THE WARRPS SURVEY. III. THE DISCOVERY OF AN X-RAY LUMINOUS GALAXY CLUSTER AT z = 0.833 AND THE IMPACT OF X-RAY SUBSTRUCTURE ON CLUSTER ABUNDANCE MEASUREMENTS

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ABSTRACT

The Wide Angle ROSAT Pointed Survey team reviews the properties and history of the discovery of Cl J0152.7−1357, an X-ray luminous, rich cluster of galaxies at a redshift of z = 0.833. At Lx = 8 × 1044 h50−2 erg s−1 (0.5−2.0 keV) Cl J0152.7−1357 is the most X-ray luminous cluster known at redshifts z > 0.55. The high X-ray luminosity of the system suggests that massive clusters may begin to form at redshifts considerably greater than unity. This scenario is supported by the high degree of optical and X-ray substructure in Cl J0152.7−1357, which is similarly complex as that of other X-ray–selected clusters at comparable redshift and consistent with the hypothesized picture of cluster formation by mass infall along large-scale filaments.

X-ray emission from Cl J0152.7−1357 was detected already in 1980 with the Einstein IPC. However, because the complex morphology of the emission caused its significance to be underestimated, the corresponding source was not included in the cluster sample of the Einstein Extended Medium-Sensitivity Survey (EMSS) and hence was not previously identified. Simulations of the EMSS source detection and selection procedure performed by us suggest a general, mild bias of the EMSS cluster sample against X-ray luminous clusters with pronounced substructure. If highly unrelaxed, merging clusters are common at intermediate-to-high redshift (as is suggested by the current data), they could create a bias in some samples as the morphological complexity of mergers may cause them to fall below the flux limit of surveys that make the implicit or explicit assumption of a unimodal spatial source geometry. Conversely, the enhanced X-ray luminosity of mergers might cause them to, temporarily, rise above the flux limit. Either effect could lead to erroneous conclusions about the evolution of the comoving cluster space density. A high fraction of morphologically complex clusters at high redshift would also call into question the validity of evolutionary studies (and, specifically, cosmological conclusions) which implicitly or explicitly assume that the systems under investigation are virialized.

Subject headings: galaxies: clusters: individual (Cl J0152.7−1357) — surveys — X-rays: galaxies

1. INTRODUCTION

The space density of distant clusters of galaxies is a measurable quantity whose theoretical value is highly sensitive to the physical and cosmological parameters of models of structure formation and evolution (e.g., Oukbir & Blanchard 1992; Bahcall & Cen 1992; Viana & Liddle 1996; Carlberg et al. 1997; Oukbir & Blanchard 1997; Eke et al. 1998).

A large number of independent measurements of the cluster X-ray luminosity function (XLF) have been performed in the past decade. Given the diversity of the original observations used in these studies and of the data analysis techniques applied, the good agreement of the results is impressive. Virtually all studies agree that the abundance of clusters of low-to-intermediate X-ray luminosity (Lx < 4 × 1044 erg s−1, 0.5−2.0 keV) does not change significantly out to z ~ 0.8 (Gioia et al. 1990a; Henry et al. 1992; Burke et al. 1997; Ebeling et al. 1997; Vikhlinin et al. 1998a; Jones et al. 1998, hereafter Paper II; Rosati et al. 1998; De Grandi et al. 1999; Nichol et al. 1999).

At higher X-ray luminosities, however, a consistent picture has yet to emerge. Reports of strong negative evolution at Lx > 3 × 1044 ergs s−1 (0.3−3.5 keV) already at moderate redshifts just beyond z = 0.3 (Gioia et al. 1990a; Henry et al. 1992; see also Nichol et al. 1997 for a contrary result) are supported by the findings of Vikhlinin et al. (1998a), although the latter rest on a statistically less secure basis. If these results are correct, a much more pronounced dearth of X-ray luminous clusters is expected at yet higher redshift unless cluster evolution is a strongly nonlinear, almost discontinuous function of X-ray luminosity and redshift. However, Luppino & Gioia (1995) show that the cluster XLF at 0.5 ≤ z ≤ 1 is consistent with the one found in the Einstein Extended Medium-Sensitivity Survey (EMSS) for the redshift range 0.3 < z < 0.6 (median z = 0.33), i.e., there appears to be no further significant evolution of luminous clusters beyond z ∼ 0.6 (although such evolution is not ruled out).

With only a handful of X-ray luminous clusters currently known at z > 0.5, the key to understanding these appar-
ently conflicting results lies clearly in new discoveries and more detailed observations of X-ray luminous (and, by inference, massive) clusters at high redshift. Any additional detection of a massive cluster at high redshift (and certainly at \( z \gtrsim 0.8 \)) is thus of paramount importance as it brings us one step closer to an accurate measurement of the cluster abundance at very high redshift, where its sensitivity to evolutionary effects is greatest.

2. THE SIGNIFICANCE OF DISTANT MASSIVE CLUSTERS

With the exception of the Bright Serendipitous High-Redshift Archival ROSAT Cluster (SHARC) survey (Nichol et al. 1999), all of the present deep Position Sensitive Proportional Counter (PSPC) cluster surveys provide sufficient depth to detect a cluster of \( L_X > 10^{45} \text{ergs s}^{-1} (0.3-3.5 \text{keV}) \) out to \( z \simeq 1 \) and beyond. When the cumulative high-redshift EMSS XLF (median \( z = 0.33 \)) is scaled to the comoving volume corresponding to the redshift range \( 0.8 < z < 1 \) (i.e., assuming no evolution between \( z \approx 0.33 \) and \( z = 0.8-1 \)), it predicts about 15 clusters with \( L_X > 10^{43} \text{ergs s}^{-1} (0.3-3.5 \text{keV}) \) per steradian, i.e., \( 4.6 \times 10^{-2} \text{deg}^{-2} \). Since the mentioned cluster surveys cover only from 18 deg\(^2\) (SHARC survey) to 160 deg\(^2\) (CfA cluster survey), the detection of only very few X-ray luminous clusters in any of these surveys places significant constraints on the evolution of clusters and large-scale structure in general. Note that this is true only for the most luminous systems; if the X-ray luminosity criterion is relaxed and clusters down to \( L_X = 4 \times 10^{44} \text{ergs s}^{-1} (0.3-3.5 \text{keV}) \) are considered, the expected cluster density in the same redshift range rises by almost an order of magnitude and any individual cluster detection becomes much less significant.

