ellipticals.

Although the dominant line features for the intragroup medium are produced by iron, strong lines are also expected from elements such as oxygen, neon, magnesium, silicon, and sulfur. The relative abundance of these various elements provides strong constraints on the star formation history of the gas. Some authors have attempted to fit the ASCA spectra with an isothermal model where the α-elements are varied together and separately from the iron abundance (Fukazawa et al 1996, 1998; Davis et al 1999; Finoguenov & Ponman 1999; Hwang et al 1999). In general, these studies find that the α-element to iron ratio is approximately solar in groups. Unfortunately, the determination of this ratio is very sensitive to the spectral model adopted (Buote 2000a) and if the isothermal assumption is not valid, these determinations are not particularly meaningful.

In summary, despite the great potential of X-ray spectroscopy to provide clues into the enrichment history of the intragroup medium, it is not possible at the present time to make strong conclusions about the metal content of the hot gas. Until we have higher resolution X-ray spectra and more complete plasma codes, the metallicity of the intragroup medium will remain an open issue.

3.4.4 Absorbing Column   The soft X-ray band is sensitive to low-energy photoabsorption by gas both within the source and along the line of sight. This absorption must be included in the X-ray spectral fits. It is usually assumed that the X-ray flux is diminished by:

$$A(E) = \exp(-N_H \sigma(E))$$

where N_H is the hydrogen column density and $\sigma(E)$ is the photo-electric

cross section (solar abundances are almost universally assumed for the absorbing gas). The cross sections in Morrison & McCammon (1983) are commonly adopted for X-ray analysis. The standard procedure is to allow N_H to be a free parameter in the spectral fit. If the best-fit spectral model returns a value of N_H significantly higher than the Galactic value, this is taken as evidence for excess absorption intrinsic to the group or central galaxy. The ROSAT and ASCA spectra of groups are often not of high enough quality to adequately constrain the absorbing column. Therefore, many authors have chosen to fix N_H to the Galactic value for spectral fits. For a few groups, however, column densities above the Galactic value have been inferred (Fukazawa et al 1996; Davis et al 1999; Buote 2000a,b). Buote (2000b) undertook the most ambitious study of absorption in groups, measuring N_H as a function of radius in a sample of 10 luminous systems observed by the ROSAT PSPC. Buote (2000b) found that the value of N_H derived depends strongly on the bandpass used in the X-ray analysis and suggested the bandpass-dependent N_H values are consistent with additional absorption in the group from a collisionally ionized gas. This excess absorption manifests itself primarily as a strong oxygen edge feature at $\sim$0.5 keV. Buote (2000b) found that within the central regions of the groups, the estimated masses of the absorbers are consistent with the matter deposited by a cooling flow over the lifetime of the flow. If a warm absorber exists in groups, as suggested by Buote (2000b), it should be verified by the next generation of X-ray telescopes.

3.4.5 X-Ray Luminosity   For a thermal plasma, the X-ray luminosity is a rough measure of the total mass in gas. Therefore, the total X-ray luminosity of a group provides a potentially interesting probe of a group's properties. In almost all cases in the literature, the total flux or luminosity quoted is out to the radius to which X-ray emission is detected. In this sense, quoted X-ray luminosities should be thought of as "isophotal luminosities." The measured luminosity is also sensitive to the exact techniques used in the X-ray analysis. For example, the total radial extent of the X-ray emission (and thus the total X-ray luminosity) is strongly dependent on the assumed background level (Henriksen & Mamon 1994, Davis et al 1996). Because of this, different authors often derive vastly different X-ray luminosities for the same group using the same ROSAT observation (Mulchaey et al 1996a).

It is a common practice to quote bolometric luminosities in the literature. The bolometric correction is estimated by extrapolating the spectral model for the gas beyond the limited bandpass of the particular telescope and by making a correction for any absorption along the line of sight. In the case of ROSAT observations, these corrections can easily double the luminosity of the source. The bolometric correction is also somewhat sensitive to uncertainties in the spectral model such as gas metallicity. For very shallow observations, such as those based on ROSAT All-Sky Survey data, a spectral model must usually be assumed to estimate the total X-ray luminosity. The bolometric luminosities of groups are typically in the range several times 10^{40} h_{100}^{-2} to nearly 10^{43} h_{100}^{-2} (Mulchaey et al 1996a,

Ponman et al 1996, Helsdon & Ponman 2000). Thus, the X-ray luminosities of groups can be several orders of magnitude lower than the X-ray luminosities of rich clusters (cf Forman & Jones 1982).

Finally, it is worth noting that because X-ray emission is usually traced only to a fraction of the virial radius in groups, it is likely that the isophotal measurements significantly underestimate the true luminosities of the hot gas. This is particularly true for the coolest groups. Helsdon & Ponman (2000) have attempted to account for the missing luminosity by extrapolating the gas density profile models out to the virial radius. A comparison of the observed isophotal luminosities to the corrected virial luminosities in the Helsdon & Ponman sample indicate that in many cases, over half of the luminosity could occur beyond the radius to which X-ray emission is currently detected.

4.   CORRELATIONS

There has been considerable interest in how the X-ray and optical properties of groups differ from those of richer clusters. Such comparisons are often limited by the poorly determined group properties. Most optical properties of groups are derived from existing redshift surveys, which typically include only the most luminous group members. Consequently, global properties such as velocity dispersion and morphological composition are subject to small number uncertainties. The properties of the hot gas also tend to be more uncertain in poorer systems than in clusters because of the lower X-ray fluxes of groups. It should also be remembered that the X-ray properties of groups and clusters are often derived over very different gas density contrasts, which further complicates the comparisons of these systems. Despite these potential problems, group and cluster comparisons have provided considerable insight into the nature of X-ray groups.

4.1   T-σ Relation

Because both the temperature of the intragroup medium and the velocity dispersion of the galaxies provide a measure of the gravitational potential strength, a correlation between these two quantities is expected. Although there is considerable scatter in the data, ROSAT observations are consistent with such a correlation (Figure 4; Ponman et al 1996, Mulchaey & Zabludoff 1998, Helsdon & Ponman 2000). High-temperature groups (T $\sim$ 1 keV) appear to follow the extrapolation of the trend found for rich clusters; the ratio of specific energy in the galaxies to specific energy in the gas is approximately one (i.e. $\beta \sim 1$ and T $\propto \sigma^2$; Mulchaey & Zabludoff 1998, Helsdon & Ponman 2000). Ponman et al (1996) and Helsdon & Ponman (2000) have claimed that the T-σ relation becomes much steeper for cooler groups. However, Figure 4 suggests that given the large scatter, evidence for a systematic deviation from the cluster relationship is at this point rather scarce.
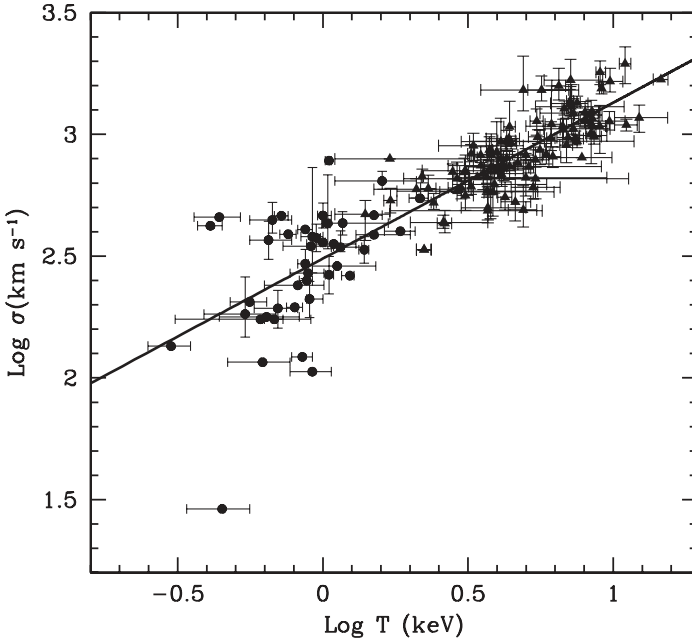
Figure 4 Logarithm of the X-ray temperature versus logarithm of optical velocity dispersion for a sample of groups (circles) and clusters (triangles). The group data are taken from the literature compilation of Xue & Wu (2000), with the addition of the groups in Helsdon & Ponman (2000). The cluster data are taken from Wu et al (1999). The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal distance regression method). Within the large scatter, the groups are consistent with the cluster relationship.

4.2 L_X-σ and L_X-T Relations

Strong correlations are also found between X-ray luminosity and both velocity dispersion and gas temperature in groups. However, there is considerable disagreement in the literature over the nature of these correlations. Figure 5 shows the L_X-σ relationship for all the groups observed by the ROSAT PSPC in pointed-mode and a sample of clusters observed with various X-ray telescopes (Wu et al 1999). The solid line shows the best-fit relationship Wu et al (1999) derived from the cluster sample alone. Figure 5 shows that for the most part, groups are consistent with the cluster relationship, although there is considerable scatter particularly among the lowest luminosity groups. This conclusion was reached by Mulchaey & Zabludoff (1998), who found that a single relationship fit their sample of groups and rich clusters. Ponman et al (1996) and Helsdon & Ponman (2000) also found that the L_X-σ for groups was basically consistent with the cluster relationship,
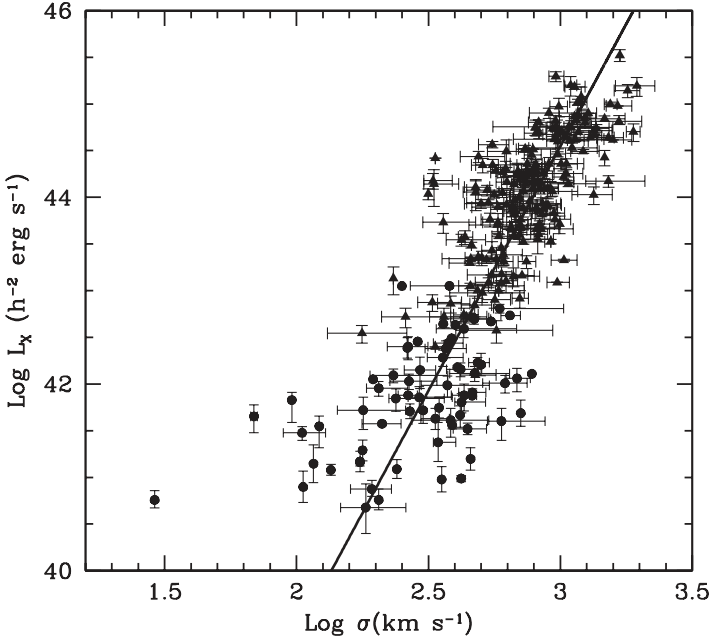
Figure 5 Logarithm of optical velocity dispersion versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal distance regression method).

