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THE X-RAY EVOLUTION OF CLUSTERS OF GALAXIES TO z=0.9

LAURENCE R. JONES[1], H. EBELING[2], C. SCHARF[3], E. PERLMAN[4], D. HORNER[5], B.W. FAIRLEY[1], S. ELLIS[1], G. WEGNER[6], M. MALKAN[7]
[1] *School of Physics & Astronomy, University of Birmingham, Birmingham, UK*
[2] *Institute for Astronomy, 2680 Woodlawn Dr, Honolulu, HI 96822, USA*
[3] *Space Telescope Science Institute, Baltimore, MD 21218, USA.*
[4] *Joint Ctr. for Astrophysics, Physics Dept, University of Maryland, Baltimore County, Baltimore, MD 21250, USA*
[5] *Lab for High Energy Astrophysics, Code 660, NASA/GSFC, Greenbelt, MD 20771, USA.*
[6] *Dept. of Physics & Astronomy, Dartmouth College, Hanover, NH 03755, USA.*
[7] *Dept. of Astronomy, UCLA, Los Angeles, CA 90024, USA.*

The evolution of the X-ray luminosity function of clusters of galaxies has been measured to z=0.9 using over 150 X-ray selected clusters discovered in the WARPS survey. We find no evidence for evolution of the luminosity function at any luminosity or redshift. The observations constrain the evolution of the space density of moderate luminosity clusters to be very small, and much less than predicted by most models of the growth of structure with Ω_m=1. All the current X-ray surveys agree on this result. Several notable luminous clusters at z>0.8 have been found, including one cluster which is more luminous (and is probably more massive) than the well known MS1054 cluster.

1 Introduction

The evolution of the space density of clusters of galaxies is a measurement sensitive to the physical and cosmological parameters of models of structure formation. We describe a deep X-ray survey of clusters of galaxies (the Wide Angle ROSAT Pointed Survey or WARPS), and use it to measure the evolution of the X-ray luminosity function (XLF) of clusters of galaxies (Scharf et al 1997, Jones et al 1998, Ebeling et al 2000a, Fairley et al 2000).

2 Survey method

Our goal was to compile a complete, and as unbiased as possible, X-ray selected sample of clusters and groups of galaxies from serendipitous detections in deep, high-latitude ROSAT PSPC pointings. The spectroscopic follow-up of the clusters is now 99% complete. The redshift range is 0.03<z<0.92 and half of the 157 clusters are at z>0.3.

A detailed review of the X-ray source detection algorithm used (Voronoi Tessellation and Percolation or VTP), the sample selection and flux correction techniques are given in Scharf et al (1997). The basic technique was to identify cluster candidates via their spatial extent in X-rays, and confirm and measure redshifts via optical imaging and spectroscopy. We estimate a core radius for each cluster individually in order to extrapolate the surface brightness and derive a total flux. At the maximum off-axis angle used (15 arcmin) the PSPC point-spread function degrades to ≈55 arcsec (FWHM, at 1 keV) and there is a possibility that some clusters at the edge of the PSPC fields (where most of the survey area is) are unresolved. To reduce this possible incompleteness, our optical follow-up observations are not limited to extended X-ray sources but also include likely point X-ray sources without obvious optical counterparts.

The flux limit of the complete sample is 6×10^{-14} erg cm^{-2} s^{-1} (0.5-2 keV) and the total solid angle 73 deg^2. Detailed simulations were performed to derive the survey sensitivity as a function of both source flux and source extent.

