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The Intragroup Medium

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Abstract

X-ray surveys over the last decade have shown that approximately half of all nearby groups of galaxies contain spatially extended X-ray emission. This X-ray emission is produced by a low-density gas component referred to as the intragroup medium. All groups with an X-ray emitting intragroup medium contain at least one early-type galaxy. In most cases, the X-ray emission is centered on an elliptical galaxy. The presence of a hot gas halo indicates that many groups are real, physical systems and not chance superpositions. Assuming the hot gas is in hydrostatic equilibrium, the temperature of the gas can be used to estimate the mass of individual groups. Such estimates indicate that X-ray groups are massive systems dominated by dark matter. The intragroup medium also carries an imprint of the physical processes that have occurred in these systems. There is now considerable evidence that groups depart from the simplest predictions of cold dark matter models. In particular, nongravitational processes have been very important in groups. While there has been considerable effort by the theoretical community in the last few years to understand these processes, recent observations suggest most of the proposed models have important flaws.

1.1 Introduction

Groups of galaxies constitute the most common galaxy associations, containing at least 50% of all galaxies at the present day (Geller & Huchra 1983; Tully 1987; Nolthenius & White 1987). Groups are, therefore, an important laboratory for studying the processes associated with galaxy formation and evolution. However, we know surprisingly little about these systems compared to rich clusters. This is because group studies are hampered by small number statistics—a typical poor group contains only a few bright 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, but rather chance superpositions or large-scale structure filaments viewed edge-on (Frederic 1995; Hernquist, Katz, & Weinberg 1995; Ramella, Pisani, & Geller 1997).

The discovery that many groups are X-ray sources has provided considerable new insight into these important systems. *ROSAT* observations indicate that the X-ray emission in groups is often extended on scales of hundreds of kiloparsecs. 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. This diffuse, extended gas component is referred to as the intragroup medium by analogy with the intracluster medium found in rich clusters of galaxies (see Mushotzky 2004).

The mere presence of a hot gas halo indicates that many groups are real, physical systems. This fact has been further demonstrated by optical studies that show that X-ray groups contain a large number of galaxies (at least ∼20–50 members down to few magnitudes fainter than M_*; Zabludoff & Mulchaey 1998). Like rich clusters, these groups also contain a high fraction of early-type galaxies and follow a morphology-density relation (Helsdon & Ponman 2003a). Thus, in some ways, X-ray groups can be thought of as "mini-clusters." However, some important physical differences exist between these systems. Many of the mechanisms that have been proposed to drive galaxy evolution in clusters (such as ram-pressure stripping and galaxy harassment) are not expected to be important in groups. Galaxy-galaxy interactions, however, are likely more frequent in groups than in rich clusters, given the lower velocity dispersions of groups. The lower masses of groups also means that nongravitational processes such as heating by supernovae and active galactic nuclei (AGNs) likely have a bigger impact on the X-ray emitting gas than in rich clusters. In fact, the potential wells of groups are small enough that they cannot be considered "closed box" systems like clusters: strong galactic winds may be able to drive baryons out of these systems (Renzini et al. 1993; Renzini 1997; Davis, Mulchaey, & Mushotzky 1999).

Although there were clues from the *Einstein* Observatory that some groups are X-ray sources (Biermann, Kronberg, & Madore 1982; Biermann & Kronberg 1983; Bahcall, Harris, & Rood 1984), detailed studies of the intragroup medium were not possible prior to the *ROSAT* mission. The low internal background, large field of view, and good sensitivity to soft X-rays made the *ROSAT* PSPC detectors ideal instruments for studying nearby groups. This meeting marks the 10-year anniversary of the first *ROSAT* papers on poor groups (Mulchaey et al. 1993; Ponman & Bertram 1993). While most of what we know about the intragroup medium is still based on *ROSAT* data, this situation is rapidly changing. I expect that in a few years the current generation of X-ray telescopes (*Chandra* and *XMM-Newton*) will play a dominant role in our understanding of the hot gas in groups.

1.2 *ROSAT* Studies

It was clear from the earliest surveys with *ROSAT* that not all groups contain an X-ray emitting intragroup medium (Ebeling, Voges, & Böhringer 1994; Pildis, Bregman, & Evrard 1995; Saracco & Ciliegi 1995; Mulchaey et al. 1996a; Ponman et al. 1996). The fraction of groups that contain extended X-ray emission has been estimated from several studies. Mahdavi et al. (2000) used the *ROSAT* All-Sky Survey to search for X-ray emission from a sample of 260 groups taken from the combined Center for Astrophysics and Southern Sky Redshift Surveys. After accounting for selection effects, they estimate that ∼40% of the groups are extended X-ray sources. Deeper exposures taken from the "pointed mode" phase of the *ROSAT* mission (during this phase *ROSAT* pointed at specific targets in the sky for exposure times typically 10 to 50 times longer than those of the All-Sky Survey) are consistent with the Mahdavi et al. (2000) estimate (Helsdon & Ponman 2000a; Mulchaey et al. 2003). Thus, approximately half of all nearby groups contain an X-ray emitting intragroup medium.

Many studies have looked for trends between the presence of X-ray gas and the global properties of the group. There appears to be very few, if any, trends between properties such as compactness and optical luminosity and the X-ray properties of groups (Mulchaey et al.

1996a; Ponman et al. 1996; Helsdon & Ponman 2000b). However, the presence of extended X-ray emission in groups is strongly linked to the presence of early-type galaxies. In fact, all of the groups detected by *ROSAT* contain at least one early-type galaxy (Mulchaey et al. 2003). This result has implications for our own Local Group, which by the present definition would be defined as a spiral-only group and thus would not be expected to be X-ray detected. (The spiral fraction of a group is generally determined from only the most luminous members of each group, and at the distance of a typical object in the *ROSAT* surveys, the Local Group would only include the Milky Way, M31, and M33).