We emphasize that, although any detection (X-ray, optical, infrared) of massive clusters at very high redshifts is an important discovery in its own right, it is clusters detected in the course of statistically complete surveys that bear the most weight. Only the latter allow the space density of such systems to be quantified and compared to predictions from theoretical models. Any systematic effects in the data analysis and interpretation that could cause such clusters to be missed or misidentified need to be thoroughly understood and corrected for before conclusions about the physical or cosmological parameters governing cluster evolution are drawn from derived statistics such as the cluster XLF.

In the rest of this paper we summarize the current observational status (§3) and give a short overview of the serendipitous cluster survey Wide Angle ROSAT Pointed Survey (WARPS) (§4). We then describe the WARPS discovery of CI J0152.7-1357, a very X-ray luminous cluster at \( z = 0.8325 \), and discuss and summarize the results from all available X-ray observations of this system (§5). Prompted by our finding that CI J0152.7-1357 was missed in the EMSS, we take a closer look at how deviations from spherical symmetry in a cluster’s X-ray emission may affect the EMSS cluster sample (and possible other cluster samples) as a whole (§6). Trying to assess the importance of biases caused by complex cluster morphology, we investigate the prevalence of substructure in distant clusters (§7) before, finally, discussing the implications of our findings for attempts to constrain cosmological parameters using X-ray flux-limited cluster samples (§8).

3. PREVIOUSLY KNOWN VERY DISTANT, X-RAY LUMINOUS CLUSTERS OF GALAXIES

Very few clusters of galaxies have been detected at redshifts greater than 0.8, and even fewer can be called X-ray luminous. Prior to the discovery of CI J0152.7-1357, only two X-ray–selected clusters were known at \( z > 0.8 \): MS 1054.4-0321 (\( z = 0.829 \), \( L_X = 1.42 \times 10^{45} \text{ergs s}^{-1} \) in the \( 0.3-3.5 \text{keV} \) band) and, much less X-ray luminous, RX J1716.6+6708 (\( z = 0.813 \), \( L_X = 3.2 \times 10^{44} \text{ergs s}^{-1} \) in the \( 0.5-2.0 \text{keV} \) band; Henry et al. 1997; Gioia et al. 1999). Slightly closer than \( z = 0.8 \) (\( z = 0.782 \); Gioia & Luppino 1994), but distant and X-ray luminous enough to be noteworthy in this context, is MS 1137.5+6625 (\( L_X = 1.03 \times 10^{45} \text{ergs s}^{-1} \) in the \( 0.3-3.5 \text{keV} \) band). The discovery of an even more distant X-ray–emitting cluster at \( z = 1.27 \) was recently reported by Rosati et al. (1999); however, at \( L_X \sim 1.5 \times 10^{44} \text{ergs s}^{-1} (0.5-2.0 \text{keV}) \) this system is even less X-ray luminous than RX J1716.6+6708.

All other presently known clusters at very high redshift have been optically selected as projected galaxy overdensities in deep CCD images (Gunn, Hoeschel, & Oke 1986, hereafter GHO; Postman et al. 1996, hereafter PDCS; Scovell et al. 1999) or were originally detected at radio or infrared wavelengths (e.g., Crawford & Fabian 1996; Delorm et al. 1997; Stanford et al. 1997). Although there are now an impressive number of optically selected clusters at \( z > 0.8 \) (Postman and coworkers alone list a dozen clusters at \( z \geq 1 \) in their PDCS sample), it ought to be emphasized that, for the majority of these possibly very distant optical clusters, the published “redshifts” are estimated statistically and are not the result of actual spectroscopic measurements. The physical reality of many of these systems thus remains to be confirmed through either X-ray or extensive spectroscopic observations. The difficulties inherent to the optical approach are evidenced by, e.g., the work of Oke, Postman, & Rubin (1998), who obtained 892 redshifts in the fields of nine distant cluster candidates selected from the GHO and PDCS catalogs. Three of their nine candidate clusters showed no significant peak in the observed redshift histogram, and three others showed between two and four equally significant peaks at very different redshift, illustrating the severity of projection effects in optically selected cluster samples. By way of contrast, Castander et al. (1994) demonstrate how X-ray observations can be used efficiently to test whether optically selected distant clusters are indeed gravitationally bound, massive systems. Castander and coworkers analyzed PSPC observations of five GHO clusters which had spectroscopic redshifts ranging from 0.7 to 0.92. They detected only two of the five and found all five to have measured X-ray luminosities, or upper limits, of less than \( 1 \times 10^{44} \text{ergs s}^{-1} (0.5-2.0 \text{keV}) \); i.e., they are, at best, poor clusters which, unless detected in very large numbers, do not provide stringent constraints on either the rate of

10 I.e., the ROSAT North Ecliptic Pole Survey (Mullis, Gioia, & Henry 1998), the ROSAT Deep Cluster Survey (Rosati et al. 1995, 1998), the southern SHARC survey (Collins et al. 1997; Burke et al. 1997), the Wide Angle ROSAT Pointed Survey (Paper I; Paper II; Fairley et al. 2000), and the CfA cluster survey (Vikhlinin et al. 1998a, 1998b, 1999).

11 Note that we use \( h = 0.5 \), \( q_0 = 0.5 \) throughout.

12 The given luminosity was derived from the archival ROSAT HRI observation of this cluster.
cluster evolution or the cosmological parameters of structure formation models.