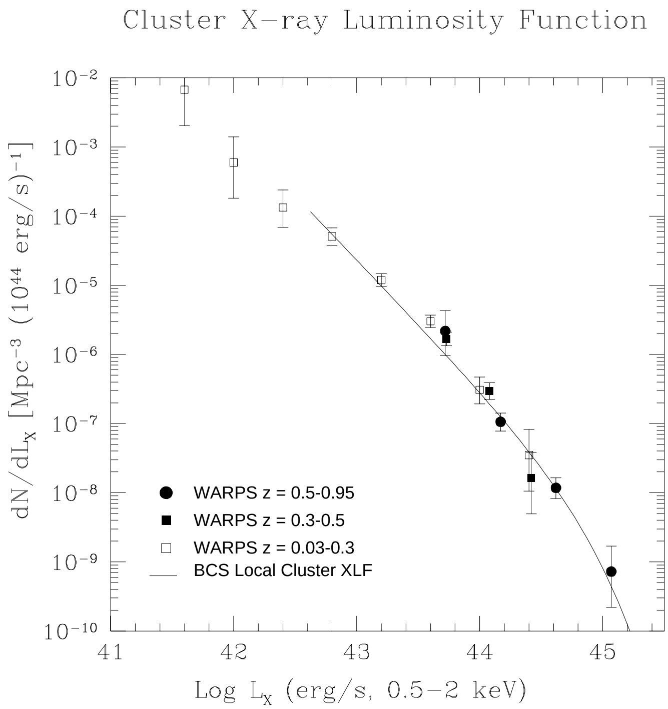

Figure 1: The X-ray luminosity function of clusters and groups of galaxies from the WARPS survey. No evolution of the space density of clusters is observed up to redshifts of z=0.95.

The optical imaging follow-up program is limited in wavelength to the I band, and does not extend into the near IR. At redshifts z>1.3 the I band samples the rest frame U band or bluer and K-corrections for elliptical galaxies become very large. We expect that this is the major reason why we have not detected clusters at z>1.

3 The X-ray luminosity function of clusters

The cluster XLF is shown in Fig 1. A value of q_0=0.5 has been assumed in calculating the luminosities and volumes but the results are qualitatively similar for q_0=0.1. The WARPS data points extend over more than 3 decades of luminosity. The low redshift points are in good agreement with the BCS XLF of Ebeling et al (1997), shown as a solid line, and extend the low redshift XLF to the low luminosities of groups.

At higher redshifts, there is no evidence for evolution of the XLF at any redshift up to z=0.95. The error bars are based on a Poissonian distribution of the number of clusters in each bin. The survey area for each cluster has been calculated using the cluster flux but making the simplifying assumption that all clusters have the same observed surface brightness profile (characterised as a constant angular core radius and β=2/3 index). Mean differences from the true survey areas are small (<10%).

As the XLFs at z=0.3-0.5 and z=0.5-0.95 are consistent with each other, in Figure 2 we have combined both redshift ranges to increase the statistical accuracy at the expense of a rather broad redshift bin. Nevertheless, the small error bars on the high redshift points (filled circles) indicate that any evolutionary factor >1.5 in the space density of moderate luminosity clusters ($L_X \approx 10^{44}$ erg s^{-1}) is ruled out.

The number of high luminosity ($L_X > 3\text{x}10^{44}$ erg s^{-1}) clusters in the survey at 0.7<z<1 is $5^{+3.4}_{-2.2}$. This is consistent with the no-evolution predictions of 6.9-11, depending on whether the

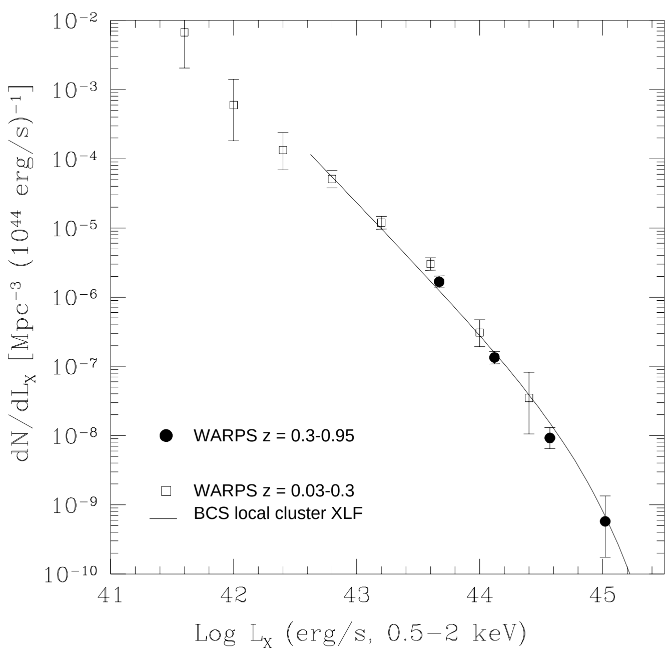

Figure 2: This figure contains the same data as figure 1, but combined into one redshift bin for z>0.3, in order to emphasize the small statistical errors.