The failure to detected spiral-only groups with *ROSAT* is not surprising when one considers the expected gas temperature and density for these systems. Based on their velocity dispersions, the virial temperatures of spiral-only groups should be lower than those of their early-type dominated counterparts (Mulchaey et al. 1996b). For a system like the Local Group, the gas temperature is likely 2–3 million degrees Kelvin (e.g., Maloney & Bland-Hawthorn 1999). Such gas would be very difficult to detect with *ROSAT*. However, a "warm" intragroup medium might produce detectable features in the far-UV or X-ray spectra of background quasars (Mulchaey et al. 1996b; Perna & Loeb 1998; Hellsten, Gnedin, & Miralda-Escudé 1998; Fang & Canizares 2000). While many high-ionization absorption features have now been detected (e.g., Fang et al. 2002; Mathur, Weinberg, & Chen 2003; Sembach et al. 2003), associating these lines with a warm intragroup medium has proved difficult. The most promising case to date was the possible detection with *Chandra* of an O VIII Lyα absorption feature at the recessional velocity of a small spiral-rich group along the sight line toward PKS 2155–304 (Fang et al. 2002). However, subsequent observations of the same target with *XMM-Newton* do not detect the O VIII feature (Rasmussen, Kahn, & Paerels 2003).

1.3 Spatial Properties of the Intragroup Medium

The morphology of the X-ray emission can provide important clues into the nature of the hot gas. Most of the groups studied with *ROSAT* have round, symmetrical morphologies (e.g., NGC 2563 group; Fig. 1.1). These morphologies are consistent with the groups being relaxed systems. In almost all cases, the X-ray emission is peaked on a luminous elliptical galaxy (Mulchaey & Zabludoff 1998; Helsdon & Ponman 2000a). The position of the central 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. In addition, the properties of the central galaxy are closely related to the group potential. For example, Mulchaey & Zabludoff (1998) note a trend for the position angle of the optical light in the central galaxy to align with the position angle of the large-scale X-ray emission. The X-ray luminosities of the central galaxies are also more strongly correlated with the X-ray luminosity of the group than with the optical light of the central galaxy (Helsdon & Ponman 2003b). These observations suggest that the formation and evolution of the central galaxy is strongly linked to the overall group potential.

A few nearby groups have bimodal X-ray morphologies (e.g., NGC 4065; Fig. 1.1). In all these cases, the second X-ray peak is also centered on a luminous early-type galaxy. These objects may be two groups in the process of merging. Based on *ROSAT* surveys, such groups are relatively rare in the nearby Universe. Although the statistics are still poor, bimodal X-ray groups may be more common at higher redshifts (Bauer et al. 2002).

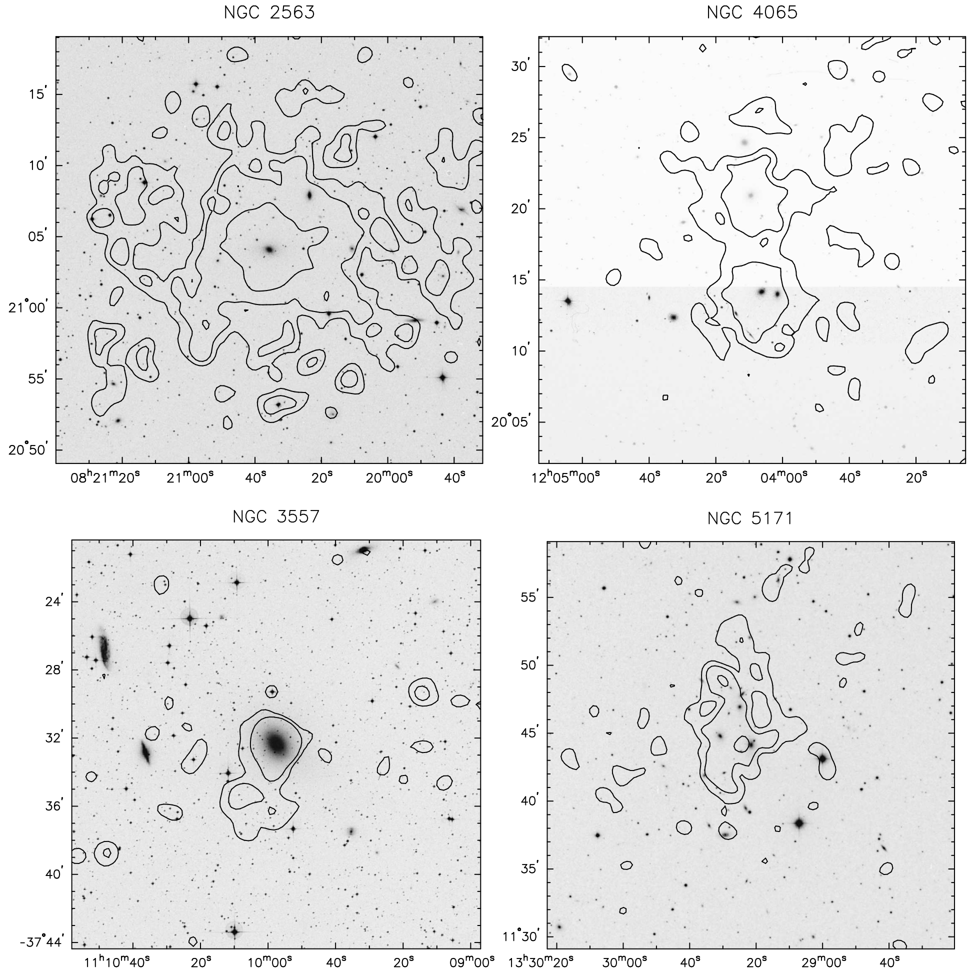

Fig. 1.1. Contour maps of diffuse X-ray emission of four groups measured with *ROSAT* overlaid on optical images. (Adapted from Mulchaey et al. 2003.)

For a few groups, the X-ray emission is not peaked on an individual galaxy (e.g., the NGC 5171 group, Fig. 1.1; see Osmond & Ponman 2004 for a detailed study of this system). In many of these systems, the X-ray emission may not be related to the global group potential at all. For example, much of the X-ray emission in HCG 16 appears to be associated with star formation and nuclear activity (Dos Santos & Mamon 1999; Turner et al. 2001; Belsole al. 2003). In HCG 92, the morphology of the X-ray emission matches the morphology of the radio continuum and optical emission-line maps, suggesting the X-ray emission is due to a large-scale shock (Pietsch et al. 1997; Sulentic et al. 2001). Regardless of the exact origin of the gas, the clumpy X-ray morphologies suggest the gas is likely not virialized in these cases.