although both studies noted that the relationship may become somewhat flatter for low velocity dispersion systems. (Within the errors, the slopes derived by Mulchaey & Zabludoff (1998), Ponman et al (1996) and Helsdon & Ponman (2000) are indistinguishable; $L_X \propto \sigma^{4.3}$, $\sigma^{4.9}$ and $\sigma^{4.5}$, respectively). Therefore, there is fairly good agreement among the ROSAT studies based on pointed-mode data. However, Mahdavi et al (1997) derived a significantly flatter slope from their ROSAT All Sky Survey data ($L_X \propto \sigma^{1.56}$) and suggested that for low velocity dispersion systems the X-ray emission is dominated by hot gas clumped around individual galaxies. More recently, Mahdavi et al (2000) presented X-ray luminosities for a much larger sample of loose groups. In agreement with their earlier result, they find a much flatter L_X-σ for groups than for rich clusters. Mahdavi et al (2000) modeled the L_X-σ relationship as a broken power law, with a very flat slope ($L_X \propto \sigma^{0.37}$) for systems with velocity dispersion less than 340 km s^{-1} and a cluster-like value ($L_X \propto \sigma^{4.0}$) for higher velocity dispersion systems. However, a visual inspection of Mahdavi et al's (2000) L_X-σ relationship (see Figure 4 of their paper) reveals that the need for a broken power law fit is driven by the one or two lowest velocity dispersion

groups (out of a total sample of 61 detected groups.) Furthermore, nearly all the L_X upper limits derived by Mahdavi et al (2000) fall below their broken power law relationship (and therefore require a "steeper" relationship). Thus, the case for deviations from the L_X-σ cluster relationship is far from compelling. It is also worth noting that the velocity dispersions of the groups that appear to deviate the most from the cluster relationship are often based on very few velocity measurements (for example the most "deviant" system in Figures 4 and 5 has a velocity dispersion based on only four velocity measurements.) Zabludoff & Mulchaey (1998) have found that when velocity dispersions are calculated for X-ray groups from a large number of galaxies, as opposed to just the four or five brightest galaxies, the velocity dispersion is often significantly underestimated. Therefore, more detailed velocity studies of low velocity dispersion groups could prove valuable in verifying deviations from the cluster L_X-σ relation.

There is also considerable disagreement in the literature about the relationship between X-ray luminosity and gas temperature. Mulchaey & Zabludoff (1998) found that a single L_X-T relationship could describe groups and clusters ($L_X \propto T^{2.8}$). However, both Ponman et al (1996) and Helsdon & Ponman (2000) found much steeper relationships for groups ($L_X \propto T^{8.2}$ and $L_X \propto T^{4.9}$, respectively). These differences might be attributed to the different temperature ranges included in the studies. Mulchaey & Zabludoff's (1998) sample was largely restricted to hot groups (i.e. $\sim$1 keV), whereas Ponman and collaborators have included much cooler systems (down to $\sim$0.3 keV). Indeed, Helsdon & Ponman (2000) found that the steepening of the L_X-T relationship appears to occur below about 1 keV. Figure 6 suggests that the deviation of the cool groups from the cluster relationship is indeed significant. The fact that the L_X-σ relationship for groups appears to be similar to the relationship found for clusters, while the relationships involving gas temperature significantly depart from the cluster trends, may be an indication that non-gravitational heating is important in groups (Ponman et al 1996, Helsdon & Ponman 2000). However, the group X-ray luminosities may be biased somewhat low because groups are detected to a smaller fraction of their virial radius than richer systems, and if comparisons are made at the same mass over-density level, groups would likely fall closer to the cluster relation.

4.3 Galaxy Richness and Optical Luminosity

Most authors have found little or no correlation between X-ray luminosity and the number of luminous galaxies in a group or the total optical luminosity of the group (Ebeling et al 1994, Doe et al 1995, Mulchaey et al 1996a, Ponman et al 1996). The lack of correlation between X-ray luminosity and number of group members is not too surprising because galaxy-galaxy merging is likely prevalent in groups, and thus the number of galaxies in a group is likely not conserved in time (Ponman et al 1996). The fact that there is no relationship between optical and X-ray luminosity is important because it suggests that the X-ray emission is
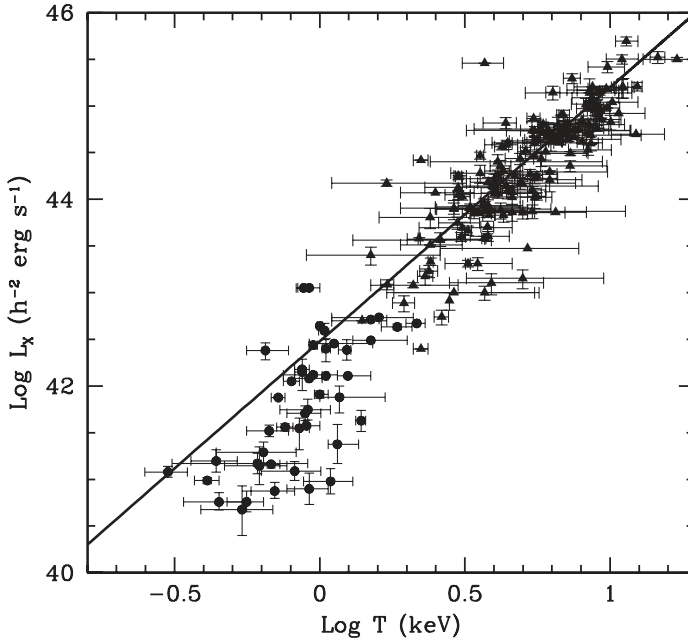
Figure 6 Logarithm of the X-ray temperature versus logarithm of X-ray luminosity for a sample of groups (circles) and clusters (triangles). The data are taken from the same sources cited in Figure 4. The solid line represents the best-fit found by Wu et al (1999) for the clusters sample (using an orthogonal distance regression method). The observed relationship for groups is somewhat steeper than the best-fit cluster relationship.

not associated with individual galaxies for most of the samples studied (Ponman et al 1996).

Mahdavi et al (1997) came to a very different conclusion with their RASS survey of optically-selected groups: They found a strong correlation between X-ray luminosity and optical luminosity. The differences between Mahdavi et al's (1997) results and those of other authors suggests that the groups in Mahdavi et al (1997) may be systems dominated by X-ray emission from individual galaxies and not intragroup gas.

## 4.4 Morphological Content

Correlations between the presence of X-ray emission and the morphological composition of groups were suggested from the earliest ROSAT studies. Ebeling et al (1994) were the first to claim such an effect, noting that all but one of the X-ray detected HCGs in the ROSAT All-Sky Survey data had spiral fraction less than 50%. Subsequent studies of small samples appeared to support this trend (Henry et al 1995, Pildis et al 1995, Mulchaey et al 1996a). However, Ponman et al
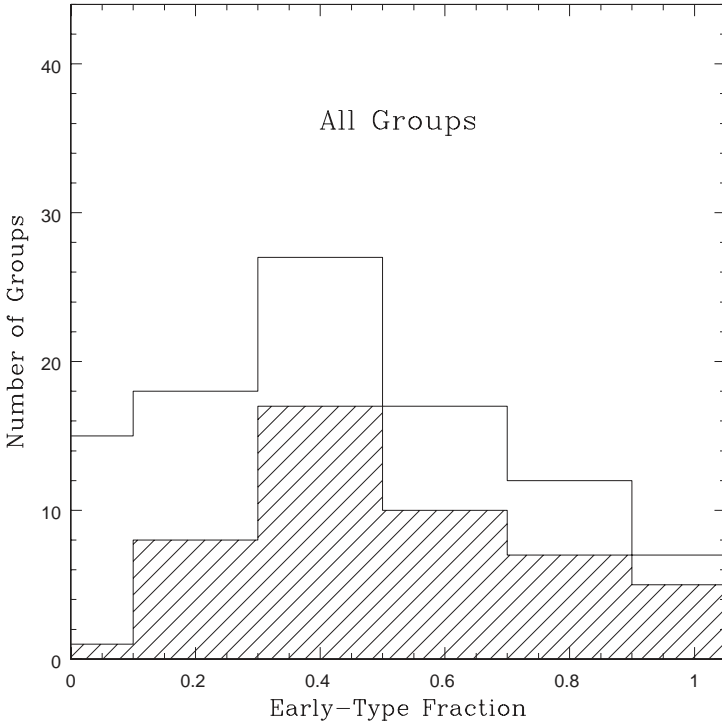
Figure 7 Distribution of early-type fraction for all groups (*open histogram*) and groups with diffuse X-ray emission (*shaded histogram*). The top panel shows the result for all published PSPC pointed-mode observations, whereas the lower panel contains only groups selected from optical redshift surveys. (*continued*)

(1996) came to a very different conclusion based on their much larger survey of the HCGs. They detected several groups with high spiral fractions, including the extreme example HCG 16, a compact group that contains only spirals.

Figure 7 shows the distribution of early-type fraction for all the groups with published pointed observations with ROSAT. For the purposes of this plot, a group is considered "X-ray detected" only if there is evidence for an extended intragroup medium component. As is apparent from this figure, a significant number of spiral-rich groups do contain diffuse X-ray emission, which confirms the conclusion of Ponman et al (1996). In fact, in contrast to the earlier studies, the distribution of early-type fractions is surprisingly flat for the X-ray detected groups. The apparent contradiction with the earlier results can be explained by the fact that the majority of the groups in the current sample were selected from optical redshift surveys and were serendipitously observed by ROSAT (Helsdon & Ponman 2000, Mulchaey et al 2000), whereas the earlier studies were biased toward X-ray luminous groups, which tend to have higher early-type fractions (Mulchaey & Zabludoff 1998).
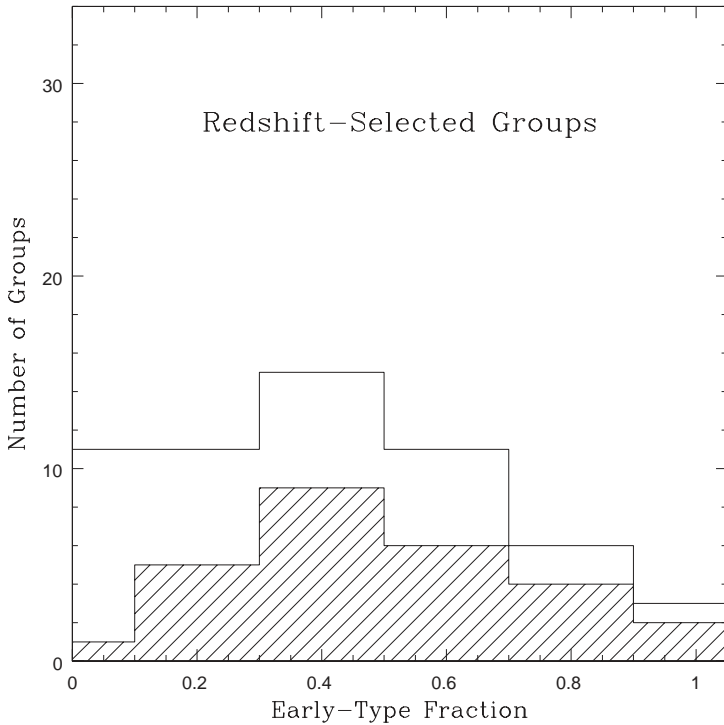
Figure 7 (*Continued*)