4. THE WARPS CLUSTER SURVEY

The goal of the WARPS is to compile a complete and unbiased, X-ray-selected sample of clusters of galaxies from serendipitous detections of X-ray sources in deep \textit{ROSAT} PSPC pointings. A comprehensive overview of the scientific goals of the project, the X-ray source detection algorithm employed (Voronoi Tesselation and Percolation; VTP), the sample selection and flux corrections techniques, as well as first results, are presented in Scharf et al. (1997, hereafter Paper I). VTP is particularly well suited for the detection and characterization of low surface brightness emission (Ebeling \& Wiedenmann 1993; Ebeling et al. 1996; Paper I) and is likely to recognize even very distant clusters as extended X-ray sources (Paper I). However, in order to reduce possible incompleteness in our cluster sample due to erroneous classification of distant clusters as point sources, our optical follow-up observations are not limited to extended X-ray sources but also include likely point sources without obvious optical counterparts (Paper II). Paper II also discusses the WARPS log \textit{N}–log \textit{S} distribution of poor clusters of galaxies and its implications for cluster evolution.

The first two WARPS papers focus on results for a complete sample of clusters compiled over a geometric solid angle of 14.7 deg$^2$ during the first phase of the project. In 1997 May, the WARPS project went into its second phase which increases the total solid angle to 73 deg$^2$ and will yield a statistically complete sample of more than 70 X-ray-selected galaxy clusters at $z > 0.3$. In this second phase, cluster candidates without obvious optical counterpart on the POSS plates (as provided by the Digitized Sky Survey) were imaged at the Michigan-Dartmouth-MIT 1.3 m and University of Hawaii 2.2 m telescopes in preparation for spectroscopic follow-up observations at larger telescopes. Although observations of a few very distant cluster candidates have yet to be performed (scheduled for spring 2000), the WARPS cluster sample is already complete at $z < 0.84$ over the full solid angle.

5. Cl J0152.7–1357

In 1996 and 1997, the cluster Cl J0152.7–1357 was discovered independently in the \textit{ROSAT} Deep Cluster Survey (RDCS) and WARPS. Later, Cl J0152.7–1357 was also detected in the Bright SHARC survey (Nichol et al. 1999).

In this section we describe the discovery of Cl J0152.7–1357 in the WARPS survey and discuss and summarize previous and subsequent X-ray observations of this system.

5.1. Discovery in the WARPS

The standard WARPS X-ray analysis detected Cl J0152.7–1357 as a very extended source 14.2 off-axis in a 20 ks PSPC pointed observation of NGC 720; the \textit{POSS}-2 Digitized Sky Survey image is blank at the position of the source. Figure 1 shows an \textit{I}-band image of Cl J0152.7–1357, taken with the University of Hawaii 2.2 m telescope on 1997 August 4, with adaptively smoothed PSPC X-ray flux contours overlaid. A blow-up of the central cluster region is shown in Figure 2. Based on the X-ray source extent and the observed overdensity of faint galaxies at and around the position of the X-ray source, it was classified as a likely distant cluster of galaxies. The X-ray emission from Cl J0152.7–1357 shows a high degree of substructure and a pronounced elongation along a position angle of about 40$^\circ$ which follows roughly the distribution of galaxies in the cluster core (see § 7 for a discussion of the dynamical state of Cl J0152.7–1357).

On 1997 August 11, we observed a total of 14 distant cluster candidates, among them Cl J0152.7–1357, with the Low-Resolution Imaging Spectrograph (LRIS) (Oke et al. 1995) on the Keck-II 10 m telescope on Mauna Kea. Using a long slit of 1.5 width and the 300/5000 grating which provides 2.4 Å pixel$^{-1}$ resolution and spectral coverage from 5000 to 10000 Å, we obtained spectra of six galaxies (see Fig. 2) close to the peak of the X-ray emission from Cl J0152.7–1357 and found redshifts as listed in Table 1. The spectra are shown in Fig. 3. All redshifts are accordant and consistent with a cluster redshift of $z = 0.8325$. All spectra show absorption features typical of old stellar populations in elliptical galaxies, and none shows emission lines that would suggest active galactic nucleus (AGN) contamination.

5.2. Other X-Ray Observations of Cl J0152.7–1357

NGC 720 was observed not only with the \textit{ROSAT} PSPC in 1992, but also with the \textit{Einstein} IPC in 1980 and with the \textit{ROSAT} HRI in 1994. We examine and compare the images from all three observations in Figure 4. The images are shown in chronological order and have been registered using the astrometry solutions in the respective FITS headers. To allow an assessment of the quality of the raw data as well as of the presence and morphology of any

| Galaxy  | R.A. (J2000) | Decl. (J2000) | $m_i$ | Redshift ($\zeta$) | Features          |
|---------|-------------|--------------|------|-----------------|------------------|
| A       | 01 52 44.9  | -13 57 04    | 20.02 ± 0.08 | 0.8360 ± 0.0004 | Ca H and K       |
| B       | 01 52 43.7  | -13 57 19    | 19.45 ± 0.06 | 0.8351 ± 0.0002 | Ca H and K, G    |
| C       | 01 52 43.8  | -13 57 20    | 19.56 ± 0.06 | 0.8368 ± 0.0005 | 4000 Å break     |
| D       | 01 52 42.9  | -13 57 35    | 20.54 ± 0.13 | 0.8346 ± 0.0007 | Ca H and K, G    |
| E       | 01 52 39.8  | -13 58 26    | 20.32 ± 0.11 | 0.8286 ± 0.0005 | Ca H and K, G    |
| F       | 01 52 39.6  | -13 58 27    | 19.67 ± 0.07 | 0.8280 ± 0.0004 | Ca H and K, G    |

Note.—Positions (accurate to better than 1$''$), \textit{I}-band magnitudes, and redshifts of the galaxies with LRIS long-slit spectra. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The quoted redshift errors are the 1σ standard deviations of the values implied by the individual features listed in the last column. The redshift of galaxy C was not used in the computation of the cluster redshift.
extended emission, we show contours of the smoothed emission (a Gaussian smoothing kernel with $\sigma = 30''$ was used) overlaid on the observed raw photon data. The latter are binned such that they slightly oversample the point-spread function of the respective instrument which is represented by the FWHM bar in the lower left-hand corner of each image.

In the following we discuss the serendipitous HRI and IPC observations of Cl J0152.7–1357 in more detail before summarizing briefly the results of a recent targeted observation of the cluster with the *BeppoSAX* satellite.