Recent *Chandra* and *XMM-Newton* observations have revealed “holes” in the surface brightness distributions of some groups (Vrtilek et al. 2000; Buote et al. 2003). These

X-ray cavities have also been observed in many clusters with *Chandra* (Fabian et al. 2000; McNamara et al. 2000; Blanton et al. 2001; David et al. 2001; McNamara et al. 2001; Heinz et al. 2002; Sun et al. 2003) and are believed to be produced by an interaction with radio lobes from a central AGN (Churazov et al. 2001; Nulsen et al. 2002; Soker, Blanton, & Sarazin 2002). Neither of the two groups that have been studied in detail (HCG 62 and NGC 5044) show evidence for a central AGN or for radio lobes in existing radio maps. One possibility is that these cavities were created during an earlier epoch when the central galaxies were active and the high-energy, radio-emitting electrons have been lost. In addition to cavities, the NGC 5044 group also displays sharp edge-like features (David et al. 1994; Buote et al. 2003) that have been interpreted as "cold fronts," discontinuities between regions of different temperature and density, in clusters (Markevitch, Vikhlinin, & Mazzotta 2001). It is difficult to determine how common such features are in groups at the present time because so few objects with deep *Chandra* or *XMM-Newton* exposures have been analyzed. This situation should change dramatically in the next few years.

Traditionally, a hydrostatic isothermal model has been used to describe the surface brightness profiles of rich clusters (e.g., Jones & Forman 1984). Most authors have also adopted this model for galaxy groups. With King's (1962) analytic approximation to the isothermal sphere, the X-ray surface brightness at a projected radius r is given by:

$$S(r) = S_0(1 + (r/r_c)^2)^{-3\beta+0.5}, \tag{1.1}$$

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

$$\beta \equiv \mu m_p \sigma^2 / kT_{gas}, \tag{1.2}$$

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. In general, the standard β model provides a good fit to the surface brightness profiles of rich clusters, with a typical β value of about 2/3 (e.g., Arnaud & Evrard 1999; Mohr, Mathiesen, & Evrard 1999).

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 β model to small radii. Mulchaey & Zabludoff (1998) suggested that the *ROSAT* profiles of groups could be adequately fit using two separate β models: one associated with the central galaxy (the "central" component) and one associated with the large-scale group emission (the "extended" component). Subsequent work by Helsdon & Ponman (2000a) found a strong correlation between the β value of the "extended" component and gas temperature, with cooler systems having lower β values. This trend has recently been verified by Sanderson et al. (2003) using a combination of *ROSAT* and *ASCA* data. Helsdon & Ponman (2000a) found a mean β value of $\sim$0.46 for the "extended" component in groups, which is significantly lower than the typical value for a rich cluster. Higher resolution *Chandra* and *XMM-Newton* data are also consistent with groups having lower β values (Helsdon, Ponman, & Mulchaey 2004; Mushotzky et al. 2004). In the absence of nongravitational heating and/or cooling, the standard cold dark matter (CDM) model predicts that the shape of the gas density profile should be similar for

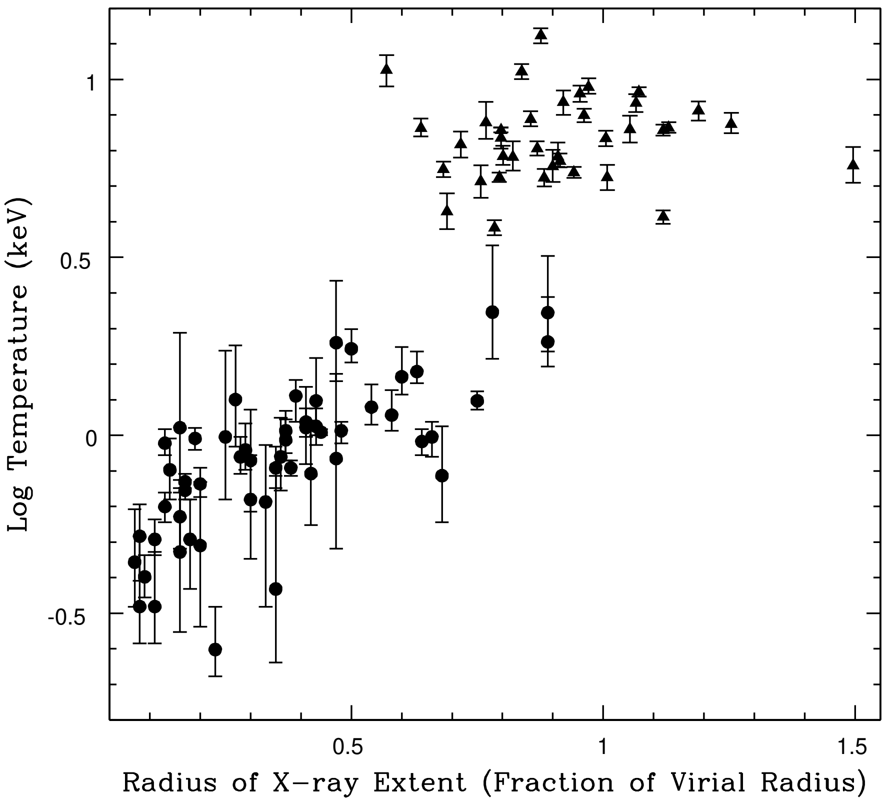

Fig. 1.2. Total radius of X-ray extent, plotted as a fraction of the virial radius, of each system versus the logarithm of the temperature for a sample of groups (circles) and rich clusters (triangles). The groups points are taken from Mulchaey et al. (2003) and the cluster points are from White (2000).

groups and clusters. Thus, the trend for β values to increase with temperature (i.e., mass) suggests that nongravitational processes have been important in groups (see § 1.6).

