Carnegie Observatories Astrophysics Series, Vol. 3:
Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004
ed. J. S. Mulchaey, A. Dressler, and A. Oemler (Cambridge: Cambridge Univ. Press)

X-ray Surveys of Low-redshift Clusters

ALASTAIR C. EDGE
Institute for Computational Cosmology, University of Durham

Abstract

The selection of clusters of galaxies through their X-ray emission has proved to be an extremely powerful technique over the past four decades. The growth of X-ray astronomy has provided the community with a steadily more detailed view of the intracluster medium in clusters. In this review I will assess how far X-ray surveys of clusters have progressed and how far they still have to travel.

1.1 Introduction

The principal baryonic component of clusters of galaxies is diffuse gas held in hydrostatic equilibrium in the gravitational potential of the cluster. This gas is hot ($10^7 - 10^8$ K), relatively dense ($10^{-4} - 10^{-2}$ atom cm^{-3}), and enriched with heavy elements (e.g., Fe of 0.3 Solar abundance). This combination results in significant X-ray emission through thermal bremsstrahlung radiation. Detailed X-ray observations of clusters can provide us with accurate total mass measurements, clues to the merger history of clusters, and a chemical record of the supernova ejecta that polluted the intracluster medium during the formation of the stars in the member galaxies.

The X-ray emission from clusters can also be exploited to select clusters irrespective of their member galaxies. While the optical selection of clusters is well established and understood, there are potential problems with projection and the imperfect scaling of the galaxy population to total cluster mass that make independent selection methods attractive.

There are four key considerations for any X-ray survey:

- **Spatial resolution** To capitalize on the extended nature of the X-ray emission in clusters, it is important to have sufficient spatial resolution to differentiate clusters from most other pointlike X-ray sources (i.e., stars and AGNs). On the other hand, the most nearby, diffuse clusters can be missed in the same way low-surface brightness galaxies may be missed in optical surveys.
- **Spectral resolution** Each class of X-ray source has a distinctive spectral signature (e.g., black body for white dwarfs), so information on the X-ray spectrum of each source can aid identification. The thermal nature of cluster spectra (temperatures mostly greater than 2 keV) give clusters relatively flat soft X-ray spectra (making them distinctive in the *ROSAT* survey), but the overall spectral shape is similar to most unabsorbed AGNs. Therefore, definitive cluster identification from spectral data alone requires many photons (>1,000), which is only feasible for the brightest detections (see Nevalainen et al. 2001 for an example using *XMM-Newton*).

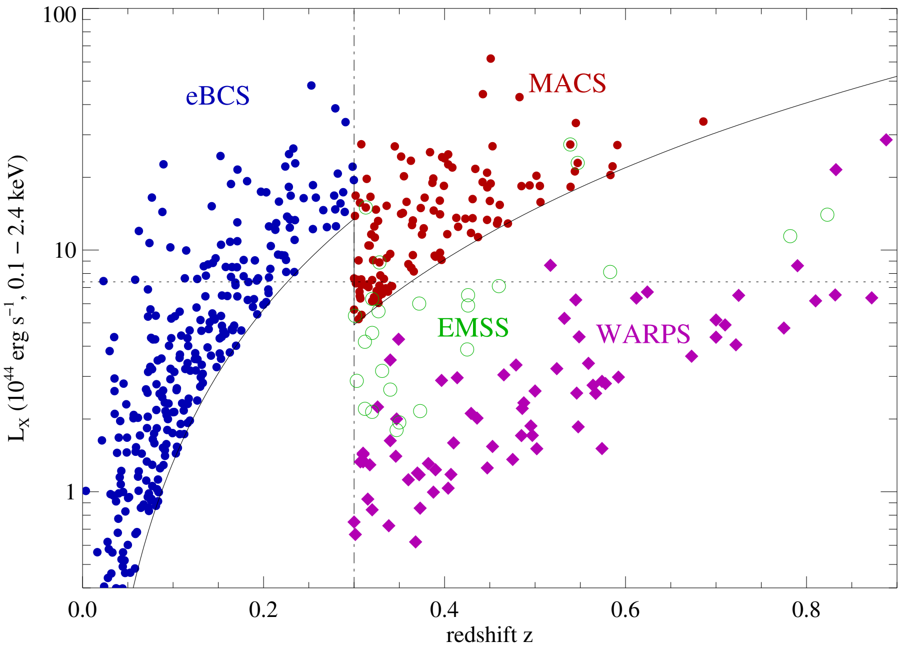

Fig. 1.1. The X-ray luminosity (0.1–2.4 keV) plotted against redshift for four X-ray samples: EMSS (Gioia et al. 1990), a serendipitous sample from *Einstein*; eBCS (Ebeling et al. 2000), a shallow, wide RASS survey; MACS (Ebeling et al. 2001), a deeper, wide RASS survey, and WARPS (Perlman et al. 2002) a much deeper serendipitous *ROSAT* survey.

- **Flux limit of the survey** This is a particularly important factor for cluster surveys as the flux-limited nature of X-ray samples translates to a selection over a wide range in redshifts, since the most luminous objects are being selected from a very much larger volume than the least luminous ones. This has its advantages but requires careful analysis. This is illustrated in Figure 1.1, where the X-ray luminosity is plotted against redshift for a variety of samples described later in the text.
- **Area of sky surveyed** In the ideal survey at any wavelength the aim is all-sky coverage. This has been achieved several times in X-ray astronomy with the earliest X-ray satellites scanning with collimated proportional counters ($\sim 1^\circ$ resolution) and *ROSAT* with a soft X-ray imaging telescope ($\sim 1'$ resolution). This wide coverage comes at the expense of depth [the *ROSAT* All-Sky Survey reaches $\sim 10^{-12}$ erg s^{-1}cm^{-2} (0.5–2 keV)]. The alternative survey strategy is to select serendipitous sources in pointed imaging observations, as pioneered by the Extended *Einstein* Medium Sensitivity Survey (EMSS; Gioia et al. 1990). This allows much deeper surveys but at the expense of the area (and hence total volume) covered.

