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X-ray Clusters at High Redshift

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Abstract

Considerable observational progress has been made over the last decade in tracing the evolution of global physical properties of galaxy clusters in the Universe, as revealed by X-ray observations. Based on X-ray selected samples covering a wide redshift range, convincing evidence has emerged for modest evolution of both the bulk of the X-ray cluster population and their thermodynamical properties since redshift unity. With the advent of *Chandra* and *XMM-Newton*, and their unprecedented sensitivity and angular resolution, these studies have revealed the complexity of the thermodynamical structure of clusters and have been extended beyond redshift unity. By $z = 1$, clusters are found already in an advanced stage of formation, with processes responsible for metal enrichment and energy injection into the intracluster medium essentially already completed. Observations of their galaxy populations at $z \simeq 1.3$ have shown the first signature that we are approaching the epoch of formation of massive cluster galaxies. The overall observational scenario is consistent with hierarchical models of structure formation in a flat, low-density Universe with $\Omega_m \simeq 0.3$ and $\sigma_8 \simeq 0.7-0.8$ for the normalization of the power spectrum, although many details remain unknown regarding the formation of clusters in their cold and hot phase. The critical redshift range $z = 1.3-2$ needs to be explored in order to unveil these formation processes.

1.1 Introduction

Galaxy clusters form via the collapse of cosmic matter over a region of several megaparsecs. Cosmic baryons, which represent approximately 10%–15% of the mass content of the Universe, follow the dynamically dominant dark matter during the collapse through large scale filaments. As a result of adiabatic compression and of shocks generated by supersonic motions during shell crossing and virialization, a thin hot gas permeating the cluster gravitational potential well is formed. For a typical cluster mass of $10^{14}-10^{15}\,M_\odot$ this gas, enriched with metals at some earlier epochs, reaches temperatures of several 10^7 K, becomes fully ionized, and therefore emits via thermal bremsstrahlung in the X-ray band. Since clusters arise from the gravitational collapse of rare, high peaks of primordial density perturbations, their number density is highly sensitive to specific cosmological models. The lower the density of the Universe (i.e., the matter density parameter $\Omega_m = \rho_m/\rho_{\rm crit}$), the higher the redshift at which the bulk of the cluster population forms.

Observations of clusters in the X-ray band provide an efficient and physically motivated method of identification, which allows (1) clusters to be unveiled out to $z > 1$, (2) the mass to be estimated from direct observables, and (3) a method to accurately compute the survey volume within which clusters are found. These are all essential ingredients to estimate how the cluster mass function varies with redshift, which is what cosmological models actually predict. For these reasons most of the cosmological studies based on clusters have used X-ray selected samples. X-ray studies of galaxy clusters thus provide an efficient way of mapping the overall structure and evolution of the Universe and an invaluable means of understanding the overall history of cosmic baryons.

X-ray cluster studies made substantial progress at the beginning of the 1990's with the advent of new X-ray missions. Firstly, the all-sky survey and the deep pointed observations conducted by the *ROSAT* satellite have been a goldmine for the discovery of hundreds of new clusters in the nearby and distant Universe. Follow-up studies with the *ASCA* and *Beppo-SAX* satellites revealed hints of the complex physics governing the intracluster gas. In addition to gas heating associated with gravitational processes, star formation processes and energy feedback from supernovae and galactic nuclear activity are now understood to play an important role in determining the thermal history of the intracluster medium (ICM), its X-ray properties, and its chemical composition. Studies utilizing the current new generation of X-ray satellites, *Chandra* and *XMM-Newton*, are radically changing our X-ray view of clusters. The large collecting area of *XMM-Newton*, combined with the superb angular resolution of *Chandra*, have started to unveil the interplay between the complex physics of the hot ICM and detailed processes of star formation associated with cool baryons. At very high redshifts (for clusters this means $z \gtrsim 1$), these new X-ray facilities have opened a window to cluster physical properties at lookback times that are critical for their formation history. These new data complement a wealth of information at optical/near-IR wavelengths, which we are now able to glean with the largest ground-based telescopes and the *Hubble Space Telescope (HST)*.

The scope of this article is to summarize the current observational status on the evolution of the X-ray cluster population out to $z \simeq 1$, and to provide some highlights of recent observations of the most distant X-ray clusters known to date. *

1.2 Evolution of the Cluster Abundance

An extensive review on X-ray cluster surveys over the last 20 years, as well as a discussion on basic methodologies adopted, can be found in Rosati, Borgani, & Norman (2002). A historical perspective and recent developments on cluster surveys at $z \lesssim 0.5$ can also be found in Edge (2004). Here, we give an up to date compilation of the latest results on the evolution of the cluster abundance out to $z \approx 1$.

The *ROSAT* All-Sky Survey was the first X-ray imaging mission to cover the entire sky, thus paving the way to large contiguous-area surveys of X-ray selected nearby clusters. To date, large cluster samples have been constructed in the northern (BCS, Ebeling et al. 2000; NORAS, Böhringer et al. 2000) and southern (the REFLEX cluster survey, Böhringer et al. 2001) hemisphere. In total, surveys covering more than 10^4 deg^2 have yielded over 1000 clusters, out to redshift $z \simeq 0.5$. A large fraction of these are new discoveries, whereas approximately one-third are identified as clusters in the Abell or Zwicky catalogs. A number of independent studies using different techniques and independent data sets have yielded local X-ray luminosity functions (XLF), in very close agreement with each other (see Rosati et al.

* Unless otherwise noted, we adopt the cosmological parameters $h = 0.65$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

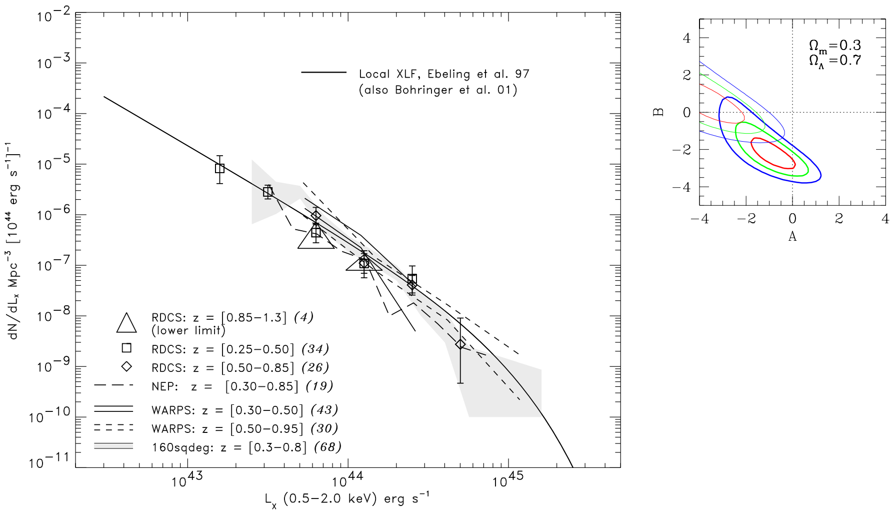


Fig. 1.1. *Left:* A compilation of X-ray luminosity functions of distant clusters from different surveys: RDCS, Rosati et al. 1998; NEP, Gioia et al. 2001; WARPS, Jones et al. 1998; 160 deg^2, Mullis et al. 2004 (an Einstein-de-Sitter Universe with h = 0.5 is adopted). *Right:* Maximum-likelihood contours (1, 2, and 3 σ) for the parameters A and B defining the XLF evolution as derived from the RDCS and EMSS samples: $\phi^* = \phi_0(1+z)^A$, $L^* = L_0^*(1+z)^B$ (see Eq. 1.1). (Updated from Rosati et al. 2002.)

