THE X-RAY LUMINOSITY FUNCTION OF NEARBY RICH AND POOR CLUSTERS OF GALAXIES: A COSMOLOGICAL PROBE

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ABSTRACT

In this letter, we present a new determination of the local (z \leq 0.09) X-ray luminosity function (XLF) using a large, statistical sample of 294 Abell clusters and the ROSAT All-Sky-Survey. Despite the optical selection of this catalog, we find excellent agreement with other recent determinations of the local XLF. Given our large sample size, we have reduced errors by \approx a factor of two for \( L_X(0.5-2.0 \text{ keV}) \geq 10^{44} h^{-2}_5 \text{ ergs/sec} \). We combine our data with previous work to produce the most tightly constrained local determination of the XLF over three orders of magnitude in \( L_X \) in order to explore possible constraints imposed by the shape of the XLF on cosmological models. A set of currently viable cosmologies is used to construct theoretical XLFs assuming \( \log L_x \propto \log M \) and a \( \alpha - \Omega_0 \) constraint (from Viana & Liddle 1996) based on the local X-ray temperature function. We fit these models to our observed XLF and verify that the simplest adiabatic, analytic scaling relation (e.g. Kaiser 1986) disagrees strongly with observations. If we assume that clusters can be described by the pre-heated, constant core entropy models of Evrard & Henry (1991) then the observed XLF is consistent only with \( 0.1 \leq \Omega_0 \leq 0.4 \) if the energy per unit mass in galaxies is roughly equal to the gas energy (i.e., if \( \beta \sim 1 \)).

Subject headings: cosmology: observations – galaxies: clusters: general – X-rays: general

1. INTRODUCTION AND BACKGROUND

Much of the work on the luminosity distributions of rich clusters has been motivated by the results of Henry et al. (1992) who found evidence for statistically significant negative evolution in the XLF (i.e. fewer high \( L_X \) clusters at higher z) at \( z \geq 0.3 \) for \( L_X(0.3-3.5 \text{ keV}) \geq 5 \times 10^{44} h^{-2}_5 \text{ ergs sec}^{-1} \) from 67 clusters in the Einstein Extended Medium-Sensitivity Survey (EMSS). Recently, Vikhlinin et al. (1998) have confirmed the EMSS result at \( z > 0.3 \) for \( L_X(0.5-2.0 \text{ keV}) \geq 3 \times 10^{44} h^{-2}_5 \text{ ergs/sec} \) from a 160 deg² survey from pointed ROSAT fields. They found a factor of 3-4 decrease in the number density of these high \( L_X \) clusters as compared to a zero-evolution model. Several other studies have claimed no evolution in the XLF out to redshifts as high as \( z = 0.8 \) (Burke et al. 1997; Jones et al. 1998; Rosati et al. 1998). However, none of these studies have sufficiently large search volumes to address evolution in the XLF at the highest X-ray luminosities and thus do not contradict the original EMSS result.

Of prime importance in any evolutionary study is an accurate determination of the local XLF as a baseline to compare with the distant cluster XLF. Until recently, even the local XLF was quite poorly constrained due to low cluster numbers. The largest local samples compiled to date are the X-ray Brightest Abell Clusters (XBACS) (Ebeling et al. 1993, 1996) and the Brightest Cluster Sample (BCS) of Ebeling et al. (1997, 1998). The BCS includes 199 X-ray selected clusters down to \( \approx 5 \times 10^{42} \text{ ergs sec}^{-1} \) in the 0.1 – 2.4keV band out to \( z \leq 0.3 \). Consistent with most previous claims, no evidence was found for evolution in the XLF at \( 0.1 < \Omega_0 < 0.4 \) if the energy per unit mass in galaxies is roughly equal to the gas energy (i.e., if \( \beta \sim 1 \)).

We have examined a statistically complete sample of 294 Abell rich clusters within \( z \leq 0.09 \) using the ROSAT All-Sky-Survey (RASS) over the energy band 0.5 – 2 keV as part of a multiwavelength study of nearby galaxy clusters. Unlike most other studies, our sample is purely optically-selected within the criteria for inclusion in Abell’s catalog. There is some overlap with both the BCS and XBACs sample, with the primary differences that we have used only Abell’s northern catalog (Abell 1958), and our X-ray flux-limit is approximately a factor of 8 lower than the BCS sample. Our sample is larger than the BCS while our volume is nearly 30 times smaller. Given our large sample size, we have reduced statistical errors in the local XLF for \( L_X \geq 10^{43} h^{-2}_5 \text{ ergs sec}^{-1} \) by up to a factor of 2 compared to previous work. Combined with the poor cluster XLF of Burns et al. (1996) (BL96), we examine the composite local XLF over more than 3 orders of magnitude in \( L_X \) in order to understand the cosmological constraints imposed by the tight power-law shape noted in BL96.