There are a number of cluster properties that can be used to constrain the nature and evolution of clusters.

- **Temperature** - For gas in hydrostatic equilibrium (which appears to hold for the majority of the volume of a cluster) the gas temperature and density can be used to directly determine the cluster mass.

- **Elemental abundances** The X-ray spectrum of clusters contains lines from a number of heavy elements. Most prominent of these is the iron 6.7 keV line. The inferred abundance ratios from X-ray spectra of O, S, Si and Fe can be used to determine the dominant supernova type (Loewenstein & Mushotzky 1996).
- **Surface brightness profiles** The distribution of gas in a cluster has a very significant effect on the total X-ray luminosity of the cluster, given that the intensity of emission is proportional to the density squared. Clusters with compact, dense cores (i.e., cooling flows; see Fabian 1994) are much more luminous that more extended clusters of the same measured X-ray temperature (Fabian et al. 1994) and can have an effect on the detection probability in X-ray surveys (Pesce et al. 1990). Also, the recent discovery of strong density discontinuities, termed "cold fronts" (Markevitch et al. 2000; Mazzotta et al. 2001) has highlighted the impact of past mergers on the intracluster medium. These factors make obtaining high-quality, high-resolution X-ray imaging a vital element of cluster studies.

Each of these requires either dedicated pointed observations or a survey drawn from the brightest serendipitous detections in pointed observations. The former is a relatively slow process requiring time allocation committees to put substantial resources into programs to observe "complete" samples. The latter is very slow given the area covered by sufficiently deep X-ray observations.

For the purposes of this review I will define "low redshift" as $z < 0.5$ and treat any paper presenting any new X-ray detection of cluster as a "survey."

In my talk I used the yardstick of exponential growth to judge progress in known numbers of X-ray emitting clusters which I modestly named "Edge's Law." This holds that for every decade of X-ray astronomy the number of clusters detected increases by an order of magnitude. I would like to stress that this was a narrative device and not a serious bid for future surveys in itself. That said, the rapid progress in cluster research in the past decades does require us to stand back and assess it as part of a larger picture.

1.2 An Historical Perspective

I would like to continue this review in a similarly light-hearted vein while giving the reader as comprehensive review as possible of X-ray cluster surveys.

1.2.1 In the Beginning...

X-ray astronomy began on the 18th of June 1962 with the detection of the X-ray background and Sco-X1 by a sounding rocket experiment (Giacconi et al. 1962). For shorthand in this review, this will be denoted as 0 Anno Giacconi (AG), and subsequent events will be quoted in these units.

During the first three years of sounding rocket experiments from 0 AG several cluster detections were in dispute [e.g., Coma claimed by Boldt et al. (1966) and discounted by Friedman & Byram (1967)], so the first unambiguous cluster detection came in 4 AG when Byram, Chubb, & Freidman (1966) detected M87/Virgo.

The numerous sounding rocket campaigns that occurred between 1962 and 1975 resulted in several more cluster detections (e.g., Perseus; Fritz et al. 1971) and the discovery that the X-ray emission in Coma was extended (Meekins et al. 1971). Unfortunately the collecting area and exposure time of these experiments ruled out the detection of all but the brightest few clusters.

On 12th December 1970 the first X-ray satellite, *UHURU*, was launched. The two-year lifetime of the mission allowed the whole sky to be scanned many times, producing the first true X-ray survey. The fourth and final UHURU catalog (4U; Forman et al. 1978) contains 52 clusters, several of which that were not known to be clusters at the time.

1.2.2 The End of the First Age of X-ray Astronomy?

UHURU was the first of a number of increasingly more complicated experiments that allowed further surveys and dedicated pointed observations. Most notable of these was *Ariel-V* (Cooke et al. 1978), which made the first iron line detection in a cluster (Mitchell et al. 1976).

The final mission in this series, *HEAO-1*, made the deepest X-ray survey (Piccinotti et al. 1982), which was the mainstay of X-ray astronomy for the two decades that followed. So at the end of this exciting period of X-ray astronomy, how well does "Edge's Law" stand up? At 17 AG a total of 95 clusters are known, which is well above the 50 required by this point.

1.3 X-ray Imaging Begins with *Einstein*

The launch of the first imaging X-ray satellite, *Einstein*, had a profound impact on our understanding of clusters.

1.3.1 Detailed Imaging and Spectra

The Imaging Proportional Counter (IPC) and High Resolution Imager (HRI) provided images of unprecedented quality (up to $5''$ FWHM). These two instruments provided a great deal of detailed information on individual clusters from targeted observations (Fabian et al. 1981; Jones & Forman 1984, 1999; Stewart et al. 1984; White, Jones, & Forman 1997). Most of the observations were of Abell clusters or other optically selected clusters, but radio galaxies in clusters were also targets. Given the nature of the targeted observations it is not possible to derive any stringent limits on the statistical properties of clusters, but a luminosity function was derived for Abell clusters (Burg et al. 1994).

Einstein also carried the first semi-conductor detector (the forerunner to today's CCDs), the Solid State Spectrometer (SSS) and a deployable Bragg Crystal, the Focal Plane Crystal Spectrometer (FPCS). Both of these instruments provided important results for clusters (Canizares et al. 1979; White et al. 1991), but were not used systematically.