However, there is some concern that the measured β values may not reflect the true values of the gas density profiles in groups. 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, Frenk, & White 1995; Bartelmann & Steinmetz 1996; Lewis et al. 2000). Indeed, Vikhlinin, Forman, & Jones (1999) find evidence for a slight steepening of the gas density slope with radius in rich clusters. In general, the X-ray emission in groups is detected out to a small fraction of the virial radius (Helsdon & Ponman 2000a; Mulchaey 2000). In fact, there is a strong trend for hotter systems to be detected to a larger fraction of the virial radius than cooler systems (Mulchaey 2000; Fig. 1.2). This is important because it suggests that a larger fraction of the gas mass, and thus X-ray luminosity, is detected in the hotter systems. Because groups tend to be detected to a smaller fraction of the virial radius than rich clusters, the derived β values for groups may also be biased low (Mulchaey 2000). Sanderson et al. (2003) have examined this effect by fitting the *ROSAT* data for two clusters over a range of radii and conclude that it is unlikely to introduce a large systematic relative bias between groups and clusters. While this is somewhat reassuring, more detailed studies of the surface brightness profiles of groups using *Chandra* and *XMM-Newton* will probably be required to put this issue to rest.

1.4 Spectral Properties of the Intragroup Medium

Although the spectral resolution of the *ROSAT* PSPC detectors was very crude ($\Delta E/E \approx 0.4$ at 1 keV), these instruments were used to derive important information about the hot gas. In particular, the *ROSAT* observations provided temperature measurements for a large number of nearby groups. The derived gas temperatures for groups range from about 0.3 keV to 2 keV (Mulchaey et al. 1996a, 2003; Ponman et al. 1996; Helsdon & Ponman 2000a). Systems with temperatures higher than $\sim$2 keV would generally be considered clusters, while groups cooler than 0.3 keV would be difficult to detect with *ROSAT*. Subsequent work with the *ASCA* telescope suggests that for systems with a temperature less than about 1.5–2 keV, the *ROSAT* data provide an accurate measurement of the temperature. For hotter systems, the *ROSAT* data tend to underestimate the true gas temperature (Hwang et al. 1999; Horner 2001; Mulchaey et al. 2003).

Recent work with *Chandra* suggests that *ROSAT* and *ASCA* spectra may be significantly contaminated by unresolved point source emission in some cases. For example, Helsdon et al. (2004) find that up to 30%–40% of the *ROSAT* flux in two nearby groups is due to points sources that can be identified with the higher resolution *Chandra* data. In one of the two groups, the point source contamination appears to have had a large impact on the temperature measured by *ROSAT*. Both of the groups studied by Helsdon et al. (2004) have low X-ray luminosities. It is likely that point source contamination is less important for the more luminous X-ray groups that have dominated most *ROSAT* studies. Still, it will be important to study many more groups with *Chandra* to determine the importance of point sources contamination on the *ROSAT* and *ASCA* measurements.

Radial temperature profiles have now been measured for a large number of groups with *ROSAT*, *ASCA*, *Chandra*, and *XMM-Newton* (Ponman & Bertram 1993; David et al. 1994; Doe et al. 1995; Davis et al. 1996; Trinchieri, Fabbiano, & Kim 1997; Mulchaey & Zabludoff 1998; Buote 2000; Helsdon & Ponman 2000a; Buote et al. 2003; Sanderson et al. 2003; Helsdon et al. 2004; Mushotzky et al. 2004). Most authors have found that the *ROSAT* and *ASCA* data are consistent with the gas being largely isothermal outside of the very centers of groups. However, *Chandra* observations suggest there is considerable temperature structure in the gas that might have been missed in the low-resolution data (Fig. 1.3). Although very few *Chandra* group results have been published to date, a quick look at groups in the *Chandra* archive suggests the profile shapes in Figure 1.3 are typical: the temperature rises rapidly from the center of the group to a maximum before declining significantly at larger radii.

The cool cores observed in the *Chandra* data are one of the standard signatures of cooling flows (Fabian 1994). However, as discussed in Donahue & Voit (2004), recent