In section 2 we describe the sample, the derivation of the local XLF, and discuss the limitations imposed by our sample selection. In section 3 we compare our new XLF with previous work. In section 4 we explore the consequences of the shape of the local XLF with regard to Press-Schechter
analytic predictions of the mass-function and possible constraints on \( \Omega_0 \) and \( \Lambda \). We list our conclusions in section 5. We adopt \( H_0 = 50 \, h_{50} \, \text{km sec}^{-1} \) and \( q_0 = 0.5 \) when dealing with the observational data.

2. THE SAMPLE AND DERIVATION OF THE XLF

Our cluster sample is derived from Abell’s Northern catalog, and includes all Abell clusters in the range \( 0.016 \leq z \leq 0.09 \) with galactic absorption less than 0.1 magnitudes at R-band (\( \log N_H \approx 20.73 \)). See Voges et al. (1999) and Ledlow & Owen (1995) for more details on the sample selection. The total sample includes 294 Abell clusters. All clusters have measured redshifts and we include all richness classes in the sample. We calculate a survey area of \( 14,155 \text{ deg}^2 \) or \( 34\% \) of the sky. Within our observed volume we find the number density of clusters to be constant as a function of richness class and redshift suggesting that our sample is nearly complete and volume-limited within the limits of Abell’s selection criteria. These findings are consistent with those of Briel & Henry (1993) and Mazure et al. (1996) with regards to the completeness of Abell’s catalog over this redshift regime.

The X-ray luminosity function was derived from images produced by the RASS as described in Voges et al. (1999). X-ray luminosities were calculated within a metric aperture of \( 0.75 \, h_{50}^{-1} \, \text{Mpc} \) in diameter over the energy band \( 0.5-2 \, \text{keV} \) assuming a thermal spectrum with \( T \approx 0.75 \). X-ray luminosities were calculated within a metric aperture of \( 0.75 \, h_{50}^{-1} \, \text{Mpc} \) in diameter over the energy band \( 0.5-2 \, \text{keV} \) assuming a thermal spectrum with \( T \approx 0.75 \). Corrections for missing flux were made according to the prescription of Briel & Henry (1993) (using \( \beta = 2/3 \)) to produce a total \( L_X \) for each cluster over our ROSAT band. The primary effect of using a different \( \beta \) would be to shift the total luminosities to higher or lower values (a larger \( \beta \) results in a smaller correction, thus lower total \( L_X \)), while not significantly changing the shape or amplitude of the XLF within the error bars.

Voges et al. found a total detection rate of 83% for this sample of Abell clusters. For non-detections, we adopt the 3\( \sigma \) upper-limits given in their Table 1. Because of variations in exposure time (and slight variations in galactic absorption) across the sky with the RASS, each cluster has a different flux-limit, or maximum volume to which the cluster could have been detected. We follow the prescription of Avni & Bahcall (1980), and calculate the observed volume separately for each cluster. The volume is evaluated from \( z_{min} = 0.016 \) to the maximum redshift at which the cluster could have been detected with a 3\( \sigma \) confidence. For clusters with only upper-limits to \( L_X \) we set \( z_{max} \) equal to the redshift of the cluster. The XLF is then found by calculating \( \frac{dn(L)}{dL} \) as the sum over all clusters divided by the maximum search volumes of each cluster. Each binned data point is then found by dividing the above sum by the binwidth (\( \Delta L_X \)). For the entire sample, we find \( \langle V/V_{max} \rangle = 0.56 \pm 0.02 \). Error bars on the data points were calculated assuming Poisson statistics following the prescription of Rosati et al. (1998).

3. THE X-RAY LUMINOSITY FUNCTION

In Figure 1 we show the differential XLF for our low-redshift cluster sample. Also on this plot are the measurements of BLL96 derived from 49 poor clusters and the BCS sample of Ebeling et al. (1998). The steady decline in volume-density observed in our rich cluster sample for \( L_X < 10^{43} h_{50}^{-2} \, \text{ergs/sec} \) can be understood from the limitations of Abell’s optical selection criteria. Because \( L_X \) varies considerably for a given optical richness (Voges et al. 1999), there are a significant number of optically poor clusters with \( L_X \) in the range of Richness Class 0 clusters which are not in our sample. Thus, our sample is truly volume-limited only for clusters above this cutoff in \( L_X \). Note, however, that for \( L_X > 10^{43} \, \text{ergs/sec} \), our Abell cluster sample and the BCS sample are in excellent agreement. The BCS also extends to higher \( L_X \) because of the larger search volume (\( z \leq 0.3 \)). Our XLF shown in Figure 1 is also consistent with that of Edge et al. (1990) and Briel & Henry (1993).