A closer examination of Figure 7 reveals that while many spiral-rich systems are X-ray sources, spiral-only groups tend not to contain a diffuse X-ray component. The one exception in Figure 7 is HCG 16. However, the true nature of the X-ray emission in HCG 16 is unclear. The ROSAT image of the group indicates that the emission is very clumpy and concentrates around the brightest group members (see Figure 2, top). Some authors have attributed all of the X-ray emission to individual galaxies (Saracco & Ciliegi 1995; see also an earlier Einstein observation by Bahcall et al 1984), whereas others have claimed the existence of intragroup gas (Ponman et al 1996). Dos Santos & Mamon (1999) have reanalyzed the ROSAT PSPC data on HCG 16, paying special attention to the removal of emission associated with galaxies. Although Dos Santos & Mamon (1999) derived a lower luminosity for the diffuse gas than Ponman et al (1996), they still found evidence for some diffuse gas. However, the presence of diffuse emission does not necessarily mean that HCG 16 contains a diffuse intragroup medium. One possibility is that the emission is related to the unusually high number of active galaxies in the group (HCG 16 contains one Seyfert galaxy, two LINERs, and three starburst galaxies; Ribeiro et al 1996). The X-ray to infrared luminosity ratio of this system is much higher than one would expect if the X-ray emission is related to the

galaxies' activity, however (Ponman, private communication). Alternatively, the X-ray emission may be associated with shocked gas, as appears to be the case in Stephan's Quintet (Pietsch et al 1997).

With the possible exception of HCG 16, all X-ray detected groups studied to date contain at least one early-type galaxy. There are several possible explanations for why spiral-only groups do not contain diffuse X-ray emission. One possibility is that all spiral-only groups are chance superpositions and not real, physical systems. This possibility seems unlikely, given the existence of our own spiral-only Local Group (see Section 5.10 for a discussion of the intragroup medium in the Local Group). Another possibility is that the intragroup gas in spiral-only groups is too cool to produce appreciable amounts of X-ray emission (Mulchaey et al 1996b). Based on velocity dispersions, the virial temperatures of spiral-only groups do tend to be lower than those of their early-type dominated counterparts (Mulchaey et al 1996b). While a cool (i.e. several million degrees K) intragroup medium would be difficult to detect in X-ray emission, such gas might produce prominent absorption features in the far-ultraviolet or X-ray spectra of background quasars (Mulchaey et al 1996b, Perna & Loeb 1998, Hellsten et al 1998). In fact, several such groups may have already been detected as OVI $\lambda\lambda 1031.93, 1037.62$ Å absorption systems (Bergeron et al 1994, Savage et al 1998). A third possibility is that the gas densities in spiral-only groups are too low to be detected in X-rays. Low gas densities in spiral-only groups are in fact consistent with recent prediction of preheating models for groups (Ponman et al 1999; see Section 5.9).

5.   COSMOLOGICAL IMPLICATIONS OF X-RAY GROUPS

5.1   The Physical Nature of Groups

Simulations of local large-scale structure suggest that a significant fraction of the groups identified in redshift surveys are not real, bound systems (Frederic 1995, Ramella et al 1997). The existence of diffuse X-ray emitting gas is often cited as evidence that a group is real. This is not necessarily the case, however. Hernquist et al (1995) noted that primordial gas may be shock-heated to X-ray emitting temperatures along filaments. When these filaments are viewed edge-on, a "fake" group with an X-ray halo could be observed. Ostriker et al (1995) proposed a test of the Hernquist et al (1995) filament model by defining an observable quantity Q, that is proportional to the axis ratio of the group. Applying this test to the early ROSAT observations of HCGs, Ostriker et al (1995) found that the Q values for most HCGs are consistent with their being frauds. However, the low Q values for groups can also be explained if the ratio of gas mass to total mass is smaller in groups than in rich clusters. Both ROSAT observations (David et al 1995, Pildis et al 1995, Mulchaey et al 1996a) and simulations (Diaferio et al 1994, Pildis et al 1996) of X-ray groups are in fact consistent with this idea, suggesting that the Ostriker et al test may in the end not be very useful.

Several arguments support the idea that at least some X-ray groups are real, bound systems and that the X-ray gas is virialized. In the most X-ray luminous groups, the diffuse gas extends on scales of hundreds of kiloparsecs and appears smooth. This is consistent with what one expects for a "smooth" group potential. The gas temperature in these cases agrees fairly well with the temperature expected, based on the velocity dispersion of the groups. Furthermore, most of these groups show evidence for cooling flows in their centers, suggesting that the gas is in an equilibrium state and has probably existed for at least several gigayears.

Ironically, perhaps the best evidence for the reality of the X-ray luminous groups has come from optical studies of these systems. Zabludoff & Mulchaey (1998) used multifiber spectroscopy to study the faint galaxy population in a small sample of groups and found large differences in the number of faint galaxies in X-ray detected and non-detected groups. All of the X-ray detected groups in the Zabludoff & Mulchaey (1998) sample contain at least 20–50 group members (down to magnitudes as faint as $M_B \sim -14+5 \log_{10} h_{100}$). Even down to these relatively faint magnitude limits, many of the X-ray detected groups have very high early-type fractions (nearly 60% in some cases). The large number of group galaxies argue that these X-ray groups must be real, physical systems and not radial superpositions. There are also strong correlations between dynamical measures of the gravitational potential (i.e. velocity dispersion/gas temperature) and the early-type fraction of the group (Zabludoff & Mulchaey 1998, Mulchaey et al 1998). These correlations imply either that galaxy morphology is set by the local potential at the time of galaxy formation (Hickson et al 1988) or that the potential grows as the group evolves (Diaferio et al 1993). Either scenario requires that most X-ray luminous groups be real, bound systems.

However, it is likely that some X-ray detected groups are not virialized systems. In particular, low-luminosity, low-temperature groups tend to have irregular X-ray morphologies with the X-ray emission distributed in the immediate vicinity of individual galaxies. These X-ray morphologies suggest that these groups are still dynamically evolving. In some cases, such as HCG 92, gas has apparently reached X-ray emitting temperatures by other mechanisms such as shocks. Therefore, X-ray detection alone does not indicate that a system is virialized.

5.2 Mass Estimates

One of the most important applications of X-ray observations of groups has been mass estimates. Prior to ROSAT, mass determinations for groups were largely based on application of the virial theorem to the group galaxies. For a typical cataloged group with only four or five velocity measurements, the virial method can be unreliable (e.g. Barnes 1985, Diaferio et al 1993).

The method used to estimate group masses from X-ray data is analogous to the technique developed for rich clusters (e.g. Fabricant et al 1980, 1984; Fabricant & Gorenstein 1983; Cowie et al 1987). The fundamental assumption is that the hot gas is trapped in the potential well of the group and is in rough hydrostatic equilibrium. This assumption is probably a reasonable one for most groups, given

the short sound-crossing times in these systems. A further assumption is that the only source of heating for the gas is gravitational, i.e. that the gas temperature is a direct measure of the potential depth and therefore of the total mass. This assumption may not be strictly true for some groups. In particular, the fact that the heavy metal abundance of the intragroup medium is non-zero suggests that some of the gas has been reprocessed in the stars in galaxies and ejected by supernovae-driven winds. In addition to polluting the intragroup gas with metals, such winds also provide additional energy to the gas. It has generally been assumed in the literature that the energy contribution of such winds is negligible. Semi-analytic models suggest that this assumption is fair as long as the temperature of the system is greater than about 0.8 keV (Balogh et al 1999, Cavaliere et al 1999). Thus, for many groups, the hydrostatic mass estimator should be valid.

With the further assumption of spherical symmetry, the mass interior to radius R is given by (Fabricant et al 1984):

$$M_{\text{total}}(<R) = \frac{kT_{\text{gas}}(R)}{G\mu m_p}\left[\frac{dlog\rho}{dlogr} + \frac{dlogT}{dlogr}\right]R$$

where k is Boltzmann's constant, $T_{\text{gas}}(R)$ is the gas temperature at radius R, G is the gravitational constant, μ is the mean molecular weight, m_p is the mass of the proton, and ρ is the gas density. In principle, all of the unknowns in this equation can be calculated from the X-ray data. Typically, the gas temperature is measured directly from the X-ray spectrum and the gas density profile is determined by fitting the standard beta model to the surface brightness profile. Unfortunately, it is often necessary to make a further assumption that the gas is isothermal (i.e. $\frac{dlogT}{dlogr} = 0$). For a few groups, the temperature profile can be directly measured. The resulting mass estimates suggest that the isothermal assumption generally results in an error in the mass of no more than about 10% (e.g. David et al 1994, Davis et al 1996). With the isothermal assumption, $M_{\text{total}}(<R) \propto T_{\text{gas}}\beta R$ (as long as R is much larger than the core radius in the beta model. Therefore, if β is underestimated from the surface brightness profile fits by a factor of $\sim$2 (see Sections 3.3.3 and 3.4.3), then the mass estimates are also too small by a factor of $\sim$2.)

ROSAT measurements indicated a small range of total group masses with nearly all of the systems clustered around $10^{13}\,h^{-1}\,M_\odot$ (see Figure 8; Mulchaey et al 1993, Ponman & Bertram 1993, David et al 1994, Pildis et al 1995, Henry et al 1995, Mulchaey et al 1996a). The narrow range of group masses is not too surprising, given that nearly all the groups in these surveys have temperatures of $\sim$1 keV.