2002). This indicates that systematic effects associated with different selection functions are negligible for nearby samples, thus providing a robust local reference against which cluster evolution can be investigated. The cluster XLF is commonly modeled with a Schechter (1976) function:

$$\phi(L_X)\,dL_X = \phi^* \left(\frac{L_X}{L_X^*}\right)^{-\alpha} \exp(-L_X/L_X^*)\,\frac{dL_X}{L_X^*} \quad . \tag{1.1}$$

ROSAT/PSPC archival pointed observations were intensively used for serendipitous searches of distant clusters. A principal objective of all these surveys (RDCS, WARPS, SHARC, NEP, 160 deg^2, to mention just a few), which are now essentially completed, has been the study of the evolution of the XLF, stimulated by the early results of the Extended Medium Sensitivity Survey (EMSS, Gioia et al. 1990).

An updated compilation of the latest determinations of the XLF out to $z \approx 1$ is reported in Figure 1.1. The right panel shows best-fit evolutionary parameters obtained by a maximum-likelihood method, which compares the observed cluster distribution on the (L_X, z) plane with that expected from an XLF model: $\phi(L,z) = \phi_0(1+z)^A L^{-\alpha} \exp(-L/L^*)$, with $L^* = L_0^*(1+z)^B$, where A and B are two evolutionary parameters for density and luminosity, and ϕ_0 and L_0^* are the local XLF values (Eq. 1.1). Figure 1.1 shows an application of this method to the RDCS and EMSS sample and indicates that the no-evolution case ($A = B = 0$) is excluded at more than 3σ levels in both samples when the most luminous systems are included in the analysis, whereas the same analysis confined to clusters with $L_X < 3 \times 10^{44}$ erg s^{-1} yields an XLF consistent with no evolution.

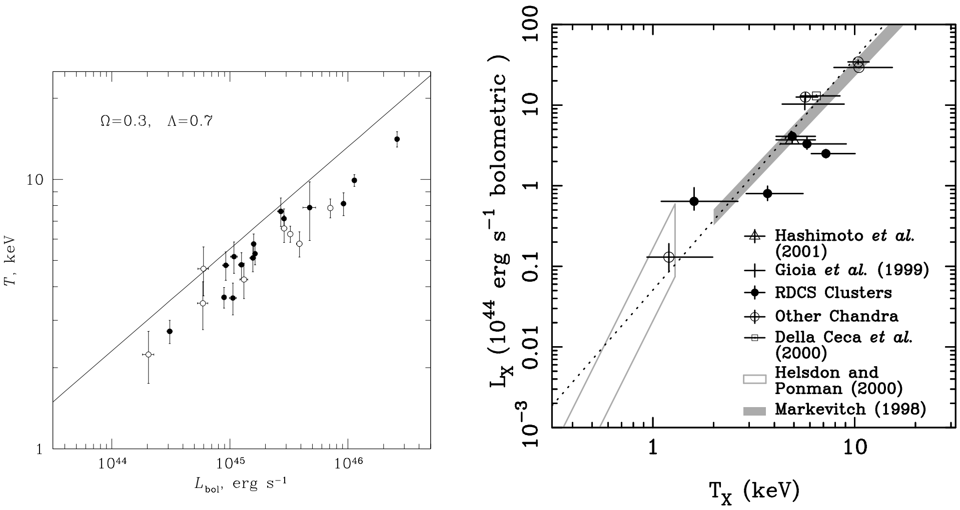


Fig. 1.2. *Left*: $L_X - T$ relation from Vikhlinin et al. (2002) (filled circles correspond to clusters at $0.4 < z < 0.7$, open circles to clusters at $z > 0.7$; the solid line is the correlation found at low redshifts by Markevitch 1998). *Right*: $L_X - T$ relation from the study of Holden et al. (2002).

In summary, by combining all the results from *ROSAT* surveys one obtains a consistent picture in which the comoving space density of the bulk of the cluster population is approximately constant out to $z \simeq 1$, whereas the most luminous ($L_X \gtrsim L_X^*$), presumably most massive clusters were likely rarer at high redshifts ($z \gtrsim 0.5$). Significant progress in the study of the evolution of the bright end of the XLF would require a large solid angle and a relatively deep survey with an effective solid angle of $\gg 100$ deg^2 at a limiting flux of 10^{-14} erg cm^{-2} s^{-1}. This will be possible, to some extent, with similar serendipitous surveys based on *Chandra* and *XMM-Newton* pointings. The convergence of the results from several independent studies illustrates remarkable observational progress in determining the abundance of galaxy clusters out to $z \approx 1$. At the beginning of the *ROSAT* era, until the mid-nineties, controversy surrounded the usefulness of X-ray surveys of distant galaxy clusters, and many believed that clusters were absent at $z \approx 1$ (including many theorists!). The observational prejudice arose from an over-interpretation of the early results of the EMSS survey, which remain correct to date, but were thought to be in contrast with results from optical surveys without understanding that these studies were probing different sections of the cluster mass function at high redshift. Such a scenario of rapid evolution of the cluster mass function was also favored by a theoretical prejudice for an $\Omega = 1$ Universe (without a cosmological constant).