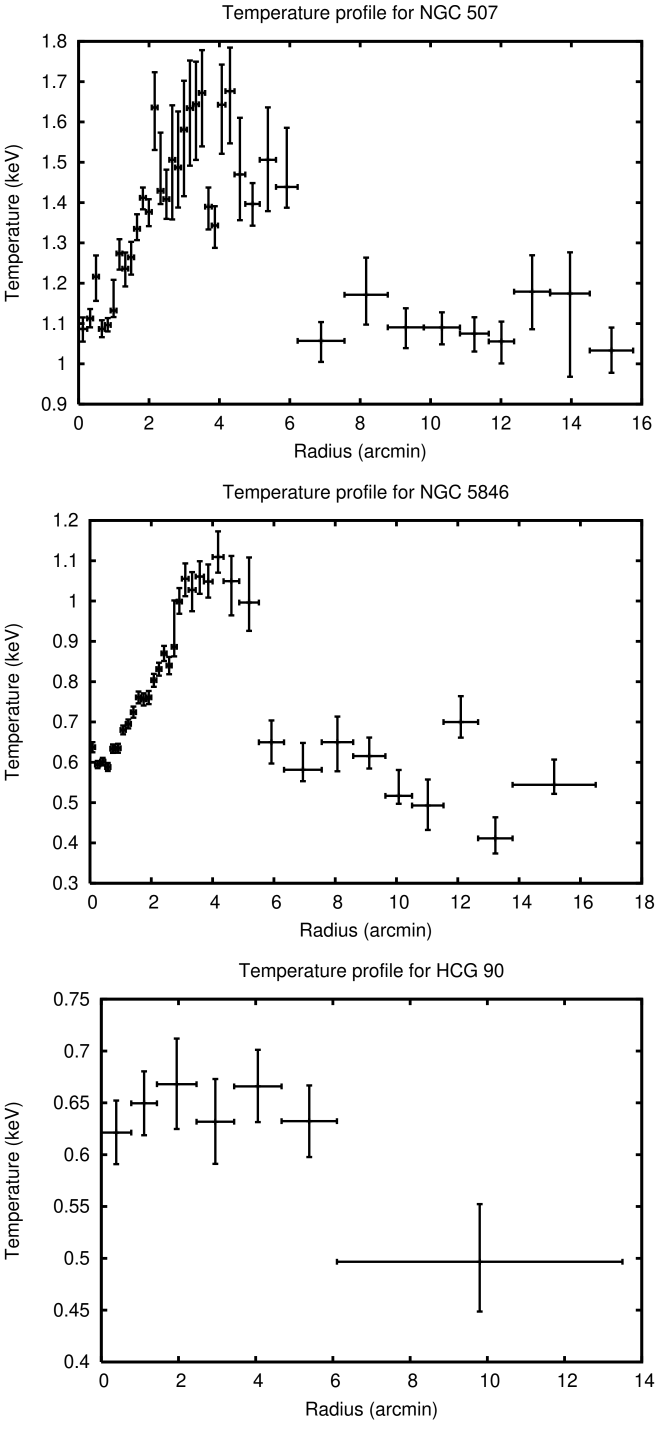

Fig. 1.3. Temperature profiles for three nearby groups derived from archival *Chandra* ACIS data.

high-resolution spectroscopy of the centers of cooling flow clusters has failed to find the emission lines expected from the cooling gas. Although only a couple of objects have been looked at in detail so far, groups seem to exhibit the same problem (Xu et al. 2002; Tamura et al. 2003). Thus, whatever mechanism is invoked to remove the cool gas must be in operation over the full range of masses from poor groups to the richest clusters. The discovery of X-ray cavities in groups and clusters (see § 1.3) suggests that AGN heating may play a role in removing the cooling gas (but see Brighenti & Mathews 2003 for potential problems with applying the cluster models to groups and individual galaxies).

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. For gas at temperatures of $\sim$1 keV ($\sim 10^7$ K), the most important emission-line features in the X-ray spectra 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, Osterheld, & Goldstein 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. 1995).

Unfortunately, the great potential to study the chemical composition of the gas has been largely diminished by the poor spectral resolution of the X-ray instruments flown to date. While many authors quote metallicity measurements based on *ROSAT* data, it is universally agreed that such measurements are highly suspect given the poor spectral resolution of the PSPC detectors. It is generally believed that the metallicity measurements from *ASCA* are more reliable, but different authors have derived vastly different results using the same data. Most authors have derived sub-solar abundances from *ASCA* data (Fukazawa et al. 1998; Davis et al. 1999; Hwang et al. 1999; Finoguenov, David, & Ponman 2000; Horner 2001). However, Buote (2000) derived approximately solar metallicity for a sample of 12 groups. The differences between metallicities derived by Buote and other authors are primarily due to different assumptions about the spectral model. Most authors have assumed a single-temperature model to derive metallicities, while Buote adopts a two-temperature model. Recent work by Buote and collaborators using *XMM-Newton* and *Chandra* (Buote 2002; Buote et al. 2003) favors a two-temperature medium in at least two groups. In the case of the NGC 5044 group, Buote et al. (2003) find that the cooler temperature component ($T \approx 0.7$ keV) has a temperature consistent with the kinetic temperature of the stars in the central galaxy, while the hotter component (($T \approx 1.4$ keV) is consistent with the virial temperature of the group.

The Buote (2000) results have proved to be very controversial, and some authors have dismissed the idea of a multi-phase intragroup medium. To resolve this issue, high-spectral resolution observations are needed. It is now possible to obtain such spectra for a few groups with *XMM-Newton*'s Reflection Grating Spectrometers (RGS). The RGS produce spectra integrated over a region $\sim 1'$–$2'$ in diameter. Unfortunately, it is only feasible to study the bright cores of groups with this instrument. Xu et al. (2002) have studied the center of the NGC 4636 group and find no evidence for the emission-line features expected in a strongly multi-phase gas. This would appear to be inconsistent with the Buote (2000) model. However, Tamura et al. (2002) find evidence for two temperature components in the RGS data for the NGC 5044 group. Thus, a strong conclusion cannot be reached at this time. To truly test the Buote (2000) results, it will be important to obtain spatially resolved, high-spectral resolution observations outside of the bright central cores of groups. This type of observation will be possible with the X-ray microcalorimeter on the *Astro E-2* mission (scheduled to be launched in 2005). Regardless of the final outcome, the work of Buote (2000) is an important reminder that the properties derived from X-ray spectroscopy are very sensitive to the choice of input model.

1.5 Mass and Baryon Fraction Estimates

The X-ray gas in groups can be used to estimate the masses of individual systems using the hydrostatic equilibrium method originally developed for rich clusters (e.g., Fabricant, Lecar, & Gorenstein 1980; Fabricant, Rybicki, & Gorenstein 1984; Cowie, Henriksen, & Mushotzky 1987). In addition to the assumption that the gas is in rough hydrostatic equilibrium, it is also assumed that the gas temperature is a direct measure of the potential depth. However, there is now considerable evidence that nongravitational processes are important for groups of galaxies (see § 1.6). How these processes have affected the measured temperatures is currently not clear. Semi-analytic "preheating" models suggest that for systems with global temperatures greater than about 0.8 keV, the measured temperature is a fair tracer of the potential depth. From their models that include both heating and cooling, Voit et al. (2002) find that these processes tend to increase the temperature of the gas near the system's center. However, these processes also decrease the gas density near the core, shifting the bulk of the system's luminosity to larger radii, where the gas temperatures are smaller. The net effect is that the luminosity-weighted temperatures of groups are not substantially changed by nongravitational processes in the Voit et al. (2002) models. Still, it is worth bearing in mind that these processes may be having some effect on the mass estimates.