### 5.2.1. ROSAT HRI

The relatively high angular resolution of the ROSAT HRI ($\sim 12''$ at an off-axis angle of 14') allows us to investigate whether contaminating point sources might contribute to the observed PSPC flux of Cl J0152.7–1357. At an off-axis angle of 14' a point source with a flux of about one-third of the flux detected from Cl J0152.7–1357 would be detectable with the HRI at greater than 5 $\sigma$ significance. However, a secure detection of diffuse emission from Cl J0152.7–1357 with the HRI would require an exposure time in excess of 100 ks. As can be seen in the bottom panel of Figure 4, no point sources are detected within the contours shown in Figure 1 but there is marginal evidence of low surface brightness excess emission at the position of the cluster, indicating that the overwhelming majority of the emission detected with the PSPC originates from the cluster. Moreover, the emission detected with the HRI shows a clear elongation along the same position angle of about 40° as the one found in the PSPC data. Although the southwestern extension of the emission detected with the PSPC does not coincide with any prominent galaxy overdensity in the University of Hawaii 2.2 m image (cf. Fig. 1), we note that, if any of the major X-ray surface brightness peaks in the PSPC image were due to a single, unvarying point source, they would have been detected with the HRI.

### 5.2.2. Einstein IPC

It is noteworthy that ours is in fact not the first detection of Cl J0152.7–1357 at X-ray wavelengths. As mentioned before, NGC 720 was not only observed with ROSAT, but

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**Fig. 1.** — $I$-band image of Cl J0152.7–1357 taken with the University of Hawaii 2.2 m telescope on 1997 August 4 in subarcsecond seeing. The total exposure time was 12 minutes. Overlaid are the adaptively smoothed X-ray flux contours in the 0.5–2.0 keV band from the serendipitous PSPC observation of the cluster. The contours are spaced logarithmically by factors of 1.5; the lowest contour level lies a factor of 3 above the background. The size of the Gaussian smoothing kernel is varied such that all features shown here are significant at the 3–4 $\sigma$ level (see Ebeling, White, & Rangarajan 2000 for details of the algorithm).
was, in 1980, also a pointing target of observations with the Einstein observatory. A source at \( \alpha = 01^h52^m42^s, \delta = -13^\circ57^\prime49^\prime\) (J2000) (i.e., within 1\arcmin of the PSPC position of Cl J0152.7−1357) is clearly detected with the Imaging Proportional Counter (IPC; sequence number of pointing I 5769); the Einstein observatory source catalog (EOSCAT) assigns this source the number 496 and quotes a significance of detection of 4.8 \( \sigma \) in the IPC broad band and within the detect cell (Harris et al. 1990). We show the IPC broadband data around this position in the upper left-hand panel of Figure 4. The position angle (approximately zero) of the apparent elongation of the source is different from the one found from the ROSAT PSPC and HRI data. However, since the IPC point-spread function has an FWHM of about 90\arcsec in the broad band, the source elongation found in this short IPC observation is only marginally significant. The same IPC source is also listed as EXSS 0150.2−1411 in the catalog of extended Einstein detections compiled by Oppenheimer, Helfand, & Gaidos (1997), who find the source significance (presumably in the broad band) to be 4.7 and 5.7 \( \sigma \) within circular apertures of 1\'25 and 2\'35 radius. Although this source therefore appears to be sufficiently significant to be included in the EMSS catalog, it remained unidentified until its rediscovery in the RDCS and WARPS surveys in 1996/1997. We will come back to the IPC detection of Cl J0152.7−1357 in § 6.1.

5.2.3. BeppoSAX

A recent pointed BeppoSAX observation of Cl J0152.7−1357 allowed the temperature and metallicity of the intracluster gas to be measured; Della Ceca et al. (2000) report values of \( kT = 6.5^{\pm 1.2} \) keV and \( Z = 0.53^{\pm 0.29} \) This gas temperature is consistent both with the temperature estimate of \( 5.9^{\pm 1.4} \) keV obtained by us from the PSPC data (cf. Fairley et al. 2000) and with the cluster X-ray luminosity−temperature relation as determined by Allen & Fabian (1998) which predicts \( kT = 7.8 \) keV. The relatively poor angular resolution of the BeppoSAX telescope does not allow any conclusions to be drawn about the possibility of point-source contamination.

5.3. X-Ray Properties

Using the Galactic neutral hydrogen column density in the direction of the cluster of \( 1.47 \times 10^{20} \) cm\(^{-2}\) (Dickey & Lockman 1990) as well as a metallicity of 0.5 and a gas temperature of 6.5 keV (Della Ceca et al. 2000), we convert the total PSPC count rate of 0.0237 \( \pm 0.0015 \) counts s\(^{-1}\) (pulse-height analyzer [PHA] channels 50–200) measured
in the WARPS analysis into a total, unabsorbed flux of 
\((2.90 \pm 0.18) \times 10^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\) (0.5–2.0 keV), corresponding to an X-ray luminosity of \((8.59 \pm 0.53) 
[(15.5 \pm 0.95), (33.7 \pm 2.08)] \times 10^{44} \ h_{50}^{-2} \ ergs \ s^{-1} \) in the 
0.5–2.0 keV (0.3–3.5 keV, bolometric) band. Thus, Cl 
J0152.7–1357 is slightly more luminous than MS 
1054.4–0321, making it the most X-ray luminous distant 
cluster detected so far. It is also worth noting that both 
Cl J0152.7–1357 and MS 1054.4–0321 are more X-ray 
luminous than any other known cluster at 
z [0.55.

We find our measurement of the total, unabsorbed cluster 
flux of Cl J0152.7–1357 in the 0.5–2.0 keV band to be in 
good agreement with all other results obtained from the 
available X-ray observations of this system.

\(\text{Einstein IPC.} \ f(<1.5 \ h_{50}^{-1} \ Mpc) = (3.76 \pm 0.84) \times 10^{-13} \ ergs \ s^{-1} \ cm^{-2} \) (this work).