The study of scaling relations in clusters is an important diagnostic tool to understand their formation history and to test the validity of our simple assumptions on their thermodynamical properties. Specifically, with *Chandra* observations, we can now investigate for the first time the $L_X - T$ relation at high redshift. In Figure 1.2, we show results from two recent studies, which indicate a mild evolution of this relation, although they still disagree on its strength. These findings are in agreement with models that require a substantial injection of

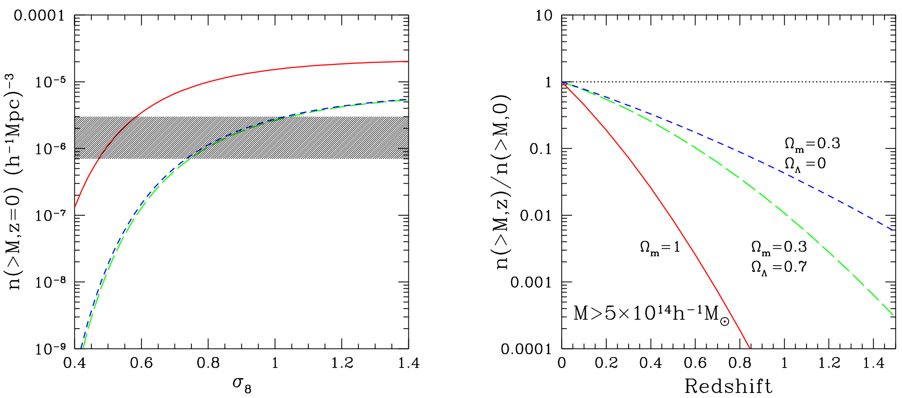


Fig. 1.3. The sensitivity of the cluster mass function to cosmological models. *Left*: The cumulative mass function at $z = 0$ for $M > 5\times10^{14}h^{-1}M_\odot$, for three cosmologies, as a function of σ_8, with shape parameter $\Gamma = 0.2$; solid line: $\Omega_m = 1$; short-dashed line: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$; long-dashed line: $\Omega_m = 0.3$, $\Omega_\Lambda = 0$. The shaded area indicates the observational uncertainty in the determination of the local cluster space density. *Right*: Evolution of $n(>M,z)$ for the same cosmologies and the same mass limit, with $\sigma_8 = 0.5$ for the $\Omega_m = 1$ case and $\sigma_8 = 0.8$ for the low-density models. (Adopted from Rosati et al. 2002.)

nongravitational energy (e.g., from supernovae or AGN activity) to explain the slope of the local $L_X - T$ relation (e.g., Evrard & Henry 1991; Cavaliere, Menci, & Tozzi 1998; Balogh, Babul, & Patton 1999; Ponman, Cannon, & Navarro 1999; Tozzi & Norman 2001; Voit et al. 2002). The reader is referred to the articles by Mushotzky (2004) and Mulchaey (2004) for a discussion on scaling relations in clusters and groups.

1.3 Cosmology with X-ray Clusters

The space density of clusters in the local Universe has been used to measure the amplitude of density perturbations on ~ 10 Mpc scales, which is commonly parameterized by σ_8, the rms density fluctuation within a top-hat sphere of $8\,h^{-1}$Mpc radius. Using only the number density of nearby clusters of a given mass M, one can constrain the amplitude of the density perturbation at the physical scale $R \propto (M/\Omega_m\rho_{\rm crit})^{1/3}$ containing this mass. Since such a scale depends both on M and on Ω_m, the mass function of nearby ($z \lesssim 0.1$) clusters is only able to constrain a relation between σ_8 and Ω_m. In the left panel of Figure 1.3 we show that, for a fixed value of the observed cluster mass function, the implied value of σ_8 increases as the density parameter decreases (with a typical scaling $\sigma_8\Omega_m^\alpha = 0.4-0.6$, with $\alpha \simeq 0.4-0.6$). Formal statistical uncertainties in the determination of σ_8 from different analyses are always far smaller, $\lesssim 5\%$, than the range of published values. This suggests that current discrepancies on σ_8 are likely to be ascribed to systematic effects, such as sample selection and different methods used to infer cluster masses. We refer the reader to the recent paper by Pierpaoli et al. (2003) for a review and a discussion on measurements of the cluster normalization.

The growth rate of the density perturbations depends primarily on Ω_m and, to a lesser extent, on Ω_Λ, at least out to $z \approx 1$, where the evolution of the cluster population is currently studied. Therefore, following the evolution of the cluster space density over a large redshift baseline, one can break the degeneracy between σ_8 and Ω_m. This is shown in the right panel of Figure 1.3: models with different values of Ω_m, which are normalized to yield the same number density of nearby clusters, predict cumulative mass functions that progressively differ by up to orders of magnitude at increasing redshifts. This plot also shows how future surveys, by amassing large samples of clusters at $z = 1-1.5$ (a daunting task indeed), will also be able to constrain the value of Ω_Λ by exploiting its dynamical effect on cluster formation (perturbations cease to grow at later epochs in the presence of a cosmological constant).

An estimate of the cluster mass function is reduced to the measurement of masses for a sample of clusters, stretching over a large redshift range, for which the survey volume is well known. Essentially four estimators of the cluster mass have been used to date: the cluster velocity dispersion, the gas temperature, the X-ray luminosity, and more recently the gravitational lensing shear strength (see Margoniner et al. 2004). The CNOC survey (e.g., Yee, Ellingson, & Carlberg 1996) still represents the state of the art of a study of the internal dynamics of a statistically complete sample of 16 clusters at $z < 0.55$. The extension of this method to large samples of distant clusters is extremely demanding from the observational point of view, which explains why it has not been pursued much further.

A conceptually robust and more popular method to estimate cluster masses is based on the X-ray measurement of the temperature of the intracluster gas. On the assumption that gas and dark matter particles share the same dynamics within the cluster potential well, the temperature T and the velocity dispersion σ_v are connected by the relation $k_B T = \beta \mu m_p \sigma_v^2$, where $\beta = 1$ would correspond to the case of a perfectly thermalized gas. If we assume spherical symmetry, hydrostatic equilibrium, and isothermality of the gas, the total cluster virial mass, $M_{\rm vir}$, is related to the ICM temperature by

$$k_B T = \frac{1.38}{\beta} \left(\frac{M_{\rm vir}}{10^{15} h^{-1} M_\odot} \right)^{2/3} [\Omega_m \Delta_{\rm vir}(z)]^{1/3} \, (1+z) \, \mathrm{keV}\,. \tag{1.2}$$

$\Delta_{\rm vir}(z)$ is the ratio between the average density within the virial radius and the mean cosmic density at redshift z ($\Delta_{\rm vir} = 18\pi^2 \simeq 178$ for $\Omega_m = 1$). Simulations have shown that cluster masses can be recovered from gas temperature with a $\sim 20\%$ precision, and the above formula holds with $0.9 \lesssim \beta \lesssim 1.3$ (e.g., Bryan & Norman 1998; Frenk et al. 1999; see also Evrard 2004). The main difficulty remains in connecting the theoretical *virial mass* with an observational equivalent, a topic that has become hotly debated by theorists and observers in recent times.