1.3.2 The EMSS

The *Einstein* survey that has had the most impact on cluster research is undoubtedly the Extended *Einstein* Medium Sensitivity Survey (EMSS). By combining most of the serendipitous detections from IPC observations, it was possible to survey 980 $\square^\circ$ and detect 99 clusters (Stocke et al. 1991). This sample has since been the basis for a great deal of work at all wavelengths (Donahue, Stocke, & Gioia 1992; Le Févre et al. 1994; Carlberg et al. 1997; Luppino et al. 1999)

1.4 The X-ray Dark Ages

The 1980's were a period of relative calm in X-ray astronomy. The only satellites launched between 1980 and 1990 were the ESA mission *EXOSAT* and two Japanese missions, *Tenma* and *Ginga*. All three of these satellites were designed for targeted follow-up of known objects, and only *EXOSAT* had any imaging capabilities. *EXOSAT* and *Ginga* contributed a significant number of accurate cluster temperature and iron abundance measurements (the data from *EXOSAT* making my thesis) but very few "new" detections.

This lull in proceedings did allow the previous scanning and *Einstein* surveys to be collated, and a complete sample of the brightest 55 clusters was compiled (Lahav et al. 1989). This sample has been used to determine the first cluster temperature function (Edge et al. 1990), the first correlation function from an X-ray sample (Lahav et al. 1989), and the fraction of cooling flows (Edge, Stewart, & Fabian 1992; Peres et al. 1998).

This "free-wheeling" in X-ray surveys leaves the number of clusters in 28 AG at 300, well short of the 630 required for my exponential growth. This gap did not last for long....

The German/UK/US satellite *ROSAT* was launched on the 1st of June 1990 (27.95 AG). The wide-field, soft X-ray imaging telescope of *ROSAT* was used to conduct a 6-month scanning survey of the whole sky, from August 1990 to February 1991, which detected in excess of 100,000 sources to a flux limit of $(0.3-1)\times10^{-12}$ erg s^{-1}cm^{-2} (0.1–2.4 keV) (depth depending on position). From March 1991 to December 1998, *ROSAT* performed a series of pointed observations with the PSPC and HRI detectors. These observations targeted many known and recently detected clusters, as well as detecting a great many clusters serendipitously.

1.4.1 *ROSAT* All-Sky Survey

The *ROSAT* All-Sky Survey (RASS) is a resource that has still yet to fully exploited 12 years after it was completed. A number of coordinated cluster surveys were embarked upon as soon as the RASS ended. The understandably tight control over the RASS data release and the time-consuming nature of the optical follow-up of the clusters has meant a significant lag in the publication of these samples. Table 1.1 lists a representative set of RASS cluster surveys, both published and unpublished. There are other RASS studies containing clusters (e.g., the RBS, a complete sample of all RASS sources to a count rate limit of 0.2 PSPC count s^{-1}; Schwope et al. 2000), and studies of groups (e.g., RASSCALS; Mahdavi et al. 2000) and Hickson compact groups (Ebeling, Voges, & Böhringer 1994). Table 1.1 will be added to in the next few years by NORAS-2, REFLEX-2, and eMACS, which will extend each of the existing surveys to lower fluxes, but these will be reaching close to the intrinsic sensitivity limit of the majority of the RASS.

The wide variety of selection criteria, detection methods and areas covered are clear from Table 1.1. However, each of the larger samples (BCS, 1BS, Ledlow, REFLEX, and NEP) agree in their derived X-ray luminosity functions (Ebeling et al. 1997; de Grandi et al. 1999; Ledlow et al. 1999; Gioia et al. 2001; Böhringer et al. 2002), so these differences do not greatly affect the samples.

One important difference in the principal RASS samples is that one set (XBACS, BCS, and eBCS) is based on a selection using a Voronoi-Percolation-and-Tesselation (VTP) technique (Ebeling & Wiedenmann 1993) and the other (1BS, SGP, NORAS, and REFLEX) is based on a growth curve analysis (GCA) technique (Böhringer et al. 2001). The flux results from both methods agree within the errors, but only VTP acts as a detection algorithm, as the GCA method requires a set of input positions of potential clusters. This difference is relevant only for the most nearby, extended sources, which are not detected by detection algorithms tuned to search for point sources. VTP will reliably detect these, but, through lack

Table 1.1. *ROSAT Survey Samples*

Survey	Identification Paper	Flux Limit (erg $s^{-1}cm^{-2}$)	Area (□°)	Number Published?
XBACS	Abell clusters	5.0×10^{-12}	All-sky	276
	Ebeling et al. (1996)	(0.1–2.4 keV)		Y
BCS	Abell, Zwicky, extended	4.5×10^{-12}	13,578	199
	Ebeling et al. (1998)	(0.1–2.4 keV)		Y
RASS1BS	Abell, extended	3-4$\times10^{-12}$	8,235	130
	de Grandi et al. (1999)	(0.5–2.0 keV)		Y
Ledlow	Abell $z < 0.09$	none	14,155	294
	Ledlow et al. (1999)			N
eBCS	Abell, Zwicky, extended	3.0×10^{-12}	13,578	299
	Ebeling et al. (2000)	(0.1–2.4 keV)		Y
HiFLUGS	All	20×10^{-12}	27,156	63
	Reiprich & Böhringer (2002)	(0.1–2.4 keV)		Y
NORAS	extended	3.0×10^{-12}	13,578	378
	Böhringer et al. (2000)	(0.1–2.4 keV)		Y
NEP	multiple	0.03×10^{-12}	80.7	64
	Gioia et al. (2001)	(0.5–2.0 keV)		Y
CIZA	CCD imaging, $\|b\| < 20°$	5×10^{-12}	14,058	73
	Ebeling, Mullis, & Tully (2002)	(0.1–2.4 keV)		Y
SGP	optical plates scans	3.0×10^{-12}	3,322	112
	Cruddace et al. (2002)	(0.1–2.4 keV)		Y
MACS	multiple, $z > 0.3$	1.0×10^{-12}	22,735	120
	Ebeling et al. (2001)	(0.1–2.4 keV)		N
REFLEX	multiple	3.0×10^{-12}	13,905	452
	Böhringer et al. (2001)	(0.1–2.4 keV)		N

of access to the full RASS data set, it was not run over the full sky during the compilation of the BCS. With all RASS data now in the public domain, this is now possible in principle.