The X-ray mass estimates can generally be applied only to a radius of several hundred kiloparsecs. Beyond that, the gas density profile is not well-constrained. Because the virial radius for a 1 keV group is approximately $\sim$0.5 h_{100}^{-1} Mpc, the X-ray method measures only a fraction of the total mass (Ponman & Bertram 1993; David et al 1995; Henry et al 1995). Simply extrapolating out to the virial radius, the total group masses are a factor of approximately two to three times larger than those implied from the X-ray studies (Mass $\propto$ R). However, if
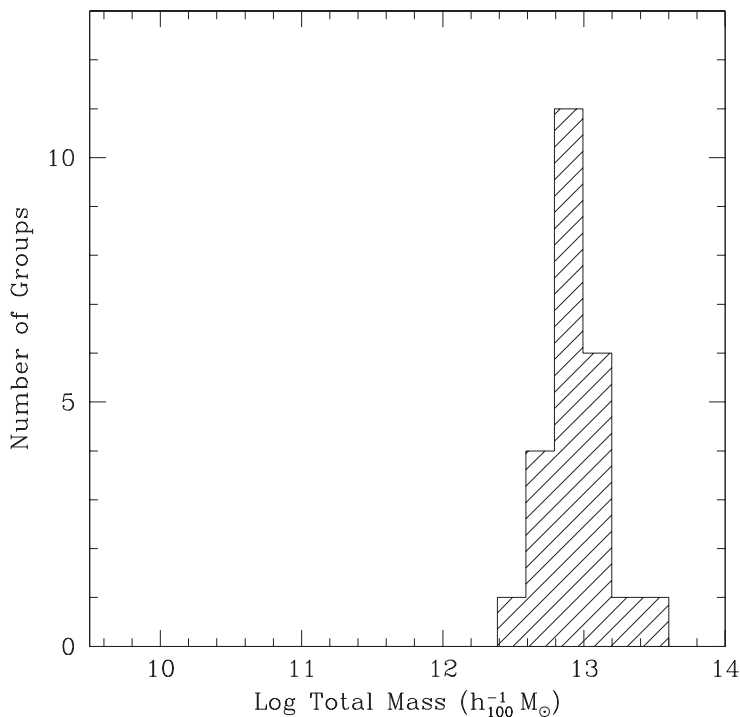
Figure 8 Distribution of X-ray–determined total group masses. In each case, the masses are determined out to the radius to which the X-ray emission is detected. The sample is based on the compilation given in Mulchaey et al 1996a, with the addition of a few groups with more recent X-ray mass estimates in the literature.

non-gravitational heat is important in groups, the extrapolation out to the virial radius is more uncertain (Loewenstein 2000).

Because of their relatively large masses, X-ray groups make a substantial contribution to the mass density of the universe (Mulchaey et al 1993, Henry et al 1995, Mulchaey et al 1996a). Based on their X-ray-selected group sample, Henry et al (1995) estimate that X-ray luminous groups contribute $\Omega \sim 0.05$. However, their sample contained only the most luminous, elliptical-rich groups. When one corrects for the groups missing from Henry et al's (1995) sample (assuming a similar mass density), groups might contribute as much as $\Omega \sim 0.25$. These estimates are comparable to the numbers found for richer clusters, which verifies the cosmological significance of poor groups.

5.3 Baryon Fraction

The ratio of baryonic to total mass in groups and clusters can provide interesting constraints on cosmological models (e.g. Walker et al 1991, White et al
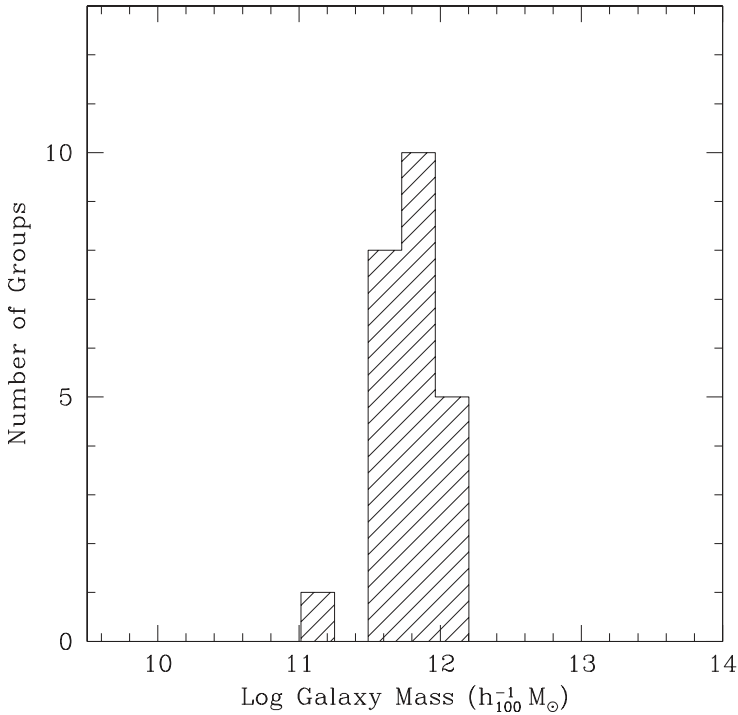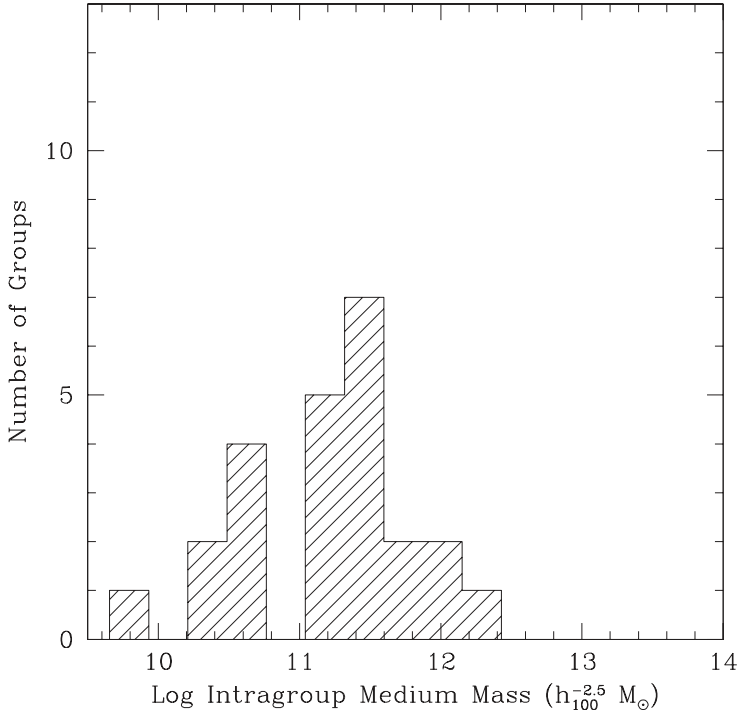
Figure 9   Distribution of galaxy mass for the sample of groups used in Figure 8.

1993). The two known baryonic components in groups are the galaxies and the hot gas. The total mass in galaxies can be estimated by measuring the total galaxy light and assuming an appropriate mass-to-light ratio for each galaxy based on its morphological type. While ideally the luminosity function of each group should be used to measure the total light, generally most authors have included only the contribution of the most luminous galaxies. Fortunately, these galaxies account for nearly all the light in the group. The mass-to-light ratios of X-ray groups are generally in the range $M/L_B \sim 120$–200 h_{100} $M_\odot/L_\odot$ (Mulchaey et al 1996a), which is comparable to the mass-to-light ratios found in rich clusters. However, these estimates are made out to the radius of X-ray detection, so the values out to the virial radius could be larger. Assuming standard mass-to-light ratios for ellipticals and spirals, the mass in galaxies in X-ray groups is typically in the range 3×10^{11}–2×10^{12} h_{100}^{-1} $M_\odot$ (Figure 9).

The mass in the intragroup medium can be estimated from the model fit to the surface brightness profile. The gas-mass estimates depend both on the radius out to which X-rays are detected (Henriksen & Mamon 1994) and on the spectral properties assumed (for example, the gas metallicity; Pildis et al 1995). For these reasons, different authors have derived significantly different gas masses for the

Figure 10 Distribution of intragroup medium mass for the sample of groups used in Figure 8.

same systems (cf Mulchaey et al 1996a). For most groups, the gas mass is in the range $\sim 2 \times 10^{10}$–$10^{12} h_{100}^{-5/2}$ $M_\odot$ (Figure 10). This is somewhat less than or comparable to the mass in galaxies. Note, however, that the gas mass is much more strongly dependent on H_0, and for more realistic (i.e. lower) values of H_0, the gas mass can be somewhat higher than the galaxy mass. The observed gas mass–to–stellar mass ratio tends to decrease as the temperature of the system decreases. This trend extends from rich clusters to individual elliptical galaxies. David et al (1995) estimate that the gas-to–total mass fraction is approximately 2% in ellipticals, 10% in groups and 20–30% in rich clusters. However, the hot gas in groups is detected to a much smaller fraction of the virial radius than in rich clusters, so comparisons made at the current level of X-ray detection may not accurately reflect the global gas fractions (Loewenstein 2000). In fact, much of the intragroup gas probably lies beyond the current X-ray detection limits, and on more global scales, groups may not be gas-poor compared to clusters. Consequently, the total gas masses of groups may be severely underestimated by ROSAT observations. On scales of the virial radius, the intragroup medium is likely the dominant baryonic component in these systems. In fact, Fukugita et al (1998) estimated that diffuse gas in groups is the
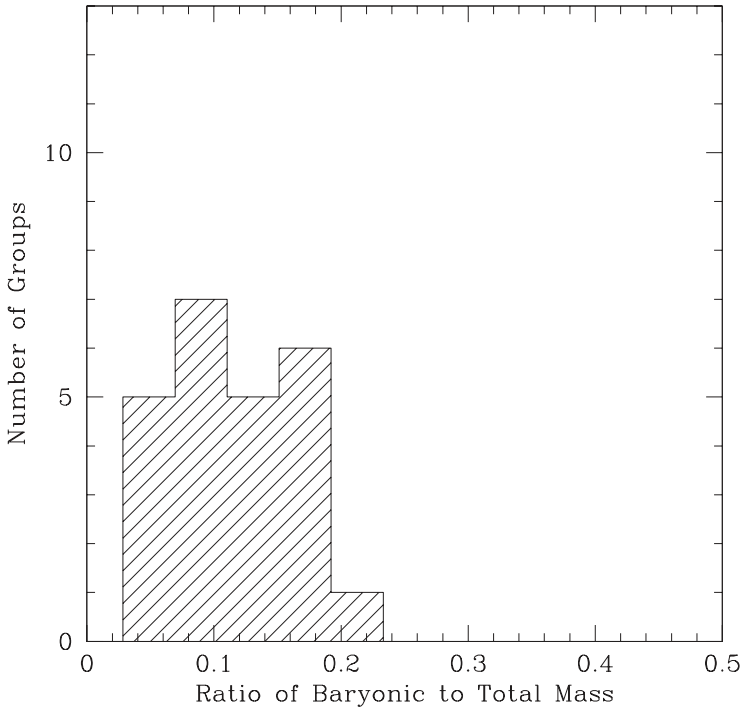
Figure 11   Distribution of total observed baryonic mass to total group mass for the sample of groups used in Figure 8. The low "baryonic fractions" derived for groups indicate that these systems are dominated by dark matter.

dominant baryon component in the nearby universe. A fundamental assumption in Fukugita et al's calculation is that all groups contain an intragroup medium and that the absence of X-ray detections in many groups is primarily a result of lower virial temperature rather than the absence of plasma. Regardless of whether this assumption is valid or not, it is now clear that intragroup gas is an important baryonic constituent of the local universe.