A number of measurements of cluster temperatures for flux-limited samples of clusters have been made over the last 15 years, using *ROSAT*, *Beppo-SAX*, and especially *ASCA*. With these data one can derive the X-ray temperature function (XTF), and hence the mass function using Equation 1.2. XTFs have been computed for both nearby (see Pierpaoli, Scott, & White 2001 for a recent review) and distant clusters (e.g., Henry 2000) and used to constrain cosmological models. The mild evolution of the XTF has been interpreted as a case for a low-density Universe, with $0.2 \lesssim \Omega_m \lesssim 0.6$. Besides questions related to the real validity Equation 1.2, a limitation of the XTF method so far has been the limited sample size (particularly at $z > 0.6$), as well as the lack of a homogeneous sample selection for local and

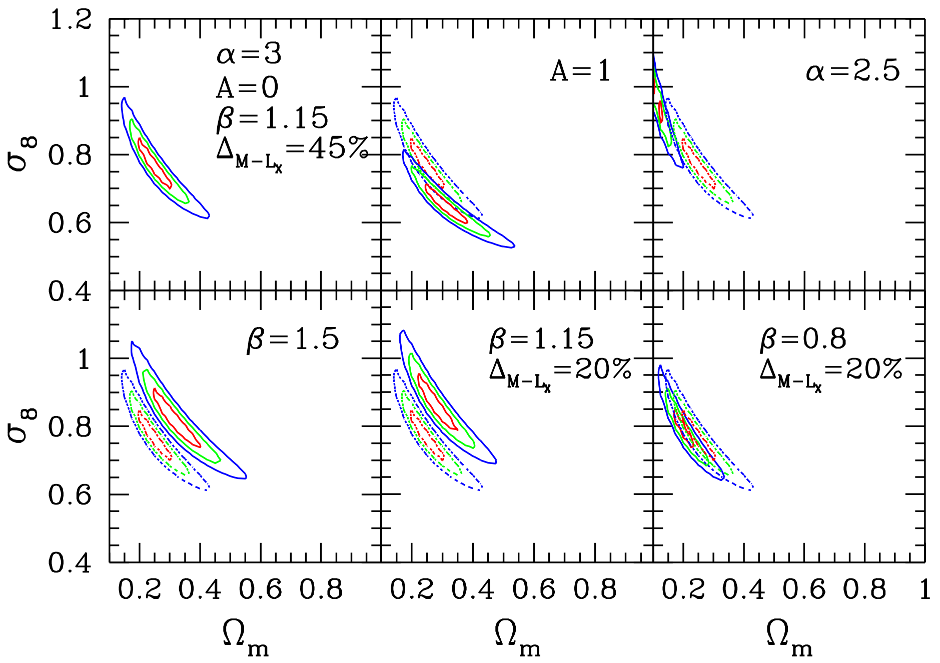


Fig. 1.4. Probability contours in the $\sigma_8 - \Omega_m$ plane from the evolution of the X-ray luminosity distribution of RDCS clusters. The shape of the power spectrum is fixed to $\Gamma = 0.2$ and a flat geometry is assumed (i.e., $\Omega_m + \Omega_\Lambda = 1$). The sequence of panels illustrates current systematics in converting cluster virial mass, M, into X-ray luminosity, L_X. The three parameters (A, α, β) describe the theoretical and observational uncertainties in converting cluster masses into temperatures ($T \sim M^{2/3}/\beta$), and temperatures into X-ray luminosities $[L_X \sim T^\alpha (1+z)^A]$. Δ_{M-L_X} is the observed scatter of the $M - L_X$ relation. The upper left panel shows the analysis corresponding to the choice of a reference parameter set. In each panel, these parameters are varied, with the dotted contours always showing the reference analysis. (From Rosati et al. 2002.)

distant clusters. In the next session, we illustrate how recent *Chandra* and *XMM-Newton* observations are contributing to change the observational scenario.

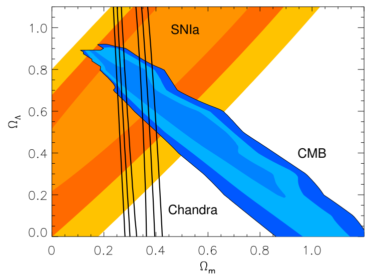
Another method to trace the evolution of the cluster number density is based on the XLF. The advantage of using X-ray luminosity as a tracer of the mass is that L_X is measured for a much larger number of clusters, which are homogeneously identified over a broad redshift baseline, out to $z \simeq 1.3$. This allows nearby and distant clusters to be compared within the same sample, i.e. with a single selection function. The potential disadvantage of this method is that it relies on the relation between L_X and $M_{\rm vir}$, which is based on additional physical assumptions and hence is more uncertain than the $M_{\rm vir} - \sigma_v$ or the $M_{\rm vir} - T$ relations. An empirical $L_X - M$ relation is well established (e.g., Reiprich & Böhringer 2002), although with some scatter. The recently improved determination of the $L_X - T$ relation, particularly its scatter and evolution out to $z \simeq 1$ (Holden et al. 2002, 2004; Vikhlinin et al. 2002; Jones et al. 2004), allows the XLF, $\phi(z)$, to be converted into an evolving mass function,

$n(m,z)$, via $L_X \to T \to M_{\rm vir}$. A Press-Schechter-like analytical approach can then be used to constrain σ_8 and Ω_m (e.g., Borgani et al. 2001). Figure 1.4 shows the application of such a method using the RDCS cluster sample. The main uncertainty is due to "systematics" in estimating cluster masses; such an effect is illustrated by changing in turn the parameters defining the $M-L_X$ relation, such as the slope α and the evolution parameter A of the L_X-T relation, the normalization β of the $M-T$ relation (see Eq. 1.2), and the overall scatter Δ_{M-L_X}. It is important to note that by varying these parameters within both the observational and the theoretical uncertainties, the matter density parameter remains confined in the range $0.1 \lesssim \Omega_m \lesssim 0.6$, with best parameters $\Omega_m \simeq 0.3$ and $\sigma_8 = 0.7-0.8$.

X-ray observations of clusters also offer a completely independent, and to some extent more robust, way of constraining Ω_m by providing a measure of the baryon mass fraction, which is essentially $f_{\rm bar} = M_{\rm gas}/M_{\rm tot}$, since the intracluster gas dominates the baryonic mass content of rich clusters. If the baryon density parameter, $\Omega_{\rm bar}$, is known from independent considerations (e.g., by combining the observed deuterium abundance in high-redshift absorption systems with predictions from primordial nucleosynthesis), then the cosmic density parameter can be estimated as $\Omega_m = \Omega_{\rm bar}/f_{\rm bar}$ (e.g., White et al. 1993). For a value of the Hubble parameter $h \simeq 0.7$ and a typical measured value $f_{\rm bar} \simeq 0.15$ (e.g., Evrard 1997; Ettori 2001), this method yields $\Omega_m \simeq 0.3 h_{70}^{-0.5}$, with a 50% scatter [using the currently most favored values of the baryon density parameter, $\Omega_{\rm bar} \simeq 0.02\, h^{-2}$, as implied by primordial nucleosynthesis and by the spectrum of cosmic microwave background (CMB) anisotropies].