\(\text{ROSAT PSPC (RDCS).} \ f(<1.5 \ h_{50}^{-1} \ Mpc) = (2.2 \pm 0.2) \times 10^{-13} \ ergs \ s^{-1} \ cm^{-2} \) (Della Ceca et al. 2000).

\(\text{ROSAT PSPC (WARPS).} \ f(\text{total}) = (2.90 \pm 0.18) \times 10^{-13} \ ergs \ s^{-1} \ cm^{-2} \) (this work).

\(\text{ROSAT PSPC (Bright SHARC).} \ f(\text{total}) = (2.93 \pm 0.16) \times 10^{-13} \ ergs \ s^{-1} \ cm^{-2} \) (Romer et al. 2000).

\(\text{ROSAT HRI.} \ f(<1.5 \ h_{50}^{-1} \ Mpc) = (2.8 \pm 1.1) \times 10^{-13} \ ergs \ s^{-1} \ cm^{-2} \) (this work).

\(\text{BeppoSAX.} \ f(<2.0 \ h_{50}^{-1} \ Mpc) = (1.9 \pm 0.4) \times 10^{-13} \ ergs \ s^{-1} \ cm^{-2} \) (Della Ceca et al. 2000).

All ROSAT flux measurements agree within the errors.\(^{13}\)


\(^{13}\) Note that the RDCS and HRI measurements use a fixed metric 
aperture, whereas WARPS and Bright SHARC measure the total cluster 
flux.

By comparison, the IPC result is high and the 
BeppoSAX 
result is low; compared directly, the discrepancy between 
these two measurements is significant at the 2 \( \sigma \) confidence 
level.

As noted before in \( \S \) 5.2.3, the measurements of the cluster 
gas temperature obtained independently from the PSPC 
data (this work) and the BeppoSAX data (Della Ceca et al. 2000) 
also agree well within their errors.

Although we cannot rule out that some of the observed 
emission originates from one or more variable point 
sources, the overall good agreement of the source positions, 
X-ray fluxes, and cluster gas temperatures measured for
Ci J0152.7–1357 between 1980 and 1998 makes major contamination unlikely.

Table 2 summarizes the optical and X-ray properties of CI J0152.7–1357.

6. POSSIBLE SYSTEMATIC BIASES IN THE EMSS CLUSTER SAMPLE

As mentioned in § 5.2.2, CI J0152.7–1357 was detected with the Einstein IPC at 4.8 $\sigma$ significance (EOSCAT: Harris et al. 1990); however, the EMSS source catalog (Gioia et al. 1990b) lists the respective IPC field (I 5769) as containing no serendipitous detections that would be significant at the greater than 4 $\sigma$ level. Since this discrepancy has been the subject of some debate, we investigate the issue in detail in the following. Specifically, we address three questions: first, how can the two catalogs, using (apparently) the same data, arrive at substantially different significances of detection for the same source? Second, what are the implications of the absence of CI J0152.7–1357 from the EMSS catalog for the overall completeness of the EMSS cluster sample? And third, what are the consequences of our findings for the clusters included in the EMSS?

6.1. The IPC Detection of CI J0152.7–1357

Both the Einstein IPC source catalog (EOSCAT: Harris et al. 1990) and the EMSS sample (Gioia et al. 1990b) were
compiled using the same source detection algorithm. It combines a sliding cell detection algorithm (cell geometry: $2.4 \times 2.4$ arcmin$^2$) with a maximum likelihood (ML) peak-finding algorithm which fits a Gaussian model of the instrumental point-spread function (the size of which varies with the chosen energy range) to the data inside the detect cell. The final source positions are taken from the ML results. While this approach is adequate for the detection of point sources, the use of a peak-finding algorithm can clearly lead to nonoptimal results in the case of extended sources with internal structure.

While the EOSCAT and EMSS results for Cl J0152.7–1357 are obtained from the same data, the compilation procedures of the two catalogs are not entirely identical. EOSCAT computes the source significance within a detect cell centered on the ML source position measured in the IPC broad band (0.16–3.5 keV), whereas the EMSS uses the ML source position determined in the IPC hard band (0.81–3.5 keV). However, both catalogs use the broad-band photons within the detect cell to compute the source significance that is used as the final criterion for the inclusion of sources in the respective catalog. The rationale behind the two-band approach chosen by the EMSS team is to take advantage of the higher resolution of the IPC in the hard band without sacrificing the better photon statistics of the broadband data (T. Maccacaro & I. M. Gioia 1999, private communication). The energy dependence of the instrumental resolution means, however, that a narrower point-spread function will be used by the ML algorithm in the hard band—which, as we shall see, is part of the reason why the EMSS missed Cl J0152.7–1357.

### 6.1.1. Reanalysis of the IPC Data for Cl J0152.7–1357

We reanalyze the IPC data for field I 5769 in both the hard band and the broad band using the same sliding cell algorithm employed by the EOSCAT and EMSS teams. For the broadband data our analysis yields results similar to those listed in EOSCAT for source 496; at the position maximizing the source significance in the broad band we find the detect cell to contain 44 photons of which 9.9 are expected to be background. The resulting signal-to-noise ratio (S/N) in the broad band is 5.1. At the ML source position quoted by EOSCAT we measure 38 counts in the detect cell (EOSCAT: 44) of which 9.8 are attributed to background (EOSCAT: 11.7); the resulting S/N value is 4.6 (EOSCAT: 4.8). Our results are also in good agreement with those of Oppenheimer et al. (1997) who, in their independent reanalysis of the *Einstein* IPC data, find the significance of their source EXSS 0150.2–1411 to be 4.7 and 5.7σ (presumably in the broad band) within circular apertures of 1.25 and 2.35 radius.

The left-hand panel in Figure 5 shows contours of the smoothed X-ray emission in the IPC broad band at the position of Cl J0152.7–1357 with both our and the EOSCAT source position marked. Also shown is the contour within which our analysis finds the S/N in the hard band and within the detect cell to exceed the threshold value of 4. Although the astrometry used to create this image is taken directly from the *Einstein* events list, the offset of the marked EOSCAT source position from the peak of the emission suggests that the satellite attitude solution used in the original EOSCAT analysis may have differed by some $10^\circ$–20°. Note that the nonsphericity of the emission causes the position of the X-ray peak to lie only marginally within the S/N = 4 contour.