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

$$M_{\rm total}(< r) = \frac{kT_{\rm gas}(r)}{G\mu m_{\rm p}}\left[\frac{d\log\rho}{d\log r} + \frac{d\log T}{d\log r}\right] r, \tag{1.3}$$

where k is Boltzmann's constant, $T_{\rm gas}(r)$ is the gas temperature at radius r, G is the gravitational constant, μ is the mean molecular weight, $m_{\rm p}$ 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 β model to the surface brightness profile. With *ROSAT* data, it is often necessary to further assume that the gas is isothermal (i.e., $\frac{d\log T}{d\log r} = 0$). The isothermal assumption appears to result in an error in the mass of no more than about 10% (e.g., David et al. 1994; Davis et al. 1996).

The hydrostatic mass has generally only been calculated for the most luminous groups, all of which have temperatures around $\sim$1 keV. It is therefore not surprising that the total masses of all of these systems tend to cluster around a single value ($\sim 10^{13} h_{100}^{-1} M_\odot$ out to approximately 1/3 of the virial radius; Mulchaey et al. 1993, 1996a; Ponman & Bertram 1993; David et al. 1994; Henry et al. 1995; Pildis et al. 1995). Based on the *ROSAT* mass estimates, X-ray groups make a substantial contribution to the total mass density of the Universe (Henry et al. 1995; Mulchaey et al. 1996a).

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 (Mulchaey et al. 1993, 1996a; Ponman & Bertram 1993; David et al. 1994; David, Jones, & Forman 1995; Davis et al. 1995; Doe et al. 1995; Pildis et al. 1995; Pedersen, Yoshii, & Sommer-Larsen 1997). Thus, X-ray groups are dark matter dominated. The gas mass fraction is considerably lower in groups than in clusters at the same fixed fraction of the virial radius (Sanderson et al. 2003). In general, it is not possible to accurately estimate the total gas mass in groups because the X-ray emission is detected to less than half of the virial radius (Helsdon & Ponman 2000a; Mulchaey 2000). If the observed gas density profiles extend out to the virial radius, than the intragroup medium comprises a significant reservoir of baryons in the local Universe (e.g., Fukugita, Hogan, & Peebles 1998).

1.6 Evidence for "Additional" Physics

Cold dark matter models have been remarkably successful at predicting the formation of structure in the Universe. In the standard model, the shape of dark matter potentials is expected to be the same over a wide range of mass (Navarro, Frenk, & White 1997). In the absence of radiative cooling and supernova/AGN heating, the gas density profiles are also expected to be similar over a range in mass. This leads to the expectation that clusters and groups of galaxies should follow similar scaling relationships between properties such as X-ray luminosity (L_X) and temperature (T). For example, assuming the emission is dominated by bremsstrahlung, one expects $L_X \propto T^2$. It has been known for over a decade, however, that the observed relationship between L_X and T is considerably steeper for rich clusters ($L_X \propto T^3$; Edge & Stewart 1991; White, Jones, & Forman 1997; Markevitch 1998).

Considerable effort has gone into understanding the nature of the $L_X - T$ relationship in the group regime. Based on *ROSAT* observations, Helsdon & Ponman (2000a) find that the $L_X - T$ relationship is considerably steeper for groups than for clusters ($L_X \propto T^{4.9}$). However, Horner (2001) finds that while there is more scatter in the relationship at low X-ray luminosities (i.e., groups), a single relationship with $L_X \propto T^3$ holds over a factor of 10^4 in X-ray luminosity. Some caution is warranted when comparing groups and clusters because the X-ray luminosities of groups are generally measured to smaller fraction of the virial radius than rich clusters (Fig. 1.2; Helsdon & Ponman 2000a; Mulchaey 2000). Thus, in general, a smaller fraction of the total gas mass and X-ray luminosity is detected in groups. A detailed study of groups and clusters taking this aperture effect into account would be valuable.

Many authors have explored the failure of the simplest CDM models to predict the slope of the observed $L_X - T$ relationship in groups and clusters. It is generally believed that the inclusion of physics other than gravity can explain the discrepancy. This additional physics may also explain the entropy ($S \propto T n^{-2/3}$) of the gas in groups and clusters. In the standard CDM model, most of the entropy in the X-ray gas is predicted to be from the accretion shock of the gas falling into the potential (Eke, Navarro, & Frenk 1998). This leads to the prediction that the entropy of the gas should increase with the mean temperature of the system. The observed entropy in groups is actually much higher than that expected from the standard model (Ponman, Cannon, & Navarro 1999; Lloyd-Davies, Ponman, & Cannon 2000; Finoguenov et al. 2002). It has been suggested by Ponman and collaborators that there is an "entropy floor": a lower limit to the entropy that a collapsed system can have.

A large amount of theoretical work has been invested in recent years to understand the excess entropy and the shape of the $L_X - T$ relationship. The proposed explanations fall into one of three main classes: (1) "preheating" models, where the intergalactic medium was heated prior to the formation of groups and clusters (Evrard & Henry 1991; Kaiser 1991; Cavaliere, Menci, & Tozzi 1998; Balogh, Babul, & Patton 1999; Valageas & Silk 1999;

Tozzi & Norman 2001; Babul et al. 2002; Dos Santos & Doré 2002; Nath & Roychowdhury 2002), (2) internal heating models, where the gas was heated inside the bound system by supernovae or AGNs (Bower 1997; Loewenstein 2000; Voit & Bryan 2001), or (3) cooling models, where the low-entropy gas was removed from the system, producing an effect similar to heating (Knight & Ponman 1997; Bryan 2000; Pearce et al. 2000; Davé, Katz, & Weinberg 2002; Muanwong et al. 2002; Wu & Xue 2002). While other mechanisms are possible (e.g., magnetic pressure, cosmic ray pressure), these have not been studied in detail.

Generally, all three classes of models can match the shape of the $L_X - T$ relationship and produce the excess entropy in groups, but the required parameters introduce problems in each case. For example, the preheating scenarios require an uncomfortably large amount of energy to be injected into the intergalactic medium at high redshift (e.g., Babul et al. 2002). Internal heating models utilizing supernovae require nearly all of the available energy to heat the gas, while AGN heating models need to be very finely tuned to match the observations. Pure cooling models overpredict the observed mass of stars in groups and clusters. Many of these problems can probably be overcome by considering more realistic scenarios with both heating and cooling (Borgani et al. 2002; Voit et al. 2002).