Under the assumption that the gas fraction, $f_{\rm gas}$, does not evolve *intrinsically* with redshift, such a method has recently been extended by measuring the apparent redshift dependence of $f_{\rm gas}$, which is mainly driven by a geometrical factor: $f_{\rm gas}(z) \propto D_A^{3/2}(\Omega_m, \Omega_\Lambda, z)$, where D_A is the angular diameter distance to the clusters (Allen et al. 2002; Ettori et al. 2003). $f_{\rm gas} =$ constant is a reasonable hypothesis, particularly for massive clusters, since these systems are expected to provide a fair sample of the matter content of the Universe, and mechanisms that would otherwise segregate baryons preferentially in cluster environments are not known. Results from the two main studies to date are shown in Figure 1.5 (see also Vikhlinin et al. 2003 for an alternative method). By using the most distant clusters, the leverage on Ω_Λ, or equivalently on the equation of state parameter w, increases (see right panel), although it becomes more difficult to estimate the total cluster mass due the inability to measure temperature profiles. Figure 1.5 shows how, by combining this method with independent cosmological constraints based on the CMB power spectrum and Type Ia supernovae, one can significantly narrow down the allowed region in the $(\Omega_m, \Omega_\Lambda)$ plane.

A more delicate issue is whether one can use the evolution of galaxy clusters for high-precision cosmology, say $\lesssim 10\%$ accuracy, particularly at the beginning of an era in which cosmological parameters can be derived rather accurately by combining methods that measure the global geometry of the Universe [the CMB spectrum (e.g., Spergel et al. 2003), Type Ia supernovae (e.g., Leibundgut 2001), and the large-scale distribution of galaxies (e.g., Peacock et al. 2001)]. Serendipitous searches of distant clusters from *XMM-Newton* and *Chandra* data will eventually lead to a significant increase of the number of high-z clusters with measured temperatures. Thus, the main limitation will lie in systematics involved in comparing the mass inferred from observations with that given by theoretical models. *Chandra* and *XMM-Newton* have revealed that physical processes in the ICM are rather complex. Our physical models and numerical simulations are challenged to explain the new level of spa-



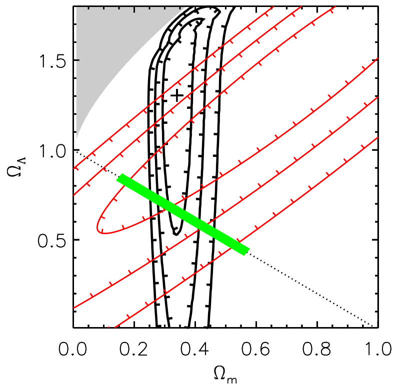


Fig. 1.5. Constraints on Ω_m and Ω_Λ from two independent analyses of the gas fraction and its redshift dependence, $f_{\rm gas}(z)$. *Left*: From Allen, Schmidt, & Fabian (2002), who used a sample of *Chandra* clusters at $0.1 < z < 0.5$. *Right*: Adapted from Ettori, Tozzi, & Rosati (2003), who used the highest redshift sample of *Chandra* clusters available to date ($0.7 < z < 1.3, T > 4\,$keV). The shaded bar represents constraints from the recent *WMAP* results (Spergel et al. 2003).

tial detail in the density and temperature distribution of the gas, and the interplay between heating and cooling mechanisms (see Donahue & Voit 2004). Such complexities need to be well understood physically before we can use clusters as high-precision cosmological tools.

The gas fraction $f_{\rm gas}(z)$ method, on the other hand, is based on a limited number of assumptions, although it still requires long *Chandra* integrations. The promise of this technique is illustrated in Figure 1.5: the combination of these constraints with the recent exquisite *WMAP* results (Spergel et al. 2003) is sufficient to obtain a small allowed region around the current "concordance model," without the need of Type Ia supernovae, whose systematics are far from being under control.

1.4 Distant X-ray Clusters: the Latest View from *Chandra*

With its unprecedented angular resolution, the *Chandra* satellite has revolutionized X-ray astronomy, allowing studies with the same level of spatial detail as in optical astronomy. *Chandra* imaging of low-redshift clusters has revealed a complex thermodynamical structure of the ICM down to kiloparsec scales (e.g., Fabian et al. 2000; Markevitch et al. 2000). At high redshifts, deep *Chandra* images still have the ability to resolve cluster cores and to map ICM morphologies at scales below 100 kpc. Moreover, temperatures of major subclumps can be measured for the first time at $z > 0.6$, and a crude estimate of the ICM metalicity can be obtained even beyond $z = 1$.

Figure 1.6 is an illustrative example of the unprecedented view that *Chandra* can offer on distant clusters. We show nine archival images of clusters at $0.8 < z < 1.3$. The intensity (in grey scale) is proportional to the square root of the X-ray emission, so that they roughly map the gas density distribution in each cluster. The images are arranged in two redshift bins, with X-ray luminosities (and generally the gas temperature) increasing from left to right. One σ error bars for gas temperatures at these high redshifts range from 20% to 40%. A close inspection of these images reveal a deviation from spherical symmetry in all systems.

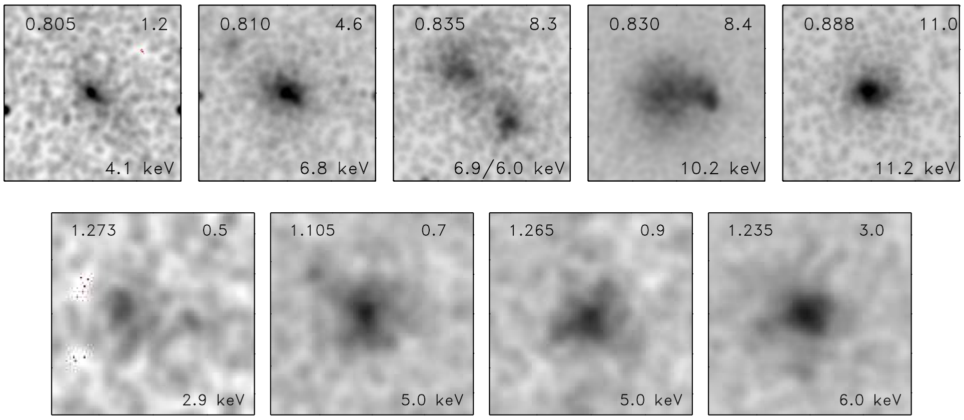


Fig. 1.6. *Chandra* archival images of nine distant clusters in the 0.5–2 keV band. Labels indicate redshifts (upper left), X-ray luminosities (upper right in the rest frame [0.5–2] keV band and in units of 10^{44} erg s^{-1}), and gas temperatures (bottom right). Images on the top row (2 Mpc across) are clusters at $0.8 < z < 0.9$ spanning a factor 10 in L_X; images on the bottom (1 Mpc across) are the four most distant clusters studied by *Chandra* to date at $1.1 < z < 1.3$. The X-ray emission has been smoothed at the same physical scale of 70 kpc (point sources in each field were removed).

