X-ray Clusters at High Redshift

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Abstract. As the largest gravitationally bound structures known, clusters provide clear constraints on the formation of structure and on the composition of the universe. Despite their extreme importance for cosmology the number of clusters at high redshift (z > 0.75) is rather small. There are only a few X-ray emitting examples reported and a handful of optically-selected ones. These clusters can provide stringent constraints on theories of large scale structure formation, if they are massive enough. I will review the status of these distant X-ray selected clusters. These objects are of special importance because their X-ray emission and presence of gravitational arcs imply that they are massive, comparable to low redshift examples, and their existence is problematic for some theories of structure formation.

1. Introduction

The very existence of a massive cluster at z > 0.5 is problematic for standard CDM theories of hierarchical structure formation (Evrard 1989; Peebles et al. 1989). While this problem has been recognized for some time, it has not been taken too seriously because of the lack of conclusive evidence of the existence of such massive systems at high redshift.

Naturally the statistics on the abundance of high z clusters are poor because the number of such clusters known at present is small. Furthermore, one might argue that many of these clusters may not be as massive as they appear due to inflation of the measured velocity dispersion from field galaxy contamination and projection effects (see among others Frenk et al. 1990). However, the number of distant clusters is steadily increasing due to the combined use of telescopes such as HST (Hubble Space Telescope) and Keck, as we have heard from many contributors at this meeting.

X-ray observations of distant (z > 0.7) optically selected clusters have shown that only a few clusters are detected (see among others Castander et al. 1994),

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and those few are relatively modest X-ray emitters \( L_x \sim 10^{44} \text{ erg s}^{-1} \), with \( L_x \) much lower than that of present day clusters. While this fact would seem to imply that extremely rich systems with large amounts of X-ray emitting gas do not exist at these high redshifts, I will show several examples that indicate that this is not the case. In Table 1, five examples of EMSS (Einstein Medium Sensitivity Survey; Gioia et al. 1990, Stocke et al. 1991) clusters with average \( z = 0.66 \), and \( z_{\text{max}} = 0.826 \) are listed. In addition to their high X-ray luminosity, there is other compelling evidence that these clusters are genuinely massive. Three of the \( z \sim 0.6-0.7 \) clusters contain large lensed arcs which allow a crude estimate of the projected mass in the cluster cores. For four of them weak lensing studies have been performed. The letter “s” in the third column of Table 1 indicates the presence of giant arcs in the cluster core, while the letter “w” indicates that weak lensing analyses have been performed. \( L_x \) is given in units of \( 10^{44} h_{50}^{-2} \text{ erg s}^{-1} \) in the 0.3–3.5 keV band, \( T_x \) is measured in the 2–10 keV band and \( N_{0.5} \) is the central richness of the cluster (defined in Bahcall 1981; notice that in the same units Coma has \( N_{0.5}=28 \)).

### Table 1. EMSS Clusters with \( z > 0.5 \)

| Name             | redshift | lensing | \( L_x \) (erg s\(^{-1}\)) | \( T_x \) (keV) | \( N_{0.5} \) | \( \sigma \) (km s\(^{-1}\)) |
|------------------|----------|---------|-----------------------------|-----------------|--------------|------------------|
| MS0015.9+1669    | 0.546\(^a\) | w       | 14.64\(^b\)                | 8.4\(^d\)       | 66±6\(^d\)   | 1324\(^c\)      |
| MS0451.6–0305    | 0.550\(^c\) | sw      | 19.98\(^b\)               | 10.4\(^f\)      | 47±5\(^d\)   | 1371\(^g\)      |
| MS1054.5–0321    | 0.826\(^b\) | w       | 9.28\(^b\)                 | 14.7\(^h\)      | 82±10\(^i\)  | 1360\(^h\)      |
| MS1137.5+6625    | 0.782\(^b\) | sw      | 7.56\(^b\)                 | 56±6\(^d\)      |              |                  |
| MS2053.7–0440    | 0.583\(^c\) | s       | 5.78\(^b\)                 |                 | 20±5\(^d\)   |                  |