The optical follow-up of clusters at redshifts above 0.3 requires additional optical imaging, as archival photographic plate material is too shallow to reliably detect cluster members. At the brighter flux limits (5×10^{-12} erg $s^{-1}cm^{-2}$) there are relatively few of these distant clusters [e.g., two in the BCS and RXJ1347–11 ($z = 0.45$) in RASS1BS], but this number increases with decreasing flux limit (e.g., there are seven in the eBCS). With these higher redshift, X-ray luminous clusters in mind, Harald Ebeling and I have searched the RASS-BSC sample (Voges et al. 1999) for $z > 0.3$ clusters using the UH 2.2 m telescope to a flux limit of 10^{-12} erg $s^{-1}cm^{-2}$, creating the MAssive Cluster Survey (MACS; Ebeling, Edge, & Henry 2001). To date, the sample contains 120 clusters with very few candidates left for imaging. The MACS sample has been extensively followed up at all wavelengths, including complete *VRI* imaging with the UH 2.2 m, multi-object spectroscopy with Keck, Gemini and CFHT, deep, wide-area imaging with Subaru/SUPRIMECAM, VLA imaging (Edge et al. 2003), Sunyaev-Zel'dovich observations (LaRoque et al. 2003), *Chandra* ob-

Table 1.2. *ROSAT Serendipitous Samples*

Survey	Selection Paper	Flux Limit (10^{-14} erg s^{-1}cm^{-2})	Area (□°)	Number Published?
RIXOS	CCD imaging Mason et al. (2000)	3.0 (0.5–2.0 keV)	15.8	25 Y
WARPS-I	CCD imaging Perlman et al. (2002)	6.5 (0.5–2.0 keV)	14.1	25 Y
160sq.deg.	extent Vikhlinin et al. (1998)	3.0 (0.5–2.0 keV)	158	203 Y
SHARC-S	extent Collins et al. (1997)	3.9 (0.5–2.0 keV)	17.7	16 N
Bright SHARC	extent Romer et al. (2000)	16.3 (0.5–2.0 keV)	179	37 Y
RDCS	extent Borgani et al. (2001)	3.0 (0.5–2.0 keV)	50	103 N
ROXS	CCD imaging Donahue et al. (2002)	2.0 (0.5–2.0 keV)	4.8	57 Y
BMW	extent Lazzati et al. (1999)	~ 10 (0.1–2.4 keV)	~ 300	$\sim$100 N
XDCS	CCD imaging Gilbank et al. (2004)	3.0 (0.5–2.0 keV)	11.0	15 N
WARPS-II	CCD imaging Jones et al., in prep.	6.5 (0.5–2.0 keV)	73	150 N

servations, and Cycle 12 *HST*/ACS imaging. This sample represents more than an order of magnitude improvement in the number of distant, X-ray luminous clusters known (i.e., two EMSS clusters with $z > 0.4$, $L_x > 10^{45}$ erg s^{-1}, compared to 39 in MACS).

1.4.2 *ROSAT* Pointed Observations

The large field of view of the PSPC detector made it very efficient at detecting serendipitous X-ray sources within $15'$ of the pointing position of the telescope. Given the substantial numbers of relatively deep observations during the *ROSAT* Pointed Phase an area of well over 500□° at high Galactic latitude has been covered by the central region of the PSPC with more than 10 ks exposure. This area is significantly reduced, as some targets are not suitable for serendipitous searches (e.g., nearby clusters, nearby galaxies, globular clusters, etc.), but the majority has been used in a series of surveys (listed in Table 1.2). As with the RASS samples, the selection strategies differ between surveys, but the results from each survey agree. For instance, the requirement of significant source extent used by SHARC certainly eases source selection, but at the potential loss of the most distant and/or compact, cooling flow clusters. These effects do not appear to have any great impact on the results.

The majority of the clusters selected in these surveys are relatively nearby ($z = 0.15 - 0.3$) and of low X-ray luminosity ($L_x = 10^{43-44}$ erg s^{-1}; 0.5–2 keV), but a few distant, luminous clusters are found (Ebeling et al. 2000, 2001), and in the deepest of the *ROSAT* serendipitous sample, RDCS (Rosati et al. 1998), there are several candidate clusters at $z > 1$ (Borgani et al. 2001).

The PSPC instrument eventually ran out of gas in mid-1994, but *ROSAT* continued to make observations with the HRI. While this instrument was less sensitive than the PSPC and covered a smaller area of sky, the excellent spatial resolution it provided has been used very effectively by the Brera Observatory group in the BMW survey (Lazzati et al. 1999; Panzera et al. 2003). While the combination of sensitivity and total area covered by the BMW survey will never match that of PSPC surveys (e.g., the 160 square degree survey; Vikhlinin et al. 1998), it does provide an important reliability test.

The full potential of the *ROSAT* pointed phase has yet to be tapped as all existing surveys have been restricted to the central $15'$–$20'$ radius where the point-spread function is best. While the flux sensitivity is poor in the outer parts of the detector, the brighter ($f_x > 10^{-13}$ erg s^{-1} cm^{-2}) sources can easily be detected. As noted above, the most time consuming part of the follow-up of X-ray selected cluster candidates at $z > 0.3$ is the deeper optical imaging required. This is exacerbated at lower X-ray fluxes by the fainter optical counterparts of all X-ray counterparts. The combination of the low-resolution X-ray imaging with deeper multicolor panoramic surveys such as SDSS, UKIDSS, and RCS2 will provide a "free" resource to identify cluster counterparts to these *ROSAT* sources.