Some of them are elongated or have cores clearly displaced with respect to the external diffuse envelope (e.g., Holden et al. 2002; Rosati et al. 2004).

Three of the most luminous clusters at $z \simeq 0.8$ (RXJ1716+6708: Gioia et al. 1999; RXJ0152.7−1357: Huo et al. 2004, Maughan et al. 2003; MS1054–0321: Jeltema et al. 2001, respectively the second, third, and fourth cutout in Figure 1.6) show a double core structure both in the distribution of the gas and in their member galaxies. It is tempting to interpret these morphologies as the result of ongoing mergers, although no dynamical information has been gathered to date to support this scenario. In a hierarchical cold dark matter formation scenario, one does expect the most massive clusters at high redshift to be accreting subclumps of comparable masses, and the level of substructure to increase at high redshifts. With current statistical samples however, it is difficult to draw any robust conclusion on the evolution of ICM substructure.

The discovery and the study of systems beyond redshift unity have the strongest leverage on testing cosmological models. This, however, has been a challenging task with X-ray searches so far due to the limited survey areas covered at faint fluxes. The second row in Figure 1.6 shows the most distant clusters observed with *Chandra* to date, which were discovered in the *ROSAT* Deep Cluster Survey (Stanford et al. 2001, 2002; Rosati et al. 2004), at the very limit of the *ROSAT* sensitivity. RXJ0848.6+4453 and RXJ0848.9+4452 (the first and second image) are only $5'$ apart on the sky (the Lynx field) and are possibly part of a superstructure at $z = 1.26$, consisting of two collapsed, likely virialized clusters (Rosati et al. 1999). These deep *Chandra* observations have yielded for the first time information on ICM morphologies in $z > 1$ clusters and allowed a measurement of their temperatures, which imply masses of $(0.5-3) \times 10^{14} h_{65}^{-1} M_{\odot}$ (Ettori et al. in prep.). For the hottest and most luminous of these systems (RDCS1252–2930), the Fe 6.7 keV iron line is clearly detected

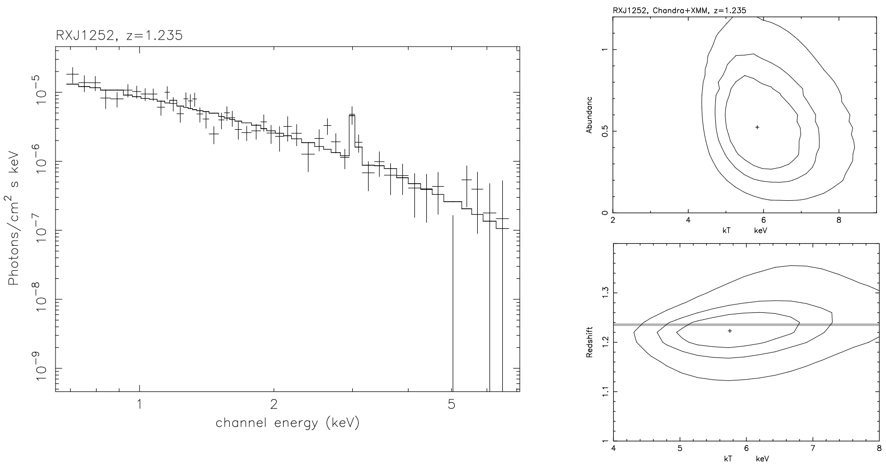


Fig. 1.7. *Left*: X-ray spectrum and best Raymond-Smith fit from *Chandra* observations (188 ks) of RDCS1252–2930 at $z_{\rm spec}$ = 1.235; a clear redshifted Fe 6.7 keV line is visible. *Right*: (top) best-fit temperature and metalicity of the gas obtained by combining *Chandra* and *XMM-Newton* (65 ks) data; (bottom) best-fit redshift of the ICM, with the horizontal shaded line marking the spectroscopic redshift based on 33 cluster members. (Adapted from Tozzi et al. 2003 and Rosati et al. 2004.)

for the first time at $z > 1$. This implies a high metal abundance consistent with the local canonical value, $Z \simeq 0.3 Z_{\odot}$ (see Fig. 1.7). These findings can be used to set new constraints on the epoch of metal enrichment via star formation processes, as well as the time scale on which metals are spread across the ICM. Interestingly, we note that X-ray observations alone are able to accurately yield the cluster redshift (bottom right panel in Fig. 1.7), a difficult task to achieve even with 8–10 m class telescopes.

In Figure 1.8, we show near-IR images of the four clusters at $z > 1$, overlaid with *Chandra* contours. Already at these large lookback times, surface brightness profiles of these systems are similar to those of low-redshift clusters. Moreover, the morphology of the gas, as traced by the X-ray emission, is well correlated with the spatial distribution of member galaxies, similar to studies at lower redshifts. This suggests that there are already at $z > 1$ galaxy clusters in an advanced dynamical stage of their formation, in which all the baryons (gas and galaxies) have had enough time to thermalize in the cluster potential well.

1.5 Galaxy Populations in the Most Distant Clusters

A discussion on galaxy populations in high-z clusters is beyond the scope of this article. We refer the reader to the reviews by Dressler (2004), Franx (2004), and Treu (2004) for both an historical and an up to date view on the evolution of cluster galaxies and their formation scenarios. In this section, we only give an example of how spectrophotometric studies of cluster galaxies at $z > 1$ can set important constraints on the mode and epoch of formation of early-type galaxies, owing to the strong leverage that these observations have on models at such large lookback times.