The shape of the entropy profile in groups provides a much stronger discriminant of the various models than the $L_X - T$ relation. In particular, preheating models predict a flat entropy profile out to radii where shocks begin to dominate (Babul et al. 2002; Voit et al. 2002). For low-mass systems like groups, the entropy profile should be isentropic over much of the observed emission. In contrast, the internal heating and cooling models tend to produce entropy profiles that are rising from the very centers of groups (although the exact shape of the profiles depends somewhat on the history of the system and the amount of cooling or heating; Brighenti & Mathews 2001; Borgani et al. 2002).

Several recent studies indicate that galaxy groups do not have large isentropic cores, but rather profiles that rise with increasing radius (Fig. 1.4; Ponman, Sanderson, & Finoguenov 2003; Pratt & Arnaud 2003; Mushotzky et al. 2004). These observations are inconsistent with current preheating models. While the observed profiles may be consistent with internal heating and cooling models, to zeroth order these models may be inconsistent with other observations. For example, although Mushotzky et al. (2004) find a wide range in entropy values at a given fraction of the virial radius in their small sample, the total stellar masses of these groups are remarkably uniform. This would appear to be inconsistent with models where cooling dominates because one would expect a correlation between entropy and stellar mass (assuming that the low-entropy gas that drops out forms stars). If supernova heating was the dominant source of the excess entropy, one might naturally predict a correlation between gas metallicity and entropy. No such trend is observed (Finoguenov et al. 2002; Mushotzky et al. 2004). At the moment, the number of systems that have detailed entropy profiles derived from *XMM-Newton* and *Chandra* data is very small. Further observations will prove useful to see if these trends (or lack thereof) still hold when larger samples are available. Regardless, more complex models will probably be required to understand the history of the hot gas in groups (e.g., Ponman et al. 2003).

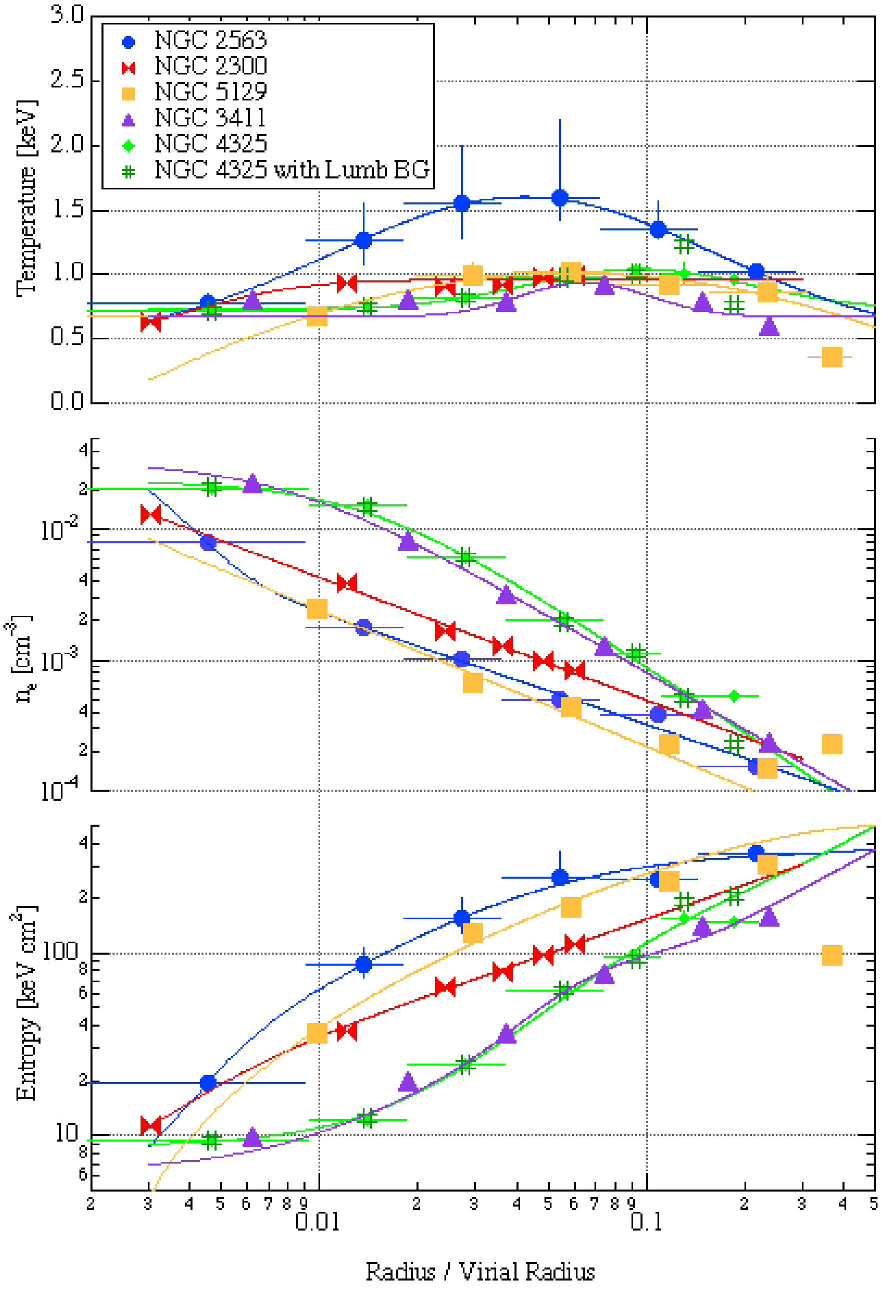

Fig. 1.4. Temperature, density and entropy profiles for five X-ray groups derived from *XMM-Newton* data (Mushotzky et al., in preparation). Note that none of the entropy profiles are consistent with the existence of isentropic cores as predicted by current preheating models.