So, how successful has *ROSAT* been overall in harvesting clusters? The RASS samples published or about to be published account for a total of around 1,200 new clusters, with a further 500–1,000 at lower fluxes. Add these to the serendipitous detections, $\sim$500 in the central region of the PSPC (of which $\sim$250 are published), $>$1,500 in the outer regions, and $\sim$300 clusters in the HRI. Therefore, the total after the *ROSAT* mission is $\sim$4,000 (when in 36.5 AG 4,500 would be required). It is worth noting that the majority of these clusters have yet to be identified and many may never be.

1.5 The Middle Age of X-ray Astronomy?

The arrival of the third decade of X-ray astronomy midway through the *ROSAT* mission coincided with advances in CCD detector technology that have allowed a vast increase in the power of X-ray spectroscopy. These advances, coupled with nested-mirror systems, mark a clear maturing in the field and a move away from large samples of objects with limited information to limited samples with very detailed information. This is an inevitable progression that emerging disciplines experience, radio astronomy being a prime example. With the advance of aperture synthesis, radio astronomers in $\sim$35 AJ (Anno Jansky) could obtain insights into the nature of individual sources and the focus moved away from surveys. In the past decade, radio astronomy has turned back to surveys (NVSS, FIRST, WENSS, 4MASS), and this will happen in X-ray astronomy (but hopefully in less than 25 years time!).

This trend for more detailed study has had a huge impact on cluster research, and the need for spatially resolved spectroscopy of clusters was apparent from the first X-ray detections of clusters. The nature of cluster surveys has also changed with a greater emphasis on understanding complete samples in many different wavelength regimes (e.g., Crawford et al. 1999; Giovannini, Tordi, & Ferretti 1999; Pimbblet et al. 2002). A sample of 200 clusters is a great resource but of little use without some information about the X-ray temperature, iron abundance, X-ray surface brightness profile, optical photometry and spectroscopy, or radio imaging. The availability of new optical, near-infrared, and radio surveys (e.g., SDSS, UKIDSS, NVSS, FIRST) will make the multiwavelength aspects of these studies much easier, but the need for further X-ray observations is hard to avoid.

1.5.1 *ASCA* Observations

The first step in this progression was the Japanese-US satellite *ASCA*. The nested, foil-replicated mirrors of *ASCA* resulted in a relatively asymmetric, broad point-spread function ($2'$ FWHM), but the excellent performance of the SIS CCD detectors provided some very high-quality spectra for clusters (Mushotzky & Scharf 1997; Markevitch 1998; Fukazawa et al. 2000; Ikebe et al. 2002).

Over the course of the seven-year pointed phase, *ASCA* provided accurate temperatures and iron abundances for most of the 350 clusters observed. While few complete samples were observed, the *ASCA* data are an excellent complement to archival *ROSAT* observations. The notable exceptions to this are the flux-limited sample of 61 *ROSAT*-selected clusters (Ikebe et al. 2002) and the complete sample of $0.3 < z < 0.4$ EMSS clusters (Henry 1997) from which limits of the evolution of the cluster temperature function can be derived.

1.5.2 The Unfulfilled Potential of *ABRIXAS*

One of the most disappointing events in X-ray astronomy was the unfortunate failure of the German satellite *ABRIXAS* in June 1998. Its simple design and the track record of the team behind *ROSAT* meant the planned 3-year, all-sky survey *ABRIXAS* would have had a huge impact on X-ray astronomy. The survey depth envisioned of 1.5×10^{-13} erg s^{-1}cm^{-2} (0.5–2.0 keV) and 9×10^{-13} (2–12 keV) would have detected in excess of 20,000 clusters (i.e., more than the number required to keep pace with exponential growth).

1.5.3 *Chandra* and *XMM-Newton*

The launch of *Chandra* and *XMM-Newton* in 1999 has seen X-ray astronomy reach full maturity. The sub-arcsecond imaging of *Chandra* and unprecedented throughput of *XMM-Newton* have had a profound impact of our understanding of clusters (e.g., McNamara et al. 2000; Peterson et al. 2001; Allen, Schmidt, & Fabian 2002). The potential for surveys with both satellites is largely through serendipitous detections, but several important pointed surveys are being undertaken.

The only large *Chandra* serendipitous survey is CHamP (Wilkes et al. 2001), which will cover 14□° in 5 years and identify 8,000 X-ray sources of all types, of which 150–250 will be clusters (which will all be spatially resolved). The relatively small number of clusters makes this sample unlikely to set any strong cosmological constraints, but it will act as an excellent control sample for past and future samples to test how spatial resolution affects detection statistics.

XMM-Newton has a program similar to CHamP, the XID program that has three tiers: faint (10^{-15} erg s^{-1}cm^{-2}, 0.5□°), medium (10^{-14} erg s^{-1}cm^{-2}, 3□°), and bright (10^{-13} erg s^{-1}cm^{-2}, 100□°). Again, like CHamP, the number of clusters detected in the XID program will be small (< 50), so from a purely cluster view-point is not particularly relevant. There are currently two dedicated serendipitous cluster surveys. One expands on the XID programme (Schwope et al. 2004) and the other (the X-ray Cluster Survey, XCS, Romer et al. 2001) aims to extract all potential cluster candidates from the *XMM-Newton* archive and compile a sample of $>$5,000 clusters from up to 1,000□° over the full lifetime of the satellite. The