In Figure 1.9 (left panel), we show the evolution of the fundamental plane of early-type galaxies in clusters at increasing redshift (van Dokkum & Stanford 2003, and references

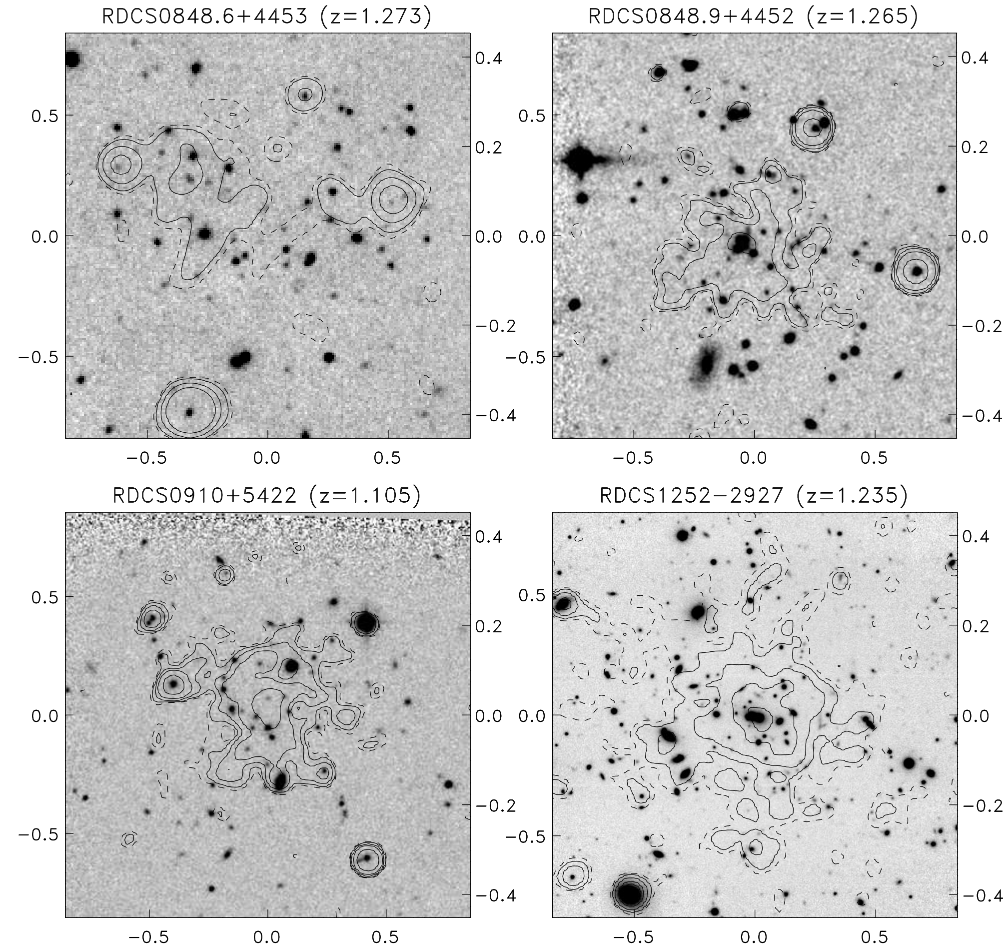


Fig. 1.8. K-band images of four *bona fide* clusters at $z > 1.1$ overlaid with contours mapping the X-ray emission detected by *Chandra* /ACIS-I (adapted from Stanford et al. 2001, 2002; Lidman et al. 2004; Rosati et al. 2004). Left and bottom axis give the scale in arcminutes; the right axis gives the scale in Mpc for our adopted cosmology.

therein). By measuring directly mass-to-light M/L ratios, one can disentangle the evolution of the galaxy luminosity function from the underlying mass function, thus providing stringent tests on hierarchical models of galaxy formation in which merging processes play a fundamental role. The data point at $z = 1.27$ is derived from the two most massive galaxies in RDCS0848+4453 (top left image in Fig. 1.8). We note how this data point, obtained by pushing spectroscopy with 10 m class telescopes to the ultimate limit, has the strongest leverage in discriminating among different models. The best-fit model, incorporating the "morphological evolution bias" (van Dokkum & Franx 2001), has a stellar formation redshift $z_{\rm form} \simeq 2.5$. In addition, spectrophotometric data of the brightest cluster galaxies indicate the presence young stellar populations (van Dokkum et al. 2001), with ages of 1–2 Gyr at the epoch of observations. These findings are corroborated by an independent spec-

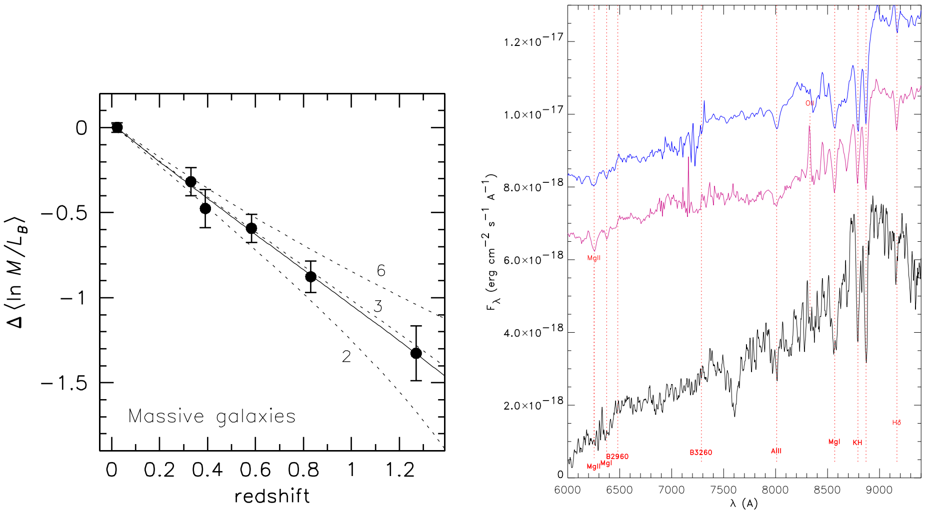


Fig. 1.9. *Left*: Evolution of the M/L ratio of early-type galaxies in clusters out to $z = 1.27$ (adapted from van Dokkum & Stanford 2003). The highest redshift data point is derived by the two most massive galaxies in RDCS0848+4453 (Fig. 1.8). Dashed lines are predictions from single-burst stellar population synthesis models with $z_{\rm form} = 6$, 3, and 2; the solid line is a more complex model by van Dokkum & Franx (2001) with $z_{\rm form} \simeq 2.5$. *Right*: Stacked spectrum of the 10 brightest early-type galaxies in the cluster RDCS1252–29 at $z = 1.235$. For comparison, the spectra of a local E and Sa galaxies are also shown at the top. (Adapted from Rosati et al. 2004.)

troscopic study of the 10 brightest members in RDCS1252–2927 (out of the 33 spectroscopically confirmed to date; Demarco et al. 2004; Rosati et al. 2004). A stacking spectral analysis (Fig. 1.9, right) shows significant Hδ absorption, indicative of a poststarburst phase, i.e. the presence of stellar populations with ages of $\gtrsim 1$ Gyr. Moreover, color-magnitude diagrams (the so-called red sequence) in these two distant clusters appear to be flatter and less tight than in low-redshift clusters. All these data indicate that at these redshifts we are approaching the epoch of formation massive cluster galaxies. These examples illustrate how spectrophotometric studies at these lookback times, when combined with *HST*/ACS imaging for morphological properties, hold promise to shed new light on their formation history.