The results of the same analysis in the IPC hard band are shown in the right-hand panel of Figure 5. Again we show the S/N = 4 (broadband) contour as well as our best estimate of the source position in the broad band. Also shown is the source position returned by the ML algorithm from the EMSS analysis of the hard band data (kindly provided by I. Gioia). As a result of the more pronounced bimodality of the source in the hard band, the ML algorithm, using a narrower model of the point spread function than in the IPC broad band, now centers on an apparent peak more than 1° north of the position that maximizes the source significance in the broad band. At the EMSS source position we measure a value of 4.1 for the broadband S/N; slight differences in the astrometric solution caused the original EMSS S/N measurement at this position to fall just below the threshold value of 4. Consequently, the EMSS rejected Cl J0152.7–1357 as not sufficiently significant to be included in the EMSS catalog and thus missed what would have been the most distant and most X-ray luminous cluster in the EMSS sample.

### Table 2

| Quantity | Value |
|----------|-------|
| Redshift (z) | 0.8325 |
| $n_h$ (cm$^{-2}$) | $1.47 \times 10^{20}$ |
| PSPC exposure time (s) | 19,912 |
| Detected VTP count rate (PHA 50–200) ($s^{-1}$) | 0.0154 ± 0.0010 |
| Total count rate (PHA 50–200) ($s^{-1}$) | 0.0237 ± 0.0015 |
| Total unabsorbed flux (0.5–2.0 keV) (ergs cm$^{-2}$ s$^{-1}$) | $(2.90 \pm 0.18) \times 10^{-13}$ |
| Observed ICM temperature (keV): | |
| *ROSAT* PSPC | 5.9$^{+3}_{-1}$ |
| *BeppoSAX* | 6.5$^{+2}_{-1}$ |
| Rest-frame luminosity: | |
| 0.5–2.0 keV ($h_{75}$ ergs s$^{-1}$) | $(8.59 \pm 0.53) \times 10^{44}$ |
| 0.3–3.5 keV ($h_{75}$ ergs s$^{-1}$) | $(1.55 \pm 0.10) \times 10^{44}$ |
| Bolometric ($h_{75}$ ergs s$^{-1}$) | $(3.37 \pm 0.21) \times 10^{44}$ |

Note.—The quoted errors of the cluster count rate, flux, and luminosity are based on the Poisson error of the detected photons. The *BeppoSAX* results are taken from Della Ceca et al. 2000.
The thick contours overlaid on both plots mark the region within which we find the S/N within the detect cell and in the broad band to exceed 4. Also shown is the broadband source position as listed in EOSCAT (plus sign in the left plot) and the hard band source position found in the EMSS analysis (plus sign in the right plot). The position maximizing the broadband S/N in our own analysis is marked by a cross in both panels.

6.1.2. Summary of Our Reanalysis of the IPC Data

As demonstrated in the previous section and illustrated in Figure 5, the use of a peak-finding ML detection algorithm in the Einstein IPC data analysis leads to significant offsets between the ML source position and the one maximizing the broadband S/N of Cl J0152.7–1357. Moreover, in the presence of emission with apparently substructure the ML source positions in different energy bands can differ significantly. If Cl J0152.7–1357 were a spherically symmetric, relaxed system with a radial surface brightness profile following a beta model, the peak-centering algorithm would very likely have come closer to returning the maximal possible source significance of 5.6 $\sigma$ (using the PSPC count rate and assuming a core radius of 250 kpc). This leads us to investigate whether the failure of the EMSS to include Cl J0152.7–1357 can be regarded as symptomatic of a general bias against unrelaxed clusters.

6.2. Detection Bias in the EMSS Cluster Sample

Before we attempt to assess the importance of cluster substructure for the efficiency of the EMSS point-source detection algorithm (or, more generally, any algorithm that explicitly or implicitly assumes a unimodal source geometry), it should be stressed that this assumption is not vital to the source detection process. The choice of source detection algorithm is crucial though, as the algorithm’s biases can have a significant impact on the statistical quality of the resulting sample. The EMSS and WARPS surveys, for instance, are inherently different due to differences in the source detection process. The EMSS is X-ray surface brightness–limited (the selection criterion is the significance of the flux in a detect cell of fixed angular size, and the survey flux limit refers to the flux in the same detect cell; Gioia et al. 1990b) while WARPS is almost completely X-ray flux–limited (the detection procedure uses a very low surface brightness threshold—see Paper I—and the limiting flux is the total flux of the cluster including the fraction that has escaped direct detection).

6.2.1. Simulations of Unrelaxed Clusters

We investigate the redshift and luminosity dependence of the EMSS detection efficiency for morphologically complex sources by simulating IPC observations of two kinds of unrelaxed clusters: first, mergers of two similarly extended components (akin to Cl J0152.7–1357) and, second, extended systems containing a compact but off-center core (similar to MS 1054–0321; see § 7). Table 3 gives an overview of the model parameters used in the simulations. In all simulations we assume a uniform background of $2.5 \times 10^{-2}$ counts s$^{-1}$ within the detect cell and an exposure time of 2.5 ks, values typical of the average IPC pointing; we also blur all simulated images by convolving them with a Gaussian of 33$''$ width (1 $\sigma$), thereby accounting for the IPC point-spread function (Lea & Henry 1988). Finally, we scale the total emission from both components such that the maximal significance in the broad band is always constant at the EMSS threshold value of 4 $\sigma$ within the detect cell. Since we are investigating a systematic effect, no Poisson noise is added to the simulated data.

Figure 6 summarizes the results of our simulations by showing, for a range of projected subcluster separations, the S/N for a detect cell centered on the overall peak of the emission as a function of redshift.