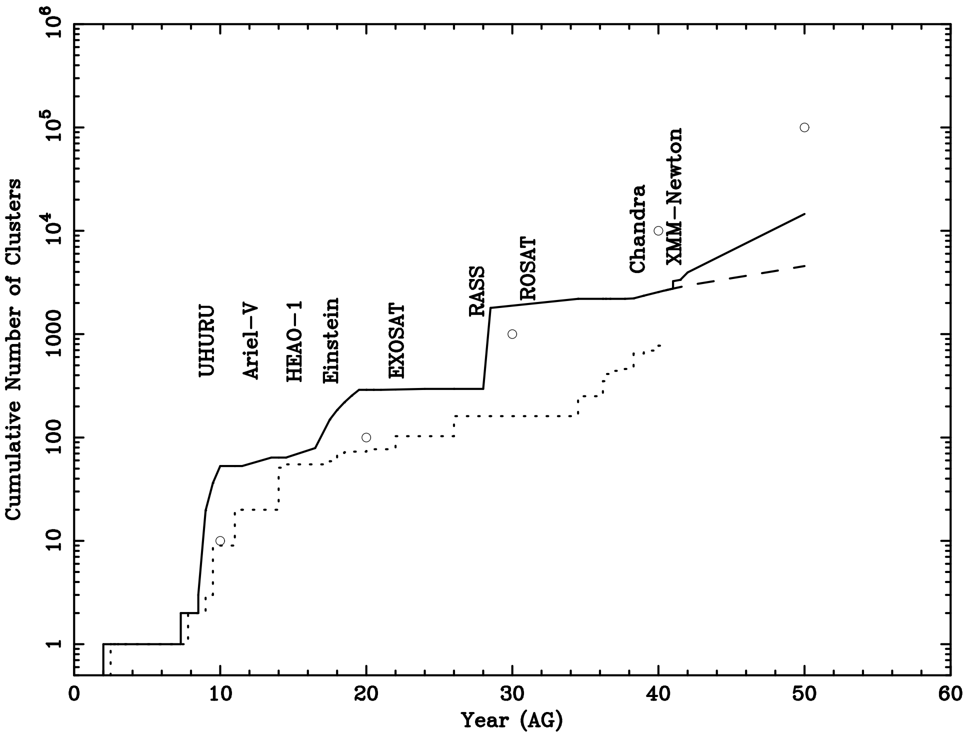

Fig. 1.2. The total number of clusters with X-ray detections known with time. The solid line marks the number detected or likely to be detected. The dotted line marks the detections published in the literature. The continuation above 40 AG is for an optimistic (solid) and pessimistic (dashed) assumption for the efficiency of *XMM-Newton* serendipitous surveys. The circles mark the number required for "Edge's Law" to hold.

contrast of XCS to CHamP and XID illustrates the huge increase in efficiency when one class of objects is chosen over the study of "complete" X-ray samples or contiguous area X-ray surveys, such as the XMM-LSS (Pierre et al. 2004), where the number of detected cluster is relatively small.

The principal pointed cluster surveys with *Chandra* and/or *XMM-Newton* target a sample of MACS clusters (Ebeling et al. 2001) with *Chandra* using GTO and GO time (PIs Van Speybroeck and Ebeling), a sample of REFLEX clusters with *XMM-Newton* in GO time (PI Böhringer) and a sample of SHARC clusters with *XMM-Newton* in GTO time (PI Lumb). Each of these projects is designed to determine the cluster temperature function, but will clearly have may other potential uses. These projects are all based on sub-samples of *ROSAT*-selected clusters to minimize the number of observations required. The reluctance of time allocation committees to devote time to complete samples in preference to the "exotica" (e.g., most distant, strongly lensing, etc., which predominate in successful proposals) is a hindrance to this "targeted" survey approach.

Table 1.3. *X-ray Missions*

Mission	Country	Status
ABRIXAS-II	German	renamed *ROSITA*
WFXT	Italian	rejected
PANORAM-X	ESA Flexi Mission	rejected
ROSITA	ESA ISS Mission	accepted phase A, could fly 2007
DUET	NASA Pathfinder	rejected

1.6 Can "Edge's Law" Hold?

The simple answer to this is question "No." Why should it? The observable Universe is finite so the number of clusters cannot grow exponentially indefinitely. Figure 1.2 shows the final version of the plot I showed during my talk with the cumulative number of clusters known with time. This illustrates the recent slowing of the number of clusters discovered and the increased lag between the detection and final publication of clusters.

As Simon White pointed out at the end of my talk, the case for ever-increasing sensitivity for the sake of it is a poor foundation for any field. The source counts for clusters crudely imply that every order of magnitude increase in number translates to an order of magnitude better sensitivity. So for the present, year 40 AG, the "Edge's Law" requirement would be equivalent to an all-sky survey to a flux of 10^{-13} erg s^{-1} cm^{-2} (0.5–2.0 keV). When I retire this will be 10^{-15} erg s^{-1} cm^{-2} (0.5–2.0 keV). This flux limit is reachable with current missions, but less than 1% of the sky could be covered.

There are, however, strong arguments for larger, deeper contiguous X-ray surveys than are available now or in the near future. The cosmological constraints that can be derived from the large-scale clustering of clusters, their mass function, and chemical evolution are complementary to those available elsewhere, most notably *WMAP* (Spergel et al. 2003). With the existence of large-area, multicolor optical and near-infrared surveys (e.g., SDSS, CHFTLS, RCS2, UKIDSS, Vista), the bottleneck of identification is eased and photometric redshifts will be sufficient for most purposes.

On a more practical level, the next generation of X-ray satellites, *XEUS* and *Constellation-X*, are optimized for the study of faint (10^{-14} erg s^{-1} cm^{-2}) sources. To get the best from the massive investment made in these missions, it would be sensible to have surveyed more than 1% of the sky to this depth.