1.6 Conclusions and Future Challenges

Considerable observational progress has been made in tracing the evolution of the global physical properties of galaxy clusters as revealed by X-ray observations. In the last five years, studies of distant clusters have not revealed any dramatic change in either their space density or their scaling relations (e.g., $L_X - T$). The *Chandra* satellite has given us the first view of the gas distribution in clusters at $z > 1$; their X-ray morphologies and temperatures show that they are already in an advanced stage of formation at these large lookback times. Moreover, X-ray spectroscopy has revealed that by this epoch the intracluster gas was already enriched with metals, with an iron abundance comparable with the local values.

These observations can be understood in the framework of hierarchical formation of cosmic structures, with a low density parameter, $\Omega_m \approx 1/3$, dominated by cold dark matter: structure formation started at early cosmic epochs and a sizable population of massive clusters was in place already at redshifts of unity. In addition, detailed X-ray observation of the intracluster gas show that the physics of the ICM needs to be regulated by additional nongravitational processes. The lack of strong evolution of cluster X-ray properties, as well as the ICM metalicity, suggest that processes responsible for energy injection (star formation feedback, AGNs) and metal enrichment (supernova explosions) might be completed by $z \simeq 1$.

In the opening era of high-precision cosmology, the role of clusters is still important since they provide a completely independent method to constrain the universal geometry. It remains remarkable that the evolution of the cluster abundance, the $f_{\rm gas}$ technique, the CMB fluctuations, Type Ia supernovae and large-scale structure—all completely independent methods—converge toward $\Omega_m \simeq 0.3$ in a spatially flat Universe ($\Omega_m + \Omega_\Lambda = 1$). Further studies with the current new X-ray facilities will help considerably in addressing the issue of systematics discussed above, although some details of the ICM in $z \gtrsim 1$ clusters, such as temperature profiles, will remain out of reach until the next generation of X-ray telescopes. Direct measurements of cluster masses at $z \gtrsim 1$ via gravitational lensing techniques will soon be possible with the Advanced Camera for Surveys (Ford et al. 1998) onboard the *HST*, which offers an unprecedented combination of sensitivity, angular resolution and field of view.

The fundamental question remains as to the mode and epoch of formation of the ICM. When and how was the gas preheated and polluted with metals? What is the epoch when the first X-ray clusters formed, the epoch when the accreted gas thermalizes to the point at which the clusters would lie on the $L_X - T$ relation? Are the prominent concentrations of star-forming galaxies discovered at redshift $z \approx 3$ (Steidel et al. 1998, 2000) the progenitors of the X-ray clusters we observed at $z \lesssim 1$? If so, cluster formation should have occurred in the redshift range 1.5–2.5.

Although the redshift boundary for X-ray clusters has recently receded from $z = 0.8$ to $z = 1.3$, a census of clusters at $z \simeq 1$ has just begun, and the search for clusters at $z > 1.3$ remains a serious observational challenge. Serendipitous searches for clusters based on *Chandra* and *XMM-Newton* pointings (e.g., Romer et al. 2001; Boschin 2002), or large-area surveys (e.g., Pierre et al. 2004) will allow good progress in this field. Using high-z radio galaxies as signposts for protoclusters has been the only viable method so far to break this redshift barrier and push it out to $z \simeq 4$. Recent work by G. Miley and collaborators has been very successful in finding significant overdensities of Lyα-emitting galaxies around selected radio galaxies, via narrow-band imaging techniques and subsequent spectroscopic confirmation. These searches have also led to the discovery of extended Lyα nebulae around distant radio galaxies (e.g., Venemans et al. 2002; Kurk et al. 2004), very similar to those discovered by Steidel et al. (2000) in correspondence with large-scale structures at $z \simeq 3$. The nature of such nebulae is still not completely understood; however, they could represent the early phase of collapse of cool gas through mergers and cooling flows. If there is an evolutionary link between "protoclusters" found around high-z radio galaxies and the X-ray clusters at $z \simeq 1.2$, viable evolutionary tracks should be found linking the galaxy populations in these systems, using their spectrophotometric and morphological properties.

Recent follow-up *Chandra* observations of high-redshift radio galaxies have revealed the presence of diffuse X-ray emission, in addition to a central point source (3C 294 at $z = 1.786$:

Fabian et al. 2003; 4C 41.17 at $z = 3.8$: Scharf et al. 2004a, b). However, their spectral energy distribution and other energetic arguments indicate that the extended emission is likely nonthermal, but rather due to inverse-Compton scattering of CMB photons by a population of relativistic electrons associated with the radio source activity. The serendipitous detection of thermal ICM at $z > 1.5$ associated with $\sim L^*$ clusters remains extremely difficult, not only for the lack of volume in current X-ray surveys, but also for the severe $(1+z)^4$ surface brightness dimming that affects X-ray observations. These limitations will be overcome by surveys exploiting the Sunyaev-Zel'dovich (1972) effect (e.g., Carlstrom, Holder, & Reese; Birkinshaw 2004), which will explore large volumes at $z > 1$. It is worth noting, however, that current sensitivity of Sunyaev-Zel'dovich observations is still not sufficient to detect any of the X-ray clusters at $z > 1$ shown in § 1.4, all having $L_X \lesssim L^* \approx 3 \times 10^{44}$ erg s^{-1}.

Near-IR large-area surveys remain a valid alternative to unveil a large number of clusters at $z \approx 1$. Surveys covering up to 10^3 deg^2 in the z band (Gladders & Yee 2000; Gladders 2004) are well underway and well suited to discover rare, massive clusters out to $z \simeq 1.2$. The next generation of large-area surveys in the *J, H*, and *K* bands (principally the UKIRT Infrared Deep Sky Survey; see http://www.ukidss.org) will push this boundary even further.

Ideally, the formation and evolution of galaxies in clusters should be linked to the evolution of the ICM, and the fact that we are still treating the two aspects as separate points to the difficulty in drawing a comprehensive, unified picture of the history of cosmic baryons in their cold and hot phase. Multiwavelength studies are undoubtedly essential to reach such a unified picture. A large-area ($> 100\,\mathrm{deg}^2$) joint survey combining Sunyaev-Zel'dovich, X-ray, and space-based near-IR observations (such experiments are being proposed or planned) could reveal the evolutionary trends in a number of independent physical parameters, including the cluster mass, the gas density and temperature, the underlying galactic mass, and star formation rates. Advances in instrumentation and observational technique will make this approach possible and will provide vital input for models of structure formation and independent constraints on the underlying cosmological parameters.

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