Ebeling et al (1997) or de Grandi et al (1999) low redshift XLF is used. The latest results from the REFLEX survey (Bohringer, these proceedings), suggest that a third no-evolution prediction would be nearer the lower number of 6.9.

The XLFs shown here are based on an initial analysis; while some details will change (eg approximate correction for AGN contamination) in a final version, we do not expect there to be major changes.

4 Newly discovered luminous, high redshift clusters

We have discovered 5 clusters at z>0.8, all with spectroscopically confirmed redshifts. Four of them have X-ray luminosities similar to, or much larger than, the Coma cluster. One in particular, J1226+3332, (z=0.888) has a bolometric X-ray luminosity of $8\text{x}10^{45}$ h_{50}^{-2} erg s^{-1} (q_0=0.5; Ebeling et al 2000b). This luminosity is slightly higher than that of MS1054, the best known example of a high redshift massive cluster. Our preliminary velocity dispersion for J1226+3332, 1600 km s^{-1}, is also consistent with a high mass (or the presence of substructure along the line of sight). The existence of more than one cluster of high mass at these redshifts is unlikely to be consistent with $\Omega_m = 1$.

5 Discussion

5.1 Comparison with results of X-ray cluster surveys

Several recent deep X-ray clusters surveys are described in these proceedings and elsewhere. In the regime where these surveys have good statistical accuracy (ie. moderate X-ray luminosities $\sim 10^{44}$ erg s^{-1}) there is excellent agreement that *no evolution of the XLF is observed to z≈0.8.*

Five surveys agree on this point (EMSS, RDCS, SHARC, CfA, WARPS) and the only disagreement (the RIXOS survey of Castander et al 1995) can be understood in terms of the RIXOS source detection algorithm.

At the higher X-ray luminosities of the most massive clusters ($L_X > 5\mathrm{x}10^{44}$ erg s^{-1}), there is some disagreement between the results of different surveys as to the degree of evolution found at z>0.3 (if any). This may partly be due to the small numbers of high luminosity clusters in any one survey. The range of evolution found is not large: from none to negative evolution of a factor ≈3.

The WARPS and RDCS (Borgani et al, these proceedings) are both consistent with no evolution of the XLF up to z=1. WARPS is not sensitive to clusters at z>1 because our optical followup does not extend into the NIR.

5.2 Revisiting the EMSS survey

In an effort to understand the EMSS results of Gioia et al (1990) and Henry et al (1992), who found negative evolution at high luminosities but relatively low redshifts (z≈0.33), we have remeasured the X-ray luminosities of the 11 EMSS clusters at z>0.3 for which deep ROSAT PSPC data exists, extending the work started by Jones et al (1998). If the X-ray luminosities of EMSS z>0.3 clusters have been significantly underestimated by a factor of ≈2, then the EMSS XLF will move toward a no-evolution result.

We use large (3 Mpc radius, H_0=50) apertures, removing point sources and using ASCA temperatures where necessary. We find that the mean ratio $L_{X,PSPC}/L_{X,EMSS} \approx 1.6$ and that the ratio is correlated with the core radius measured from the PSPC images. This suggests that the assumption of a constant core radius of 250 kpc in the EMSS (a reasonable assumption, given the data available at the time) has led to an underestimate of the luminosities of clusters with larger core radii.

Henry (2000) has investigated EMSS cluster luminosities and notes that the original EMSS extrapolation of the surface brightness profile to give the total flux (a mean correction factor of ≈2.5) did not take into account the Einstein IPC psf. Including the effect of the psf revises the EMSS luminosities upwards by a factor of 1.37, explaining a major part of the discrepancy with the ROSAT luminosities. However, Henry (2000) also notes that luminosities measured with ASCA are only 17% higher than EMSS luminosities.

5.3 Future work

Future work will concentrate on the handful of clusters in the WARPS survey at z≈0.8, on measurements of the evolution of the cluster X-ray temperature function using Chandra and XMM, and studies of galaxy evolution in X-ray selected clusters. We are also studying the WARPS sample of 'fossil' groups of galaxies, to help understand the formation of luminous elliptical galaxies.

New wide area X-ray surveys, designed to detect the rare high luminosity, massive clusters in large numbers at high redshifts (z>0.5) are planned (see Lumb & Jones 2000 and Ebeling et al 2000c). It is the most massive clusters which have the greatest leverage to constrain cosmological parameters.

Acknowledgments

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