\(^a\)Dressler & Gunn 1992  
\(^b\)Gioia & Luppino 1994  
\(^c\)Furuzawa et al. 1994  
\(^d\)Luppino & Gioia 1995  
\(^e\)Maccacaro et al. 1994  
\(^f\)Donahue 1996  
\(^g\)Carlberg et al. 1996  
\(^h\)Donahue et al. 1997  
\(^i\)Luppino & Kaiser 1997

#### 2. EMSS \( z > 0.5 \) clusters

Since its discovery MS0015.9+16 (alias CL0016+16, Koo 1981) has been the archetypal rich, X-ray luminous, distant cluster. It is part of the EMSS since it was “rediscovered” in an observation pointed at another target. The cluster is very rich and has a linear structure elongated in the NE-SW direction. Smail et al. (1994) reported detection of weak shear, which has been reconfirmed by the analysis performed by Luppino et al. (1996) using different deep images with a larger field of view and a different technique (Kaiser and Squires, 1993; Squires...
and Kaiser, 1996). Two hours of R band Keck data are in hand but the images have not been assembled yet (Clowe, private communication).

MS0451−03 with an $L_x$ of almost $2 \times 10^{45} \text{erg s}^{-1}$ is the most X-ray luminous cluster in the EMSS and among the brightest clusters known. ASCA data by Donahue (1996) show a hot cluster at 10.4 Kev with iron abundance of 15% solar and a total mass (within $1h^{-1}\text{Mpc}$) of $9.7^{+3.8}_{-2.2} \times 10^{14} \text{M}_\odot$. The shear signal detection, performed by Luppino et al. (1996) on a 7200s R band image taken with the UH 2.2m telescope is at $>5\sigma$. Two hours of R band Keck data are in hand also for this cluster but the analysis has not been performed yet.

MS1054−03 is the most distant cluster of the EMSS and among the most distant X-ray selected clusters known. The cluster has a filamentary morphology with the X-ray coming from the center and elongated in the same E–W direction as the optical galaxies (Donahue et al. 1997). MS1054−03 is extremely rich and quite hot at $14.7^{+4.6}_{-3.9}$ keV as obtained by ASCA (Donahue et al. 1997). A strong shear signal at 6$\sigma$ level is detected (Luppino & Kaiser, 1997). The total mass (within 1 Mpc) from X-rays and from weak lensing are consistent ($2.6 \times 10^{14} h^{-1}_5 \text{M}_\odot$ vs $3.0 \times 10^{14} h^{-1}_5 \text{M}_\odot$).

Deep imaging of MS1137+66 with Keck and with the UH 2.2m have been collected. From the reduced images a large arc has been discovered close to the cluster center (Clowe et al. 1997). Differently from MS1054–03 and MS0015.9 +16 this cluster is compact and concentrated with no filamentary structure. A weak lensing analysis, performed by Clowe et al. on a 8700 second R-band exposure of Keck, using the I band (7500 s) 2.2m data as a color selection to remove cluster galaxies, finds a nice centrally concentrated mass peak falling exactly on the brightest cluster galaxy. The mass from weak lensing comes out to be $2.9 \times 10^{14} h^{-1}_5 \text{M}_\odot$ at 500 $h^{-1}$ kpc (assuming the background galaxies lie at $z=2$).

Also for MS2053-04 two hours of R band Keck data are in hand but the images have not been assembled. A recent observation of this cluster has been performed with the Italian-Dutch BeppoSAX satellite by Scarabell et al. (in preparation). The data have not been fully reduced yet. A preliminary analysis shows this cluster to be much cooler than MS1054–03 or MS0451−03.