For the merger scenario we find no evidence for a systematic underestimation of the source significance at any redshift as long as the projected separation of the two cluster components remains less than about 400 kpc. This is not surprising; at redshifts greater than 0.3 such small separations are simply not resolved by the IPC. For projected subcluster separations of more than 400 kpc, however, the source significance is systematically underestimated when measured around the position of the highest peak within the...
emission region. The effect is small \([\delta(S/N) < 0.2]\) but redshift dependent. The underestimation is most severe for X-ray luminous systems \((L_X > 5 \times 10^{44} \ h_{50}^{-2} \ \text{ergs s}^{-1}, 0.3-3.5 \text{ keV})\) at intermediate-to-high redshift, although it takes pronounced substructure on the scale of more than 700 kpc (in projection) to produce a noticeable effect at \(z \sim 0.8\).

For the offset core scenario we find the redshift and luminosity dependence to be reversed: now it is nearby clusters \((z < 0.3)\) of moderate luminosity \((L_X < 3 \times 10^{44} \ h_{50}^{-2} \ \text{ergs s}^{-1}, 0.3-3.5 \text{ keV})\) that are most strongly affected.

These trends are consistent with the mentioned observations of clusters at \(z \sim 0.8\); while Cl J0152.7−1357 is missed by the EMSS, MS 1137.5+6625 and MS 1054.4−0321 (the first apparently relaxed, the latter a case of substructure akin to our second simulated scenario; see § 7) are both detected. Taken together, our results thus indicate that, in the presence of different kinds of substructure, the EMSS peak-finding algorithm tends to underestimate the significance both of nearby clusters of low-to-moderate X-ray luminosity and of distant clusters of very high X-ray luminosity.

While Figure 6 suggests that the underestimation of the S/N within the detect cell is small (0.1−0.2), we note that the real effect will be magnified by photon noise (not included in our simulations) which will cause the peak position found by the EMSS ML algorithm to deviate from the true position. The resulting positional error is considerable: for the photon statistics of our simulated example we find a radius of 20° for the 90% confidence error circle of the ML peak position. In most cases measuring the source significance around this ML fit position will yield values that are lower than those in Figure 6. This is underlined by the very case of Cl J0152.7−1357, a distant, X-ray luminous cluster with substructure on the scale of 600 kpc. Its source position as determined by the EMSS peak-finding algorithm in the IPC hard band lies so far off the X-ray centroid that the source significance in the IPC broad band is underestimated by more than 1 \(\sigma\)—far more than what is implied by Figure 6.

6.2.2. Impact of the Detection Bias on the EMSS Cluster Sample

Although the above arguments suggest that the EMSS detection bias against unrelaxed clusters could be severe, a reanalysis of the Einstein IPC data or numerical simulations beyond the scope of this paper would be required to accurately quantify the effect. To be conservative, the values from our simple simulation may be taken at face value, in which case the smallness of the amplitude of the bias might cause one to believe that its impact on the EMSS cluster sample will be negligible. This is, however, not necessarily true. The EMSS catalog as used for the definition of the EMSS cluster sample (Gioia et al. 1990a) comprises 733

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**Table 3**

| \(r_{c,1}\) (kpc) | \(r_{c,2}\) (kpc) | \(L_1:L_2\) | \(\Delta\) Range (kpc) | \(L_{tot}\), Range \((10^{44} \ h_{50}^{-2} \ \text{ergs s}^{-1})\) |
|------------------|------------------|-------------|------------------------|--------------------------------|
| 250......        | 250              | 2 : 3       | 0.2−1.0                | 200−1000                        |
| 100......        | 350              | 1 : 4       | 0.2−1.0                | 100−400                          |

Note—Parameters of the \(\beta\) models used in the simulations described in § 6.2. All models assume \(\beta = \frac{2}{3}\) and are normalized such that the S/N is constant at 4, which corresponds to a total of 27 counts within an optimally placed EMSS detect cell. \(r_{c,1}, r_{c,2},\) and \(L_1 : L_2\) are the core radii and relative X-ray luminosities of the two components. Also listed are the ranges in redshift, projected metric separation \(\Delta,\) and total luminosity \(L_{tot}\) explored by our simulations. The quoted luminosities are computed in the 0.3−3.5 keV band assuming the IPC on-axis response matrix.

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Fig. 6.—S/N measured within an IPC detect cell centered on the highest peak of the simulated emission from unrelaxed clusters as a function of redshift. The top panel shows the results of simulations assuming a merger of two similarly compact clusters for separations ranging from 100 to 1000 kpc. The results in the bottom panel were obtained assuming a very extended cluster with a compact core that is offset by between 100 and 400 kpc. In all cases the true (maximal) significance within the detect cell is very extended cluster with a compact core that is offset by between 100 and 1000 kpc. In all cases the true (maximal) significance within the detect cell is
sources, 93 of which were identified as clusters of galaxies. From the distribution of source significances we estimate the number of sources with significances between 3.8 and 4 $\sigma$ to be about 60; five of these are expected to be clusters at redshifts greater than 0.2. Since the fraction of significantly unrelaxed clusters at these redshifts is almost certainly nonnegligible (see § 7) and considering the inherent uncertainties of our crude analysis, we are left with the conclusion that the number of distant and X-ray luminous but unrelaxed clusters missed by the EMSS is likely to be of the order of a few. While not immediately alarming, this estimate is still disconcertingly high given that the EMSS cluster sample contains only a handful of distant X-ray luminous clusters to begin with.

7. THE X-RAY MORPHOLOGY OF DISTANT CLUSTERS

In addition to the cosmological relevance of the sheer existence of a distant cluster as X-ray luminous as Cl J0152.7−1357, the complex optical and X-ray morphology of this cluster provides further important clues. As can be seen from Figure 1, Cl J0152.7−1357 consists of at least two pronounced subclusters which are (in projection) about 600 kpc apart and are likely to merge within a few Gyr (assuming a true spatial separation of 1 to a few Mpc and equal masses of a few $10^{14} M_\odot$ for the two main cluster components).