Several proposals have been made to do this and are listed in Table 1.3. To date none of these missions is fully approved. The case for *DUET* was based on a survey of the SDSS area (Jahoda et al. 2003) and would have detected 20,000 clusters. It is likely that a proposal of this type will succeed (probably *ROSITA*) so some form of all/part-sky survey will have been performed by 50–55 AG. It is very unlikely that any mission (proposed or yet to be proposed) is likely to reach the limits required to keep above "Edge's Law," but the constant progress made in X-ray astronomy will see the number of clusters increase to well above 30,000 by 60 AG. This should be sufficient for cosmological work and more detailed studies with the next generation of X-ray satellites.

1.7 Conclusions

The success of X-ray surveys in the selection and understanding of clusters of galaxies over the past four decades has been remarkable. The statistical properties of X-ray selected samples of clusters have been used to determine cosmological parameters, and the detail found in individual clusters can be used to understand the evolution of that cluster. Current and planned surveys will build on these previous studies and will undoubtedly reveal further complexity in the intracluster medium, thereby refining our understanding of the astrophysics of these systems.

1.8 A Coda

As some of you will know, I was only able to attend the conference for one day due to the death of my father, David Edge. Fewer of you will know that one of my father's many legacies is one of the cornerstones of modern astronomy, the 3rd Cambridge Radio Catalogue (3C), which was his Ph.D. thesis. He always kept a keen interest in astronomy but moved on to become a leading figure in the sociology of science. I would like to thank Keith Taylor for his help on the evening before my departure and Richard and Barbara Ellis for providing the venue. Thanks too to all my friends and colleagues who have contacted me since then.

Acknowledgements. I owe Dave Gorman thanks for providing me with a presentation format that kept the audience awake. I am grateful to all those with whom I have worked on X-ray surveys, but particular thanks go to Harald Ebeling, whose contribution to the field is unrivaled.

References

Allen, S. W., Schmidt, R. W., & Fabian, A. C. 2002, MNRAS, 334, L11
Böhringer, H., et al. 2000, ApJS, 129, 435
——. 2001, A&A, 369, 826
——. 2002, ApJ, 566, 93
Boldt, E., McDonald, F. B., Riegler, G., & Serlemitsos, P. 1966, Phys. Rev. Lett., 17, 447
Borgani, S., et al. 2001, ApJ, 561, 13
Burg, R., Giacconi, R., Forman, W., & Jones, C. 1994, ApJ, 422, 37
Byram, E. T., Chubb, T. A., & Freidman, H. 1966, Science, 152, 66
Canizares, C. R., Clark, G. W., Markert, T. H., Berg, C., Smedira, M., Bardas, D., Schnopper, H., & Kalata, K. 1979, ApJ, 234, L33
Carlberg, R. G., et al. 1997, ApJ, 485, L13
Collins, C., Burke, D. J., Romer, A. K., Sharples, R. M., & Nichol, R. C. 1997, ApJ, 479, L117
Cooke, B. A., et al. 1978, MNRAS, 182, 489
Crawford, C. S., Allen, S. W., Ebeling, H., Edge, A. C., & Fabian, A. C. 1999, MNRAS, 306, 857
Cruddace, R., et al. 2002, ApJS, 140, 239
de Grandi, S., et al. 1999, ApJ, 514, 148
Donahue, M., et al. 2002, ApJ, 569, 689
Donahue, M., Stocke, J. T., & Gioia, I. M. 1992, ApJ, 385, 49
Ebeling, H., et al. 2000, ApJ, 534, 133
Ebeling, H., Edge, A. C., Allen, S. W., Crawford, C. S., Fabian, A. C., & Huchra, J. P. 2000, MNRAS, 318, 333
Ebeling, H., Edge, A. C., Böhringer, H., Allen, S. W., Crawford, C. S., Fabian, A. C., Voges, W., & Huchra, J. P. 1998, MNRAS, 301, 881
Ebeling, H., Edge, A. C., Fabian, A. C., Allen, S. W., Crawford, C. S., & Böhringer, H. 1997, ApJ, 479, L101
Ebeling, H., Edge, A. C., & Henry, J. P. 2001, ApJ, 553, 668
Ebeling, H., Jones, L. R., Fairley, B. W., Perlman, E., Scharf, C., & Horner, D. 2001, ApJ, 548, L23
Ebeling, H., Mullis, C. R., & Tully, B. R. 2002, ApJ, 580, 774