Adding up the baryons in galaxies and intragroup gas and comparing to the total mass, one finds that the known baryonic components typically account for only 10–20% of the total mass that is derived using the X-ray data (Figure 11; Mulchaey et al 1993; Ponman & Bertram 1993; David et al 1994; Pildis et al 1995; David et al 1995; Doe et al 1995; Davis et al 1995, 1996; Mulchaey et al 1996a; Pedersen et al 1997). This provides some of the strongest evidence to date that small groups of galaxies are dominated by dark matter. The ratio of mass in observed baryonic components to total mass (i.e. the "baryon fraction") in general is smaller in groups than in rich clusters (David et al 1995, David 1997). However, the lower observed baryon fractions of groups may largely reflect the fact that

much of the hot gas occurs beyond the radius of current X-ray detection. Even if the observed baryon fractions of groups are representative of the global values, the baryon fractions in X-ray groups are still too high to be consistent with the low baryon fractions required for $\Omega = 1$ and standard big bang nucleosynthesis (cf White et al 1993).

5.4 Large-Scale Structure

Redshift surveys of the nearby universe indicate that groups of galaxies are good tracers of large-scale structure (e.g. Ramella et al 1989). The presence of a hot intragroup medium in many groups suggests that X-ray observations can also be used to map out the distribution of mass in the universe. Recent ROSAT results demonstrate the great potential of large area X-ray surveys. Mullis et al (2000) have recently completed an optical follow-up survey of the $\sim$500 X-ray sources detected in the ROSAT All-Sky Survey in a 9×9 square-degree region around the north ecliptic pole. They identify 65 galaxy systems, $\sim$30% of which are poor groups. Remarkably, some 23% of the galaxy systems found in this field belong to a single wall-like structure at $z = 0.088$. Although a supercluster consisting of six Abell clusters had previously been identified in this region (Batuski & Burns 1985), the X-ray data reveal that this supercluster is significantly larger than implied by the optical data alone. Furthermore, the X-ray data show that the massive Abell clusters are linked together by groups and poor clusters. The supercluster spans the entire area surveyed by Mullis et al (2000), suggesting that the true extent of this structure could be larger still. Numerical simulations imply that future X-ray missions such as CHANDRA and XMM will be able to map out even lower-density regions such as filaments (Pierre et al 2000). Such X-ray studies will be very important because many current models suggest that the majority of baryons occur in these filaments (Miralda-Escude et al 1996, Cen & Ostriker 1999).

5.5 Moderate Redshift Groups

Despite the cosmological significance of groups, remarkably little is known about these systems at high redshift. Optical studies of high redshift groups have been limited because low galaxy densities make groups difficult to recognize even at moderate redshifts. X-ray emission from the intragroup medium provides a potentially useful method for finding groups at high redshift. A number of searches for faint, extended X-ray sources have been performed in recent years using deep ROSAT PSPC observations (e.g. Rosati et al 1995, Griffiths et al 1995, Scharf et al 1997, Burke et al 1997, Jones et al 1998, Schmidt et al 1998, Vikhlinin et al 1998, Zamorani et al 1999). Although the goal of these surveys is often to find rich clusters of galaxies at high redshift, many X-ray groups at redshifts $z = 0.1$–0.6 have also been found. Unfortunately, the ROSAT observations of these groups generally contain very few counts, so it is not possible to determine the temperature or the metallicity of the gas with the existing data. However, studies of the spectral properties of the intragroup medium out to $z \sim 0.3$ will be possible with

both XMM and CHANDRA. Furthermore, deep images with these telescopes will likely uncover X-ray groups at even higher redshifts. Therefore, the first studies of the evolution of the intragroup medium should be possible within the next decade.

5.6 Gravitational Lensing

The efficiency of a massive system to act as a gravitational lens is a function of both the mass-density profile and the source-lens-observer geometry (cf Blandford & Narayan 1992). Given their relatively high mass densities, X-ray groups at moderate ($z > 0.2$) redshifts are expected to be efficient lenses (Mendes de Oliveira & Giraud 1994, Montoya et al 1996). Unfortunately, because very few samples of galaxy groups at moderate redshift exist in the literature, systematic searches for lensing in these objects have not been carried out. However, several of the well-studied, multiple-image QSO systems are lensed by galaxies that belong to spectroscopically-confirmed poor groups (Kundic et al 1997a,b; Tonry 1998; Tonry & Kochanek 2000). Although the primary lens in each of these cases is an individual galaxy, the group potential also contributes to the observed lensing. The presence of an extended group potential acts as a source of external sheer (Keeton et al 1997; Kundic et al 1997a,b). To properly model the lensing system, the group potential must be included. Most authors have attempted to measure the velocity dispersion of the group and then assume a form for the potential. Unfortunately, these dispersions are based on only a few velocity measurements and are subject to the large uncertainties that have plagued optical studies of nearby groups. Still, good fits to the lensing data are often obtained. In the case of the quadruple lens PG 1115+080, the measured velocity dispersion of the group (Kundic et al 1997a; Tonry 1998) is consistent with the value predicted earlier from the lensing data (Schecter et al 1997). Obtaining an adequate model for the group potential is also necessary to derive cosmological parameters like the Hubble Constant (H_o) from lensing experiments. Future X-ray observations may be the key to such techniques. High-resolution X-ray images taken with CHANDRA and XMM should allow the potential of the lensing groups to be mapped in detail. A better determination of the lensing potential will result in tighter constraints on cosmological parameters.

5.7 Cooling Flows

Galaxy groups display many of the signatures of cooling flows that have previously been observed in rich clusters and elliptical galaxies (Fabian 1994). The surface brightness profiles of the X-ray emission are sharply peaked, indicating that the gas density is rising rapidly towards the center of the group. In addition, at least half of all groups with measured temperature profiles show direct evidence for cooler gas in the central regions (Ponman & Bertram 1993; David et al 1994; Trinchieri et al 1997; Mulchaey & Zabludoff 1998; Helsdon & Ponman 2000). In some cases, the central gas is cooler than the mean gas temperature by nearly 50%. Cooling flow models also appear to provide a better fit to the ASCA spectra of

groups than an isothermal plasma model (Buote 2000a). While these observations are consistent with the cooling flow interpretation, there are other possibilities. For example, Mulchaey & Zabludoff (1998) noted that the above features could also be explained if there is a distinct X-ray component associated with the central elliptical galaxy.

Perhaps the strongest case for a cooling flow in a low-mass system is the NGC 5044 group. David et al (1994) obtained a very deep ROSAT PSPC observation of this system that allowed the construction of a detailed temperature profile. They found evidence for a cooling flow with an essentially constant mass accretion rate from approximately 20 h_{100}^{-1} kpc out to the cooling radius ($\sim$50–75 h_{100}^{-1} kpc). This suggests a nearly homogeneous cooling flow. In contrast, the cooling flows in rich clusters tend to be inhomogeneous; a significant amount of the gas cools out at large radii (cf Fabian 1994). David et al (1994) suggest that gravitational heating is more important in the NGC 5044 group than in clusters because in groups the temperature of the hot gas is comparable to the virial temperature of the central galaxy, whereas for rich clusters the gas temperature is significantly higher. Therefore, most of the observed X-ray emission in the cooling flow region can be provided by the gravitational energy in groups, whereas mass deposition dominates in rich clusters.

5.8 Fossil Groups

Because of their relatively low velocity dispersions and high galaxy densities, groups of galaxies provide ideal sites for galaxy-galaxy mergers. Numerical simulations suggest that the luminous galaxies in a group will eventually merge to form a single elliptical galaxy (Barnes 1989, Governato et al 1991, Bode et al 1993, Athanassoula et al 1997). The merging timescales for the brightest group members ($M \approx M^*$) are typically a few tenths of a Hubble time for an X-ray detected group (Zabludoff & Mulchaey 1998). Therefore, by the present day some groups have likely merged into giant ellipticals. Outside of the high-density core, the cooling time for the intragroup medium is longer than a Hubble time; thus, while the luminous galaxies in some groups have had enough time to merge into a single object, the large-scale X-ray halo of the original groups should remain intact. This means that a merged group might appear today as an isolated elliptical galaxy with a group-like X-ray halo (Ponman & Bertram 1993).

Using the ROSAT All-Sky Survey data, Ponman et al (1994) found the first such "fossil" group candidate. The RXJ1340.6+4018 system has an X-ray luminosity comparable to a group, but $\sim$70% of the optical light comes from a single elliptical galaxy (Jones et al 2000). The galaxy luminosity function of RXJ1340.6+4018 indicates a deficit of galaxies at approximately M^*. The luminosity of the central galaxy is consistent with it being the merger product of the missing M^* galaxies. Jones et al (2000) have studied the central galaxy in detail and find no evidence for spectral features implying recent star formation, which indicates the last major merger occurred at least several gigayears ago.

Several other fossil group candidates are now known. Mulchaey & Zabludoff (1999) discovered a large X-ray emitting halo around the optically- selected isolated elliptical NGC 1132. Although the NGC 1132 system contains no other luminous galaxies, there is evidence for an extensive dwarf galaxy population clustered around the central galaxy. The dwarfs in NGC 1132 are comparable in number and distribution to the dwarfs found in X-ray groups (Zabludoff & Mulchaey 1998). The existence of a clustered dwarf population in fossil groups is not surprising because the galaxy-galaxy merger and dynamical friction timescales for faint galaxies in groups are significantly longer than the timescales for the luminous galaxies (Zabludoff & Mulchaey 1998). Hence, the dwarf galaxy population, like the X-ray halo, will remain long after the central elliptical has formed.

Vikhlinin et al (1999) have found four potential fossil groups in their large-area ROSAT survey of extended X-ray sources. (Their sample includes RXJ1340.6+4018 and two X-ray sources detected in earlier Einstein surveys but not previously recognized as potential group remnants.) Given the large surface area they covered in their survey, Vikhlinin et al were able to estimate the spatial density of X-ray fossil groups for the first time and found that these objects represent ~20% of all clusters and groups with an X-ray luminosity greater than $5 \times 10^{42} \, h_{100}^{-2}$ ergs s^{-1}. The number density of fossil groups is comparable to the number density of field ellipticals, so most, if not all, luminous field ellipticals may be the product of merged X-ray groups.