The fact that Cl J0152.7−1357 is still in the process of formation has several interesting implications. First, the
subclusters observed today are likely to have existed as separate clusters of $L_x \approx 4 \times 10^{44}$ ergs s$^{-1}$ (0.5–2.0 keV) at a redshift considerably greater than unity, and second, the X-ray luminosity of Cl J0152.7−1357 is bound to increase as the merger proceeds, possibly rendering Cl J0152.7−1357 more X-ray luminous than any cluster observed to date. Third, Cl J0152.7−1357 is the third X-ray-selected cluster (out of five) detected at $z \gtrsim 0.8$ that shows pronounced substructure and is distinctly non-virialized, in contrast to the morphologically much more diverse local cluster population.

The last point is illustrated by Figure 7, which shows adaptively smoothed X-ray flux contours of all three $z \sim 0.8$ clusters for which high-resolution X-ray images are currently available. Our HRI data reduction corrects for particle background as well as exposure time variations using software kindly provided by Steve Snowden. For each cluster we align and merge all available observations, which yields total exposure times as follows: MS 1137.5+6625 ($z = 0.782$), 98.0 ks; MS 1054.4−0321 ($z = 0.829$), 186.6 ks; and RX J1716.6+6708 ($z = 0.813$), 167.2 ks. The final images use a pixel size of $2.5 \times 2.5$ arcsec$^2$, thus slightly oversampling the HRI point-spread function. Using ASMOOTH (Ebeling et al. 2000), the HRI counts image is then adaptively smoothed with a Gaussian kernel the size of which is adjusted such that the local significance of the signal within the kernel exceeds 99%. The boxy thick contours in Figure 7 mark the regions within which the signal is high enough for this criterion to be met and within which all structure apparent in the contour plots is thus significant at greater than 99% confidence. The dashed boxes illustrate the effect of a placement of the EMSS detect cell on the highest peak in the emission region. According to Figure 7, the only relaxed cluster of the three is MS 1137.5+6625, while both MS 1054.4−0321 and RX J1716.6+6708 exhibit significantly nonspherical emission with off-center cores.

Although this high-redshift sample is still too small to allow more quantitative conclusions, the rarity of relaxed systems is intriguing and may indicate that we are beginning to actually observe the epoch of formation of the majority of massive clusters.

8. SUMMARY AND CAVEAT EMPTOR

The discovery of the X-ray luminous, unrelaxed galaxy cluster Cl J0152.7−1357 in the WARPS cluster survey has important implications for our understanding of the evolution of clusters as a function of X-ray luminosity and redshift.

Cl J0152.7−1357 was previously detected in a pointed observation with the Einstein IPC; however, because of an underestimation of its significance the source is missing from the EMSS catalog. Cl J0152.7−1357 would have been the most distant and most X-ray luminous cluster in the EMSS sample. Simulations of IPC observations of unviralized clusters show that the absence of Cl J0152.7−1357 from the EMSS cluster sample may reflect a general bias of the EMSS against unrelaxed, distant clusters. We cannot currently quantify accurately the amplitude of such a bias; however, conservative estimates suggest that of the order of a few X-ray luminous clusters may have been missed at $z > 0.3$.

We attempt to assess the frequency of significant substructure in distant X-ray luminous clusters by comparing the X-ray morphology of all such systems observed to date with the ROSAT HRI. Although the resulting sample is small, we find tentative evidence that highly unrelaxed systems such as Cl J0152.7−1357 may indeed be common at high redshift.

An important implication of our findings is that quantitative cosmological conclusions based on measurements of the abundance of X-ray luminous, distant clusters ought to be regarded with caution. Any comparison of cluster space densities with the predictions of structure formation models assumes that the clusters used satisfy the collapse criteria specified in those models (e.g., Press-Schechter). In the light of our morphological observations we add a cautionary note that it is possible that many of these distant systems do not yet meet these conditions. Clearly this would seriously complicate the measurement of cosmological quantities using cluster counts. However, it could also offer a new means to tackle these questions through detailed observation and a dynamical analysis of merger rates in statistically selected “protoclusters.”

As far as the representative nature of current cluster samples is concerned, the dynamical state of a cluster could complicate matters beyond the detection bias discussed in § 6.2. Numerical simulations by Ricker (1998) indicate that shock fronts created in the primary collision of two merging clusters can increase the total X-ray luminosity of the merging system by up to an order of magnitude compared to the combined X-ray luminosity of the progenitor clusters. While this effect is expected to be prominent only for less than half the sound crossing time (typically a few times $10^8$ yr), it may still, to some extent, counteract any detection bias against merging clusters (see § 6.2) by causing such systems to be preferentially detected in X-ray flux-limited surveys.

If cluster mergers are indeed common at high redshift and the net X-ray emission of these systems does not adequately distinguish between formed and forming systems, we may be forced to develop much more sophisticated models and data analysis strategies in order to draw secure conclusions about the physical mechanisms and cosmological implications of cluster evolution.

Deeper observations and more detailed analyses of a sizeable, representative sample of distant X-ray luminous clusters are required to conclusively address these issues.

9. CL J0152.7−1357: OUTLOOK

Observing time with Chandra’s ACIS-I imaging spectrometer is scheduled in Cycle 1 for a high-resolution X-ray study of Cl J0152.7−1357; the cluster is also a Guaranteed Time Observation target of XMM. In combination with ongoing observations at optical and infrared wavelengths from the ground these X-ray observations will allow in-depth studies of the internal dynamics and mass distribution of this system. A detailed optical study of the cluster galaxy population with the Keck-II telescope is underway and first results will be presented shortly. For now we only mention that our recent multislit spectroscopy observations yielded more than 20 accordant redshifts for this system.

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Viana, P. T. P., & Liddle, A. R. 1996, MNRAS, 281, 323
Vikhlinin, A., McNamara, B. R., Hornstrup, A., Quintana, H., & V располагается в городах Швеции, Хельсинки и Санкт-Петербург. Всего в проекте участвуют 12 учёных из разных стран. Благодаря использованию данных о космических объектах, полученных с помощью спутников, ученые смогли исследовать разные аспекты космической активности. Данные о космических объектах были получены с помощью спутников, расположенных в разных частях мира. Благодаря использованию данных о космических объектах, ученые смогли исследовать разные аспекты космической активности. Данные о космических объектах были получены с помощью спутников, расположенных в разных частях мира.