1.7 The Intragroup Medium in The Local Group

There has been a lot of interest in the last few years in the intragroup medium in the Local Group. As noted in § 1.2, spiral-only groups like the Local Group are not detected in X-ray surveys. However, the intragroup medium in these groups is expected to produce detectable absorption features in the far-UV or X-ray spectra of background quasars. While a clear detection of a warm intragroup medium in other spiral-only groups has yet to be made, the case for the detection of warm gas in the Local Group is now considerably stronger. The grating spectrometers on *Chandra* and *XMM-Newton* have recently been used to detect O VII, O VIII, and Ne IX absorption features at $z \approx 0$ in the spectra of several background AGNs (Kaspi et al. 2002; Nicastro et al. 2002; Fang, Sembach, & Canizares 2003; Rasmussen et al. 2003). Assuming collisional equilibrium, Rasmussen et al. (2003) estimate that the electron temperature of the absorbing gas is in the range of $(2-5) \times 10^6$ K. They also derive a lower limit for the length scale of the gas of 140 kpc. Based on these properties, they conclude that the hot gas is associated with the Local Group's intragroup medium. Nicastro et al. (2002) have studied the bright blazar PKS 2155–304, and in this case the X-ray features are associated with a known O VI UV absorber detected by *Far Ultraviolet Spectroscopic Explorer (FUSE)*. If a single temperature is assumed for both the UV and X-ray features, the physical properties of the absorber are also consistent with the expectations for the Local Group intragroup medium. However, the single-temperature assumption may not be a good one. Heckman et al. (2002) have considered a radiative cooling model that contains gas over a broad range of temperatures. In this model, the scale length of the gas can be much smaller than in the isothermal models, allowing the gas to be associated with the disk or halo of the Milky Way (see also Fang et al. 2003 for a nice discussion of the high-ionization absorbers along the line of sight to 3C 273). Thus, the origin of these X-ray features is still not clear.

At the temperatures expected for a warm intragroup medium, many of the most prominent absorption features fall in the far-UV region. The strongest of these lines is expected to be the O VI doublet at $\lambda\lambda$1031.93, 1037.62 Å. A few of the O VI systems discovered with *HST* have properties that may be consistent with intervening groups (Bergeron et al. 1994; Savage, Tripp, & Lu 1998). The number of known O VI systems has increased dramatically in the last few years with the launch of *FUSE*. Particularly interesting is the discovery of a class of high-velocity O VI clouds (Sembach et al. 2000, 2003). Nicastro et al. (2003) have examined the velocity distribution of these objects and find that the amplitude of the average velocity vector decreases significantly as one moves from the Local Standard of Rest to the Local Group rest frame. This suggests that these clouds may originate in a warm intragroup medium distributed throughout the Local Group. However, other explanations are possible. In particular, it seems likely that at least some of the O VI high-velocity clouds originate in the Milky Way (Fang et al. 2003; Sembach et al. 2003; Sternberg 2003).

Several other observations imply 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 ~0.2 keV, which could be due to a warm intragroup medium in the Local Group (see, however, Sidher, Sumner, & Quenby 1999, who argue that the X-ray halo of the Galaxy dominates). Maloney & Bland-Hawthorn (1999) have shown that the ionizing flux produced by warm intragroup gas in the Local Group may be sufficient to induce detectable Hα emission from the outer parts of H I disks. Indeed, an encounter between intragroup gas and the Magellanic Stream may be responsible for the strong Hα emission detected by

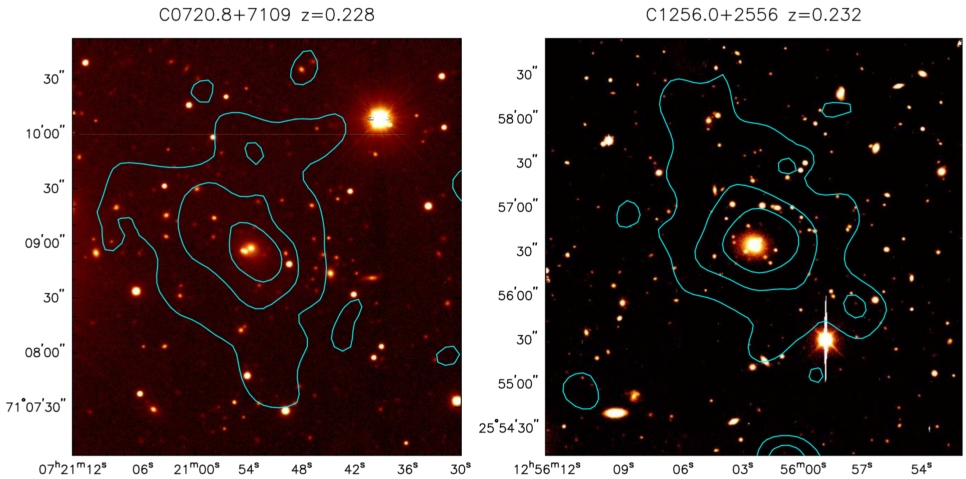

Fig. 1.5. X-ray contours derived from *XMM-Newton* data overlaid on optical images of two moderate-redshift groups (Mulchaey et al. 2004). These *XMM-Newton* data have enough counts to allow a temperature and metallicity measurement.

Weiner & Williams (1996; the Magellanic Stream has also been detected in O VI, Sembach et al. 2000, 2003). Future searches for Hα emission near the outer parts of H I disks in the Local Group could set interesting limits on intragroup gas in our own system.

1.8 Concluding Remarks

While X-ray studies of rich clusters have been underway for several decades now, the study of the hot gas in groups is still a relatively new field. We have learned a tremendous amount from the *ROSAT* and *ASCA* missions. A large number of groups have already been observed with *Chandra* and *XMM-Newton*, and I anticipate many new results in the coming years. X-ray studies of rich clusters have now been extended to redshifts beyond $z \approx 1$. So far, X-ray group studies have been restricted to the nearby Universe. This situation is rapidly changing as groups are now being studied out to moderate redshifts with *XMM-Newton* and *Chandra* (Fig. 1.5; Grant et al. 2004; Mulchaey et al. 2004). Therefore, it should be possible to directly study the evolution of the intragroup medium out to $z \approx 0.5$ in the near future.

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