Although the X-ray and optical properties of some luminous, isolated elliptical galaxies are consistent with the merged group interpretation, another possibility is that these systems may have simply formed with a deficit of luminous galaxies (Mulchaey & Zabludoff 1999). Distinguishing between these two scenarios will be difficult, if not impossible. Regardless, these objects are massive enough and found in large enough numbers that they are cosmologically important. Vikhlinin et al (1999) estimated that the contribution of fossil groups to the mass density of the universe is comparable to the contribution of massive clusters. These objects are also an important reminder that galaxies are not always good tracers of mass and large-scale structure: optical group catalogs would miss these large mass concentrations.

5.9   The Origin and Evolution of the Intragroup Medium

The presence of heavy elements in the intragroup medium indicates that a substantial fraction of the diffuse gas must have passed through stars. The presence of iron is particularly important because it suggests that supernovae played an important role in the enrichment of the gas. In principle, X-ray spectroscopy can provide detailed constraints on the stars responsible for the enrichment. For example, the relative abundance of the α-burning elements to iron is a measure of the relative importance of Type II to Type 1a supernovae (Renzini et al 1993, Renzini 1997, Gibson et al 1997). For the gas temperatures characteristic of groups (~1 keV), strong emission lines are expected for many of the α elements including oxygen,

neon, magnesium, silicon and sulfur. Although most ASCA studies suggest that the α/Fe ratio is approximately solar in groups, this result is somewhat inconclusive at present because of uncertainties in the spectral modeling.

Renzini and collaborators have used the concept of iron mass-to-light ratio to study the history of the hot gas in groups and clusters (Renzini et al 1993, Renzini 1997). They find that the X-ray emitting gas in rich clusters contains ~ 0.01 $h^{-1/2}$ $M_\odot$ of iron for each $L_\odot$ of blue light. The iron mass-to-light ratio is effectively constant for clusters with temperature between ~ 2 and 10 keV. However, this ratio is typically a factor of ~ 50 lower in X-ray groups (Renzini et al 1993, Renzini 1997, Davis et al 1999). The iron mass-to-light ratios of groups are lower than those of clusters because both the overall iron abundance and the gas-to–stellar mass ratio are lower in groups than in clusters (Renzini 1997). The low iron mass-to-light ratios may be evidence that a significant amount of mass has been lost in groups. The escape velocities of groups are comparable to the escape velocities of individual galaxies. Thus, material that is ejected from galaxies may also escape the group. Several mechanisms have been proposed to eject material from groups, including galactic winds and outflows powered by supernovae or nuclear activity (Renzini 1997). The material lost from groups may have contributed significantly to the enrichment of the intergalactic medium (Davis et al 1999).

The iron mass-to-light ratios of groups could be somewhat underestimated if the true iron abundances are higher than the sub-solar values usually derived from isothermal model fits. However, the gas-mass estimates are less sensitive to the iron abundance assumed and uncertainties in the iron abundances likely lead to inaccuracies in the gas-mass estimates of at most $\sim 50\%$ (Pildis et al 1995). A potentially bigger problem is that many groups are detected to a much smaller fraction of the virial radius than their rich clusters counterparts. Thus, the true gas masses in some groups may be significantly underestimated from the existing X-ray data. In fact, it is possible that the differences in the iron mass-to-light ratios of groups and clusters may largely be a result of this effect and not necessarily evidence for mass loss.

The mechanisms responsible for producing metals may also inject energy into the gas. Numerical simulations indicate that in the absence of such non-gravitational heating, the density profiles of groups and clusters are nearly identical (Navarro et al 1997). There is now considerable evidence for departures from such uniformity. In the standard hierarchical clustering models, the X-ray luminosity is expected to scale with temperature as $L_X \propto T^2$ (e.g. Kaiser 1991). The observed relationship is considerably steeper, especially for small groups (see Figure 6). Furthermore, the ratio of specific energy of the galaxies to specific energy of the gas (i.e. the β parameter) is less than one for low-mass systems. (However, see Section 3.3.3 for a discussion of why the observed β values for groups may be biased low.) Both of these observations suggest that the gas temperature may not be a good indicator of the virial temperature in poor groups. Entropy profiles for groups and clusters indicate that the entropy of the group gas is also higher than can be achieved through gravitational collapse alone (David et al 1996, Ponman

et al 1999, Lloyd-Davies et al 2000). All of these observations are consistent with preheating models for the hot gas (Kaiser 1991; Evrard & Henry 1991; Metzler & Evrard 1994; Knight & Ponman 1997; Cavaliere et al 1997, 1998, 1999; Arnaud & Evrard 1999; Balogh et al 1999; Tozzi et al 2000; Loewenstein 2000; Tozzi & Norman 2000). Such preheating leads to a more extended gas component in groups than in rich clusters (i.e. lower central gas densities and shallower density slopes). Moreover, without preheating, groups appear to over-produce the X-ray background (Wu et al 2000).

Ponman and collaborators have estimated the excess entropy associated with the preheating in groups and find that it corresponds to a temperature of ~0.3 keV (Ponman et al 1999, Lloyd-Davies et al 2000). The preheating temperature can be combined with the excess entropy to estimate the electron density of the gas into which the energy was injected. The resulting value ($n \sim 4 \times 10^{-4} h_{100}^{0.5}$ cm^{-3}) implies that the heating occurred prior to the cluster collapse but after a redshift of $z \sim 10$ (Lloyd-Davies et al 2000). The current estimates for the entropy associated with the preheating have been based on rather small samples of groups and clusters, and these techniques will undoubtably improve with the next generation of X-ray telescopes. Already it is clear that such research can provide considerable insight into the history of the gas and group formation.

5.10 The Local Group

Finally, it is interesting to consider the implications X-ray observations of other groups have for our own Local Group. The idea that the Local Group might contain a hot intragroup medium dates back to the work of Kahn & Woltjer (1959). The X-ray detection of other groups has led to renewed interest in this idea. Suto et al (1996) proposed that a hot halo around the Local Group with a temperature of ~1 keV and column density $N_H \sim 10^{21}$ cm^{-2} could explain the observed excess in the X-ray background below 2 keV. The X-ray halo would also generate temperature anisotropies in the microwave background via the Sunyaev-Zeldovich effect. There is no evidence for such anisotropies in the COBE MDR maps, however (Banday & Górski 1996). Furthermore, the gas temperature and column density assumed by Suto et al (1996) are probably overestimated, given the ROSAT observations of other groups (Pildis & McGaugh 1996). In fact, the strong trend for spiral-only groups not to be X-ray detected suggests that the Local Group is unlikely to produce appreciable amounts of X-ray emission (Pildis & McGaugh 1996, Mulchaey et al 1996b).

Although the Local Group is probably not X-ray bright, a significant gas component may exist at cooler temperatures (Mulchaey et al 1996b, Fields et al 1997). Given the expected virial temperature of the Local Group (~0.2 keV), the detection of this gas in emission would be exceedingly difficult. However, an enriched collisionally ionized gas at these temperatures is expected to produce prominent absorption features in the far-UV region. The strongest features result from lithium-like ions O VI, Ne VIII, Mg X and Si XII (Verner et al 1994). Lines

of sight to hot stars in the Magellanic Clouds are known to show O VI absorption features, but it is not clear whether this gas is associated with intragroup gas or gas in our own Galaxy. There may be other ways to infer the presence of warm gas in the Local Group. Wang & McCray (1993) found evidence in the soft X-ray background for a thermal component with temperature $\sim$0.2 keV, which could be due to a warm intragroup medium in the Local Group (see, however, Sidher et al 1999, who argue that the X-ray halo of the Galaxy dominates). Maloney & Bland-Hawthorn (1999) have recently considered the ionizing flux produced by warm intragroup gas and find that it is unlikely to dominate over the cosmic background or the ultraviolet background produced by the luminous members of the Local Group. Still, encounters between the intragroup gas and the Magellanic Stream may be responsible for the strong Hα emission detected by Weiner & Williams (1996).

The existence of an intragroup medium in the Local Group may also be relevant to the H I high velocity clouds (HVCs; for a review see Wakker & van Woerden 1997). Recently, Blitz et al (1999) revived the idea that many of the HVCs may be dark-matter dominated structures falling onto the Local Group. In this scenario, some of the HVCs collide near the center of the Local Group and produce a warm intragroup medium. If the Blitz et al (1999) scenario is correct, one would expect to find similar H I clouds in other nearby groups. Blitz et al (1999) suggested that several HVC analogs have indeed been found. However, Zwaan & Briggs (2000) completed a H I strip survey of the extragalactic sky with Arecibo and detected no objects resembling the HVCs in other groups. The failure of the Arecibo survey to detect H I does not necessarily rule out the Blitz et al (1999) model. One possibility is that the groups in the Zwaan & Briggs (2000) survey contain an X-ray-emitting intragroup gas and that the H I clouds do not survive this hostile environment. Unfortunately, the X-ray properties of the Zwaan & Briggs (2000) groups are currently unknown. The conclusions of Zwaan & Briggs (2000) are also sensitive to the masses assumed for the H I clouds. Braun & Burton (2000) argued for a lower HVC H I mass and concluded that the sensitivity and coverage of Zwaan & Briggs's (2000) survey was not sufficient to detect analogs of the HVCs in other groups. A more serious problem may be the number statistics of moderate redshift Mg II and Lyman limit absorbers, which appear to be inconsistent with a Local Group origin for the HVCs (Charlton et al 2000). Regardless, it is clear that future H I surveys of X-ray detected and X-ray–non-detected groups could provide important insight into the relationship between hot and cold gas in galaxy groups.

6.   FUTURE WORK

X-ray telescopes launched in the 1990s have firmly established the presence of a hot X-ray-emitting intragroup medium in nearby groups of galaxies. X-ray obser-vations suggest that many groups are real, physical systems. The masses of X-ray

groups are substantial and make a significant contribution to the mass density of the universe. Although most of the mass in groups appears to be in dark matter, the intragroup medium may be the dominant baryonic component in the nearby universe.

While we have made significant progress towards understanding groups in the last decade, there are still many outstanding issues. Ambiguities about the proper spectral model for the gas and our inability to detect gas to a large fraction of the virial radius are particularly troubling because the resulting uncertainties propagate into cosmological applications. Furthermore, the contribution of individual galaxies to the observed X-ray emission remains a point of contention. Our ability to understand the intragroup medium has largely been limited by the poor spatial and spectral resolution of the X-ray instruments. This situation is about to change drastically, however, with the availability of new powerful X-ray telescopes. Recently, NASA successfully launched CHANDRA (formerly known as AXAF). This telescope will produce high-resolution X-ray images of groups ($\sim 1''$) that will allow the relative contribution of galaxies and diffuse gas to be quantified. In late 1999, the European Space Agency (ESA) launched XMM-Newton. Although the spatial resolution of XMM-Newton is poorer than that of CHANDRA, the collecting area of this telescope is much greater. Therefore, XMM-Newton will obtain the deepest X-ray exposures ever of nearby groups and will extend the studies of the group environment to higher redshifts. The combination of CHANDRA and XMM-Newton will probably answer many of the questions raised by the recent generation of X-ray telescopes.