3. The ROSAT NEP Survey

The North Ecliptic Pole (NEP) region of the Rosat All-Sky Survey (RASS; Trümper 1991) has the largest exposure time (approaching 10 ks) of the all RASS. The NEP region covers a $9^\circ \times 9^\circ$ field, and contains a total of 465 X-ray sources detected at $>4\sigma$ in the 0.1–2.4 keV (Mullis et al. 1998). We are identifying all sources in the field. The principal derivative is a statistically complete sample of galaxy clusters appropriate for a better characterization of the X-ray luminosity function evolution. We have discovered a very distant cluster in the NEP at $z=0.81$. RXJ1716+66 (Henry et al. 1997) is among the most distant X-ray selected clusters together with MS1054–03 and the X-ray
clusters detected by Rosati (1997) in the RDCS (ROSAT Deep Cluster Survey) or Ebeling et al. (1997) in the WARPS (Wide Angle ROSAT Pointed Survey).

3.1. RXJ1716+66

As with MS1054−03, it is not likely that RXJ1716+66 is in virial equilibrium. The galaxies in RXJ1716+66 are in an inverted S-shaped filament running north-east to southwest (Fig. 1). Cluster members extend all along the S. The distance from the top to the bottom of the S is about 1.5 Mpc ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$). X-ray follow-up observations with ASCA (100 ks) and with the ROSAT HRI (171 ks) provide a temperature in 2−10 keV of $kT = 6.7^{+3.2}_{-1.8}$ (68% confidence) and a flux in 0.5−2.0 keV of $1.16^{+0.33}_{-0.33} \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$. It is intriguing that the morphology of RXJ1716+66 and MS1054−03 is filamentary with the X-rays coming from the center. We note this since the initial formation of protoclusters is often described as matter flowing along filaments (Bond et al. 1996) with the X-rays generated at the impact point of the two colliding streams of matter (Henry et al. 1997).

Fig. 1-A 1024×1024 subarray image of RXJ1716+66 extracted from the center of a 4500s exposure in the I-band taken by G. Luppino and M. Metzger with the UH 8K×8K CCD mosaic camera on the CFHT prime focus in Sept 1995. North is up and East to the left. This image spans 3′.6×3′.6 (0.9h$^{-1}$ Mpc at $z = 0.81$) at a scale of 0.′′21/pixel.
Both CFHT 8K×8K mosaic CCD deep images and Keck R-band (7500s) images were taken. The weak lensing analysis was performed on the R-band Keck image, using 2.2m I-band data (26,100s) for color terms (Clowe et al. 1997). The mass peak is just east of the BCG, and an arm of mass to the NE, neatly following the line of galaxies NE of the cluster core is detected. Doug Clowe' analysis gives a very strong signal of $4 \times 10^{14} h^{-1} M_\odot$ (background galaxies at $z=1.5$). The $M/L_V$ is equal to 210$h$. Both the optical lightmap and weak lensing massmap have two spatially distinct massive sub-clusters, as well as a long filamentary structure.

4. Conclusions

There is clear evidence from the existing data that large, dense mass concentrations existed at an early epoch. Another possible search strategy to find distant X-ray clusters is to look for clusters around powerful radio galaxies. High $z$ massive structures have been found around several 3C radio galaxies (i.e.: 3C184, at $z=0.99$, Delorme et al. 1997; 3C324, at $z=1.2$, Smail & Dickinson, 1995, just to quote a few). Cluster abundances has been cited as one of the strongest evidence against the standard CDM model as normalized to reproduce the microwave background anisotropies seen by COBE satellite. The number of high-$z$ massive clusters predicted by standard CDM, or other mixed Dark Matter models, is too low with respect to the number of clusters observed. In low-density universes there is less evolution and nearly all $10^{15} M_\odot$ clusters formed by $z=0.5$. In a high-density universe, instead, only 5% of the present day $10^{15} M_\odot$ clusters have formed by the same redshift. Thus massive clusters should be much rarer at epochs earlier than 0.5 if $\Omega=1$, contrary to the observations. Alternatives have been suggested with low $\Omega$ models (Viana & Liddle, 1996; Eke et al. 1996). The open CDM ($\Omega=0.3$) and $\Lambda$-dominated CDM models are preferred because they are compatible with the data. It may be possible to estimate $\Omega$ from forthcoming observations of intermediate-distant clusters (up to $z \sim 1$).

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