Ebeling, H., Voges, W., & Böhringer, H. 1994, ApJ, 436, 44
Ebeling, H., Voges, W., Böhringer, H., Edge, A. C., Huchra, J. P., & Briel, U. G. 1996, MNRAS, 281, 799
Ebeling, H., & Wiedenmann, G. 1993, Phys. Rev. E, 47, 704
Edge, A. C., Ebeling, H., Bremer, M., Röttgering, H., van Haarlem, M. P., Rengelink, R., & Courtney, N. J. D. 2003, MNRAS, 339, 913
Edge, A.C., Stewart, G. C., & Fabian, A. C. 1992, MNRAS, 258, 177
Edge, A. C., Stewart, G. C., Fabian, A. C., & Arnaud, K. A. 1990, MNRAS, 245, 559
Fabian, A. C. 1994, ARA&A, 32, 277
Fabian, A. C., Crawford, C. S., Edge, A. C., & Mushotzky, R. F. 1994, MNRAS, 267, 779
Fabian, A. C., Hu, E. M., Cowie, L. L., & Grindlay, J. 1981, ApJ, 248, 47
Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., & Giacconi, R., 1978, ApJS, 38, 357
Friedman, H., & Byram, E. T. 1967, ApJ, 147, 399
Fritz, G., Davidsen, A., Meekins, J. F., & Friedman, H. 1971, ApJ, 164, L81
Fukazawa, Y., Makishima, K., Tamura, T., Nakazawa, K., Ezawa, H., Ikebe, Y., Kikuchi, K., & Ohashi, T. 2000, MNRAS, 313, 21
Giacconi, R., et al. 1962, Phys. Rev. Lett., 9, 439
Gilbank, D. G., Bower, R. G., Castander, F. J., & Ziegler, B. L. 2004, MNRAS, submitted
Gioia, I. M., Henry, J. P., Mullis, C. R., Voges, W., Briel, U. G., Böhringer, H., & Huchra, J. P. 2001, ApJ, 553, L105
Gioia, I. M., Maccacaro, T., Schild, R. E., Wolter, A., Stocke, J. T., Morris, S. L., & Henry, J. P. 1990, ApJS, 72, 567
Giovannini, G., Tordi, M., & Ferretti, L. 1999, NewA, 4, 141
Henry, J. P. 1997, ApJ, 489, L1
Ikebe, Y., Reiprich, T., Böhringer, H., Tanaka, Y., & Kitayama, T. 2002, A&A, 383, 773
Jahoda, K., et al., 2003, AN, 324, 132
Jones, C., & Forman, W. 1984, ApJ, 276, 38
——., 1999, ApJ, 511, 65
Lahav, O., Edge, A. C., Fabian, A. C., & Putney, A. 1989, MNRAS, 238, 881
LaRoque, S. J., et al. 2003, ApJ, 583, 559
Lazzati, D., Campana, S., Rosati, P., Panzera, M. R., & Tagliaferri, G. 1999, ApJ, 524, 414
Ledlow, M., Loken, C., Burns, J. O., Owen, F. N., & Voges, W. 1999, ApJ, 516, L53
Le Févre, O., Hammer, F., Angonin, M. C., Gioia, I. M., & Luppino, G. A. 1994, ApJ, 422, L5
Loewenstein, M., & Mushotzky, R. F. 1996, ApJ, 466, 695
Luppino, G. A., Gioia, I. M., Hammer, F., Le Févre, O., & Annis, J. A. 1999, A&AS, 136, 117
Mahdavi, A., Böhringer, H., Geller, M. J., & Ramella, M. 2000, ApJ, 534, 114
Markevitch, M. 1998, ApJ, 504, 27
Markevitch, M., et al. 2000, ApJ, 541, 542
Mason, K. O., et al. 2000, MNRAS, 311, 456
Mazzotta, P., Markevitch, M., Vikhlinin, A., Forman, W. R., David, L. P., & Van Speybroeck, L. 2001, ApJ, 555, 205
McNamara, B. R., et al. 2000, ApJ, 534, L135
Meekins, J. F., Gilbert, F., Chubb, T. A., Friedman, H., & Henry, R. C. 1971, Nature, 231, 107
Mitchell, R. J., Culhane, J. L., Davison, P. J., & Ives, J. C. 1976, MNRAS, 176, 29
Mushotzky, R. F., & Scharf, C. A. 1997, ApJ, 482, 13
Nevalainen, J., Lumb, D., dos Santos, S., Siddiqui, H., Stewart, G. C., & Parmar, A. N. 2001, A&A, 374, 66
Panzera, M. R., Campana, S., Covino, S., Lazzati, D., Mignani, R. P., Moretti, A., & Tagliaferri, G. 2003, A&A, 399, 351
Peres, C., Fabian, A. C., Edge, A. C., Allen, S. W., Johnstone, R. M., & White, D. A. 1998, MNRAS, 298, 416
Perlman, E. S., Horner, D. J., Jones, L. R., Scharf, C. A., Ebeling, H., Wegner, G., & Malkan, M. 2002, ApJS, 140, 265
Pesce, J. E., Fabian, A. C., Edge, A. C., & Johnstone, R. M. 1990, MNRAS, 244, 58
Peterson, J. R., et al. 2001, A&A, 365, L104
Piccinotti, G., Mushotzky, R. F., Boldt, E. A., Holt, S. S., Marshall, F. E., Serlemitsos, P. J., & Shafer, R. A. 1982, ApJ, 253, 485
Pierre, M., et al. 2004, A&A, submitted (astro-ph/0305191)

Pimbblet, K. A., Smail, I., Kodama, T., Couch, W. J., Edge, A. C., Zabludoff, A. I., & O'Hely, E. 2002, MNRAS, 331, 333
Reiprich, T., & Böhringer, H. 2002, ApJ, 567, 716
Romer, A. K., et al. 2000, ApJS, 126, 209
Romer, A. K., Viana, P. T. P., Liddle, A. R., & Mann, R. G. 2001, ApJ, 547, 594
Rosati, P., Della Ceca, R., Norman, C., & Giacconi, R. 1998, ApJ, 492, L21
Schwope, A., et al. 2000, AN, 312, 1
Schwope, A., Lamer, G., Burke, D., Elvis, M., Watson, M.G., Schulze, M.P., Szokoly, G., & Urrutia, T., 2004, Proc. World Space Conf. Houston, October 2002, Adv. Space Res., in press (astro-ph/0306112)
Spergel, D. N., et al. 2003, ApJS, 148, 175
Stewart, G. C., Fabian, A. C., Jones, C., & Forman, W. 1984, ApJ, 285, 1
Stocke, J. T., Morris, S. L., Gioia, I. M., Maccacaro, T., Schild, R., Wolter, A., Fleming, T., & Henry, J. P. 1991, ApJS, 76, 813
Vikhlinin, A., McNamara, B. R., Forman, W., Jones, C., Quintana, H., & Hornstrup, A. 1998, ApJ, 498, 21
Voges, W., et al. 1999, A&A, 349, 389
White, D. A., Fabian A. C., Johnstone, R. M., Mushotzky, R. F., & Arnaud, K. 1991, MNRAS, 252, 72
White, D. A., Jones, C., & Forman, W. 1997, MNRAS, 292, 419
Wilkes, B. J., et al. 2001, in New Era of Wide Field Astronomy, ed. R. G. Clowes, A. J. Adamson, & G. E. Bromage (San Fransisco: ASP), 47