ACKNOWLEDGMENTS

Visit the Annual Reviews home page at http://www.AnnualReviews.org

LITERATURE CITED

Albert CE, White RA, Morgan WW. 1977. *Ap. J.* 211:309–10

Allen SW, Fabian AC, Edge AC, Böhringer H, White DA. 1995. *MNRAS* 275:741–54

Arimoto N, Matsushita K, Ishimaru Y, Ohashi T, Renzini A. 1997 *Ap. J.* 477:128–143

Arnaud M, Evrard AE. 1999. *MNRAS* 305:631–40

Aschenbach B. 1988. *Appl. Optics* 27:1404–13

Athanassoula E, Makino J, Bosma A. 1997. *MNRAS* 286:825–38

Bahcall NA, Harris DE, Rood HJ. 1984. *Ap. J.* 284:L29–33

Bahcall NA, Lubin LM. 1994. *Ap. J.* 426:513–15

Balogh ML, Babul A, Patton DR. 1999. *MNRAS* 307:463–79

Banday AJ, Górski KM. 1996. *MNRAS* 283:L21–25

Barnes JE. 1985. *MNRAS* 215:517–36

Barnes JE. 1989. *Nature* 338:123–26

Bartelmann M, Steinmetz M. 1996. *MNRAS* 283:431–46

Batuski DJ, Burns JO. 1985. *Astron. J.* 90:1413–24

Bauer F, Bregman JN. 1996. *Ap. J.* 457:382–89

Bergeron J, Petitjean P, Sargent WLW, Bahcall JN, Boksenberg A, et al. 1994. *Ap. J.* 436:33–43

Biermann P, Kronberg PP. 1983. *Ap. J.* 268:L69–73

Biermann P, Kronberg PP, Madore BF. 1982. *Ap. J.* 256:L37–40

Bird CM, Mushotzky RF, Metzler CA. 1995. *Ap. J.* 453:40–47

Blandford RD, Narayan R. 1992. *Annu. Rev. Astron. Astrophy.* 30:311–58

Blitz L, Spergel DN, Teuben PJ, Hartmann D, Burton WB. 1999. *Ap. J.* 514:818–43

Bode PW, Cohn HN, Lugger PM. 1993. *Ap. J.* 416:17–25

Braun R, Burton WB. 2000. *Astron. Astrophys.* submitted

Buote DA. 1999. *MNRAS* 309:685–714

Buote DA. 2000a. *MNRAS* 311:176–200

Buote DA. 2000b. *Ap. J.* in press

Buote DA. 2000c. *Ap. J.* in press

Burke DJ, Collins CA, Sharples RM, Romer AK, Holden BP, et al. 1997. *Ap. J.* 488:L83–86

Burns JO, Gregory SA, Holman GD. 1981. *Ap. J.* 250:450–63

Burns JO, Ledlow MJ, Loken C, Klypin A, Voges W, et al. 1996. *Ap. J.* 467:L49–52

Cavaliere A, Menci N, Tozzi P. 1997. *Ap. J.* 484:L21–24

Cavaliere A, Menci N, Tozzi P. 1998. *Ap. J.* 501:493–508

Cavaliere A, Menci N, Tozzi P. 1999. *MNRAS* 308:599–608

Cen R, Ostriker JP. 1999. *Ap. J.* 514:1–6

Charlton JC, Churchill CW, Rigby JR. 2000. *Ap. J.* submitted

Cooke BA, Ricketts MJ, Maccacaro T, Pye JP, Elvis M, et al. 1978. *MNRAS* 182:489–515

Cowie LL, Henriksen M, Mushotzky R. 1987. *Ap. J.* 317:593–600

David LP. 1997. *Ap. J.* 484:L11–15

David LP, Arnaud KA, Forman W, Jones C. 1990. *Ap. J.* 356:32–40

David LP, Jones C, Forman W. 1995. *Ap. J.* 445:578–90

David LP, Jones C, Forman W. 1996. *Ap. J.* 473:692–706

David LP, Jones C, Forman W, Daines S. 1994. *Ap. J.* 428:544–54

Davis DS, Mulchaey JS, Mushotzky RF. 1999. *Ap. J.* 511:34–40

Davis DS, Mulchaey JS, Mushotzky RF, Burstein D. 1996. *Ap. J.* 460:601–11

Davis DS, Mushotzky RF, Mulchaey JS, Worrall DM, Birkinshaw M, Burstein D. 1995. *Ap. J.* 444:582–89

Dell'Antonio IP, Geller MJ, Fabricant DG. 1994. *Astron. J.* 107:427–47

de Vaucouleurs G. 1965. in *Stars and Stellar Systems*, ed. A. Sandage, M. Sandage and J. Kristian (Chicago: Univesity of Chicago Press)

Diaferio A, Geller MJ, Ramella M. 1994. *Astron. J.* 107:868–79

Diaferio A, Geller MJ, Ramella M. 1995. *Astron. J.* 109:2293–2303

Diaferio A, Ramella M, Geller MJ, Ferrari A. 1993. *Astron. J.* 105:2035–46

Doe SM, Ledlow MJ, Burns JO, White RA. 1995. *Astron. J.* 110:46–67

Dos Santos S, Mamon GA. 1999. *Astron. Astrophys.* 352:1–18

Ebeling H, Voges W, Böhringer H. 1994. *Ap. J.* 436:44–55

Edge AC, Stewart GC. 1991. *MNRAS* 252:428–41

Evrard AE, Henry JP. 1991. *Ap. J.* 383:95–103

Evrard AE, Metzler CA, Navarro JF. 1996. *Ap. J.* 469:494–507

Fabian AC. 1994. *Annu. Rev. Astron. Astrophys.* 32:277–318

Fabian AC, Arnaud KA, Bautz MW, Tawara Y. 1994. *Ap. J.* 436:L63–66

Fabricant D, Gorenstein P. 1983. *Ap. J.* 267:535–46

Fabricant D, Lecar M, Gorenstein P. 1980. *Ap. J.* 241:552–60

Fabricant D, Rybicki G, Gorenstein P. 1984. *Ap. J.* 286:186–95

Fields BD, Mathews GJ, Schramm DN. 1997. *Ap. J.* 483:625–37

Finoguenov A, Ponman TJ. 1999. *MNRAS* 305:325–37

Forman W, Jones C. 1982. *Annu. Rev. Astron. Astrophys.* 20:547–85

Frederic JJ. 1995. *Ap. J. Suppl.* 97:259–74

Fukazawa Y, Makishima K, Matsushita K, Yamasaki N, Ohashi T, et al. 1996. *Publ. Astron. Soc. Japan* 48:395–407

Fukazawa Y, Makishima K, Tamura T, Ezawa H, Xu H, et al. 1998. *Publ. Astron. Soc. Japan* 50:187–93

Fukugita M, Hogan CJ, Peebles PJE. 1998. *Ap. J.* 503:518–30

Geller MJ, Huchra JP. 1983. *Ap. J. Suppl.* 52:61–87

Gendreau KC. 1995. *X-ray CCDs for Space Applications: Calibration, Radiation Hardness, and Use for Measuring the Spectrum of the Cosmic X-ray Background.* PhD thesis. Massachusetts Institute of Technology.

Gibson BK, Loewenstein M, Mushotzky RF. 1997. *MNRAS* 290:623–28

Governato F, Bhatia R, Chincarini G. 1991. *Ap. J.* 371:L15–18

Governato F, Tozzi P, Cavaliere A. 1996. *Ap. J.* 458:18–26

Griffiths RE, Georgantopoulos I, Boyle BJ, Stewart GC, Shanks T, Della Ceca R. 1995. *MNRAS* 275:77–88

Griffiths RE, Schwartz DA, Schwarz J, Doxsey RE, Johnson MD, et al. 1979. *Ap. J.* 230:L21–25

Hellsten U, Gnedin NY, Miralda-Escude J. 1998. *Ap. J.* 509:56–61

Helsdon SF, Ponman TJ. 2000. *MNRAS* in press

Henriksen MJ, Mamon GA. 1994. *Ap. J.* 421:L63–66

Henry JP, Gioia IM, Huchra JP, Burg R, McLean B, et al. 1995. *Ap. J.* 449:422–30

Hernquist L, Katz N, Weinberg DH. 1995. *Ap. J.* 442:57–60

Hickson P. 1982. *Ap. J.* 255:382–91

Hickson P. 1997. *Annu. Rev. Astron. Astrophys.* 35:357–88

Hickson P, Huchra J, Kindl E. 1988. *Ap. J.* 331:64–70

Holmberg E. 1950. *Medd. Lunds Obs. Ser. 2* 128:1–56

Horner DJ, Mushotzky RF, Scharf CA. 1999. *Ap. J.* 520:78–86

Huchra JP, Geller MJ. 1982. *Ap. J.* 257:423–37

Humason ML, Mayall NU, Sandage AR. 1956. *Ap. J.* 61:97–162

Hunt R, Sciama DW. 1972. *MNRAS* 157:335–48

Hwang U, Mushotzky RF, Burns JO, Fukazawa Y, White RA. 1999. *Ap. J.* 516:604–18

Hwang U, Mushotzky RF, Loewenstein M, Markert, TH, Fukazawa Y, Matsumoto H. 1997. *Ap. J.* 476:560–71

Ikebe Y, Ezawa H, Fukazawa Y, Hirayama M, Izhisaki Y, et al. 1996. *Nature* 379:427–29

Ishimaru Y, Arimoto N. 1997. *PASJ* 49:1–8

Jones C, Forman W. 1984. *Ap. J.* 276:38–55

Jones LR, Ponman TJ, Forbes DA. 2000. *MNRAS* 312:139–50

Jones LR, Scharf C, Ebeling H, Perlman E, Wegner G, et al. 1998. *Ap. J.* 495:100–14

Kaastra JS, Mewe R. 1993. *Astron. Astrophys. Suppl.* 97:443–82

Kahn FD, Woltjer L. 1959. *Ap. J.* 130:705–17

Kaiser N. 1991. *Ap. J.* 383:104–111

Keeton CR, Kochanek CS, Seljak U. 1997. *Ap. J.* 482:604–20

King IR. 1962. *Astron. J.* 67:471–85

Knight PA, Ponman TJ. 1997. *MNRAS* 289: 955–72

Kriss GA, Canizares CR, McClintock JE, Feidelson ED. 1980. *Ap. J.* 235:L61–65

Kriss GA, Cioffi DF, Canizares CR. 1983. *Ap. J.* 272:439–48

Kundic T, Cohen JG, Blandford RD, Lubin LM. 1997a. *Astron. J.* 114:507–10

Kundic T, Hogg DW, Blandford RD, Cohen JG, Lubin LM, et al. 1997b. *Astron. J.* 114:2276–83

Ledlow MJ, Loken C, Burns JO, Hill JM, White RA. 1996. *Astron. J.* 112:388–406

Liedahl DA, Kahn SM, Osterheld AL, Goldstein WH. 1990. *Ap. J.* 350:L37–40

Liedahl DA, Osterheld AL, Goldstein WH. 1995. *Ap. J.* 438:L115–118

Lloyd-Davies EJ, Ponman TJ, Cannon DB. 2000. *MNRAS* In press

Loewenstein M. 2000. *Ap. J.* In press

Mahdavi A, Böhringer H, Geller MJ, Ramella M. 1997. *Ap. J.* 483:68–76

Mahdavi A, Böhringer H, Geller MJ, Ramella M. 2000. *Ap. J.* in press

Mahdavi A, Geller MJ, Böhringer H, Kurtz MJ, Ramella M. 1999. *Ap. J.* 518:69–93

Maloney PR, Bland-Hawthorn J. 1999. *Ap. J.* 522:L81–84

Mamon GA. 1986. *Ap. J.* 307:426–30

Materne J. 1979. *Astron. Astrophys.* 74:235–43

Matsushita K, Ohashi T, Makishima K. 2000. *PASJ* in press

McWilliam A. 1997. *Annu. Rev. Astron. Astrophys.* 35:503–56

Mendes de Oliveira C, Giraud E. 1994. *Ap. J.* 437:L103–106

Metzler CA, Evrard AE. 1994. *Ap. J.* 437:564–83

Mewe R. 1991. *Astron. & Astrophys. Review* 3:127–68

Mewe R, Gronenschild EHBM, van den Oord GHJ. 1985. *Astron. Astrophys. Suppl.* 62:197–254

Miralda-Escude J, Cen R, Ostriker JP, Rauch M. 1996. *Ap. J.* 471:582–616

Mohr JJ, Evrard AE. 1997. *Ap. J.* 491:38–44

Mohr JJ, Mathiesen B, Evrard AE. 1999. *Ap. J.* 517:627–49

Montoya ML, Dominguez-Tenreiro R, Gonzalez-Casado G, Mamon GA, Salvador-Sole E. 1996. *Ap. J.* 473:L83–86

Morgan WW, Kayser S, White RA. 1975. *Ap. J.* 199:545–48

Morrison R, McCammon D. 1983. *Ap. J.* 270:119–22

Mulchaey JS, Davis DS, Mushotzky RF, Burstein D. 1993. *Ap. J.* 404:L9–12

Mulchaey JS, Davis DS, Mushotzky RF, Burstein D. 1996a. *Ap. J.* 456:80–97

Mulchaey JS, Davis DS, Mushotzky RF, Burstein D. 2000. *Ap. J.* in preparation

Mulchaey JS, Mushotzky RF, Burstein D, Davis DS. 1996b. *Ap. J.* 456:L5–8

Mulchaey JS, Zabludoff AI. 1998. *Ap. J.* 496:73–92

Mulchaey JS, Zabludoff AI. 1999. *Ap. J.* 514:133–37

Mullis CR, Henry JP, Gioia IM, Böhringer H, Briel UG. 2000. *Ap. J.* in preparation.

Mushotzky RF. 1984. *Physica Scripta* T7:157–62

Navarro JF, Frenk CS, White SDM. 1995. *MNRAS* 275:720–40

Navarro JF, Frenk CS, White SDM. 1997. *Ap. J.* 490:493–508

Nolthenius R. 1993. *Ap. J. Suppl.* 85:1–25

Nolthenius R, White SDM. 1987. *MNRAS* 225:505–30

Ohashi T, Ebisawa K, Fukazawa Y, Hiyoshi K, Horii M, et al. 1996. *PASJ* 48:157–70

Oort JH. 1970. *Astron. Astrophys.* 7:381–404

Ostriker JP, Lubin LM, Hernquist L. 1995. *Ap. J.* 444:L61–64

Pedersen K, Yoshii Y, Sommer-Larsen J. 1997. *Ap. J.* 485:L17–20

Perna R, Loeb A. 1998. *Ap. J.* 503:L135–138

Pfeffermann E, Briel UG, Hippmann H, Kettenring G, Metzner G, et al. 1988. *Proc. SPIE* 733:519–32

Pierre M, Bryan G, Gastaud R. 2000. *Astron. Astrophys.* Submitted

Pietsch W, Trinchieri G, Arp H, Sulentic JW. 1997. *Astron. Astrophys.* 322:89–97

Pildis RA, Bregman JN, Evrard AE. 1995. *Ap. J.* 443:514–26

Pildis RA, Evrard AE, Bregman JN. 1996. *Astron. J.* 112:378–87

Pildis RA, McGaugh SS. 1996. *Ap. J.* 470:L77–79

Ponman TJ, Allan DJ, Jones LR, Merrifield M, McHardy IM, et al. 1994. *Nature* 369:462–64

Ponman TJ, Bertram D. 1993. *Nature* 363:51–54

Ponman TJ, Bourner PDJ, Ebeling H, Böhringer H. 1996. *MNRAS* 283:690–708

Ponman TJ, Cannon DB, Navarro JF. 1999. *Nature* 397:135–137

Price R, Duric N, Burns JO, Newberry MV. 1991. *Astron. J.* 102:14–29

Ramella M, Geller MJ, Huchra JP. 1989. *Ap. J.* 344:57–74

Ramella M, Geller MJ, Huchra JP, Thorstensen JR. 1995. *Astron. J.* 109:1458–75

Ramella M, Pisani A, Geller MJ. 1997. *Astron. J.* 113:483–91

Raymond JC, Smith BW. 1977. *Ap. J. Suppl.* 35:419–39

Renzini A. 1997. *Ap. J.* 488:35–43

Renzini A, Ciotti L, D'Ercole A, Pellegrini S. 1993. *Ap. J.* 419:52–65

Rhee G, van Haarlem M, Katgert P. 1992. *Astron. J.* 103, 1721–28

Ribeiro ALB, De Carvalho RR, Coziol R, Capelato HV, Zepf SE. 1996. *Ap. J.* 463:L5–8

Ricker G, Doxsey RE, Dower RG, Jernigan JG, Delvailee JP, et al. 1978. *Nature* 271:35–37

Rosati P, Della Ceca R, Burg R, Norman C, Giacconi R. 1995. *Ap. J.* 445:L11–14

Ruderman MA, Spiegel EA. 1971. *Ap. J.* 165:1–15

Saracco P, Ciliegi P. 1995. *Astron. Astrophys.* 301:348–58

Sarazin CL. 1986. *Review Modern Physics* 58:1–115

Sarazin CL, Burns JO, Roettiger K, McNamara BR. 1995. *Ap. J.* 447:559–71

Savage BD, Tripp TM, Lu L. 1998. *Astron. J.* 115:436–50

Scharf CA, Jones LR, Ebeling H, Perlman E, Malkan M, et al. 1997. *Ap. J.* 477:79–92

Schechter PL, Bailyn CD, Barr R, Barvainis R, Becker CM, et al. 1997. *Ap. J.* 475:L85–88

Schmidt M, Hasinger G, Gunn, J, Schneider D, Burg R, et al. 1998. *Astron. Astrophys.* 329:495–503

Schwartz DA, Schwarz J, Tucker W. 1980. *Ap. J.* 238:L59–62

Sidher SD, Sumner TJ, Quenby JJ. 1999. *Astron. Astrophys.* 344:333–41

Silk J, Tarter J. 1973. *Ap. J.* 183:387–410

Sulentic JW, Pietsch W, Arp H. 1995. *Astron. Astrophys.* 298:420–26

Suto Y, Makishima K, Ishisaki Y, Ogasaka Y. 1996. *Ap. J.* 461:L33–36

Tanaka Y, Inoue H, Holt SS. 1994. *Publ. Astron. Soc. Japan* 46, L37–41

Tonry JL. 1998. *Astron. J.* 115:1–5

Tonry JL, Kochanek CS. 2000. *Astron. J.* 117:2034–38

Tozzi P, Norman C. 2000. *Ap. J.* in press

Tozzi P, Scharf C, Norman C. 2000. *Ap. J.* in press

Trinchieri G, Fabbiano G, Kim D-W. 1997. *Astron. Astrophys.* 318:361–75

Tully RB. 1987. *Ap. J.* 321:280–304

Verner DA, Tytler D, Barthel PD. 1994. *Ap. J.* 430:186–90

Vikhlinin A, McNamara BR, Forman W, Jones C, Quintana H, et al. 1998. *Ap. J.* 502:558–81

Vikhlinin A, McNamara BR, Hornstrup A, Quintana H, Forman W, et al. 1999. *Ap. J.* 520:L1–4

Voges W. 1993. *Adv. Space Res.* 13:12391–97

Wakker BP, van Woerden H. 1997. *Annu. Rev. Astron. Astrophys.* 35:217–66

Walke DG, Mamon GA. 1989. *Astron. Astrophys.* 225:291–302

Walker TP, Steigman G, Kang HS, Schramm DM, Olive KA. 1991. *Ap. J.* 376:51–69

Wang QD, McCray R. 1993. *Ap. J.* 409:L37–40

Ward MJ, Wilson AS, Penston MV, Elvis M, Maccacaro T, et al. 1978. *Ap. J.* 223:788–97

Weiner BJ, Williams TB. 1996. *Astron. J.* 111:1156–63

Wells A, Abbey AF, Barstow MA, Cole RE, Pye JP, et al. 1990. *Proc. SPIE* 733:519–532

White DA. 2000. *MNRAS* 312:663–88

White RA, Bliton M, Bhavsar SP, Bornmann P, Burns JO, et al. 1999. *Astron. J.* 118:2014–37

White RE. 1991. *Ap. J.* 367:69–77

White SDM, Navarro JF, Evrard AE, Frenk CS. 1993. *Nature* 366:429–33

Wu KKS, Fabian AC, Nulsen PEJ. 2000. *MNRAS* in press

Wu X-P, Xue Y-J, Fang L-Z. 1999. *Ap. J.* 524:22–30

Xue Y, Wu X-P. 2000. *Ap. J.* in press

Zabludoff AI, Mulchaey JS. 1998. *Ap. J.* 496:39–72

Zamorani G, Mignoli M, Hasinger G, Burg R, Giacconi R, et al. 1999. *Astron. Astrophys.* 346:731–52

Zwaan MA, Briggs FH. 2000. *Ap. J.* 530:L61–64