The local, differential XLF is remarkably well represented by a power-law over more than three orders of magnitude in \( L_X \). The high luminosity break in the XLF occurs at \( > 10^{45} h_{50}^{-2} \, \text{ergs/sec} \), and can be seen when we include the highest luminosity point from the BCS sample. Using the combined XLF of BLL96 and our new determination of the local rich-cluster XLF (for \( L_X > 10^{43} h_{50}^{-2} \, \text{ergs/sec} \)), we find a power-law fit of the form \( \phi(L) = KL_{44}^{\alpha} \) where \( L_{44} \) is the X-ray luminosity in units of \( 10^{44} \, \text{ergs sec}^{-1} \) and \( K \) is in units of \( 10^{-7} \, \text{Mpc}^{-3} \, L_{44}^{-1} \). We find best-fit values of \( \alpha = 1.83 \pm 0.04 \) and \( K = 2.35 \pm 0.24 \). For completeness, we also fit a Schechter function after including the highest-\( L_X \) point from the BCS. For a fit of the form: \( \frac{dN}{dL} = A \exp(-L/L_X^*) \, L_X^{-\alpha} \), we find \( A = (2.93 \pm 0.14) \times 10^{-7} \, (\text{Mpc}^{-3} \, L_{44}^{-1}) \), \( L_X(0.5-2.04 \, \text{keV}) = 5.49 \pm 0.39 \times 10^{44} \, \text{ergs/sec} \), and \( \alpha = 1.77 \pm 0.01 \). These values are consistent within the errors to the BCS, the RDCS XLF (Rosati et al. 1998) out to \( z = 0.6 \), and the Southern SHARC survey (Burke et al. 1997) for \( 0.3 < z < 0.7 \). Note that these results do not conflict with the claimed negative evolution in the XLF observed by Henry et al. (1992), and most recently by Vikhlinin et al. (1998) at the highest luminosities.

As noted by BLL96, the remarkable power-law shape over such a large range in \( L_X \) suggests a continuity in that the bulk X-ray properties of poor clusters must not be fundamentally different from richer systems. We explore the
consequences of this result in the next section.

4. DERIVATION OF THE THEORETICAL XLF

In order to assess the constraints our local XLF imposes on cosmological models, we compare it with various analytic predictions. We proceed by using the Press-Schechter (PS) formalism (e.g., Press & Schechter 1974; Bond et al. 1991) to construct theoretical mass functions and then convert these to XLFs assuming a form for the X-ray mass-to-light ratio (c.f., Evrard & Henry 1991; hereafter EH91).

We begin with the set of cosmological models whose parameters are listed in Table 1. These models form a representative sample of current views as they include open and flat universes spanning a range in $\Omega_o$. For each model, the rms density fluctuation on $8 h^{-1}$Mpc scales ($\sigma_8$) was determined from the $\sigma_8 - \Omega_o$ relation of Viana & Liddle (1996) which, in turn, was fixed by the local number density of 7 keV clusters. The Hubble constant was chosen to give an age for the Universe of roughly 12.5 Gyrs (consistent with globular cluster age determinations; e.g., Chaboyer et al. 1998). For each model we list the relative contributions of matter ($\Omega_m$), baryonic matter ($\Omega_b$), and the cosmological constant ($\Omega_{\Lambda}$) to the overall energy density. Power spectra for all the models were generated using the code described in Klypin & Holtzman (1997) and then PS mass functions (with $\delta_c = 1.3$) were computed at $z = 0$.

Our PS mass functions can be converted to XLFs by assuming a form for the mass-luminosity relation and correcting to our bandpass. We assume the bolometric X-ray luminosity is related to cluster mass as $L_{bol} = c M^p$ and will later fit for the parameters $c$ and $p$. There exist at least two theoretical predictions for the value of the exponent $p$. The self-similar model of Kaiser (1986), derived assuming a power-law initial perturbation spectrum and purely adiabatic gas physics, predicts $p = 4/3$ but it is well known that this fails to give the correct shape for the XLF (e.g., EH91; see also below). However, preheating of the ICM at an early epoch (possibly by galaxy formation) results in a different scaling relation and also resolves several discrepancies between theoretical and observational results concerning evolution in the XLF (e.g., Evrard 1990, Navarro, Frenk & White 1995). For the case of a constant entropy core, EH91 derived a scaling which implies $p = (10 \beta - 3)/3\beta$ where $\beta = \mu m_p a^2/kT$ is the usual ratio of dark matter to gas ‘temperatures’.

We correct our bolometric luminosities to the 0.5-2 keV bandpass by calculating temperatures and applying a correction appropriate for a plasma with a metallicity of $Z=0.3Z_\odot$. Specifically, the temperature corresponding to a given mass can be calculated from the analytic $M-T$ relation derived from the virial theorem (e.g., Bryan & Norman 1998): $kT = L_{bol}/c \left(\frac{M}{10^{14} M_\odot}\right)^{2/3} \left(\frac{\Delta_v}{L}\right)^{1/3} \left(\frac{\Omega_{\Lambda}}{\Omega_0}\right)^{2/3} \text{keV}$ where $\Delta_v$ is the current density contrast within the cluster virial radius. The luminosity in our bandpass is then calculated by applying the usual bremsstrahlung correction factor as well as a multiplicative factor to account for the presence of metals (Bryan & Norman 1998; eqn. 21).

Using the relation for $L_{bol}$ and the bandpass correction, we converted our PS mass functions to differential luminosity functions and made $\chi^2$-squared fits to a subset of the observational data. The observational points used in the fits are all four poor cluster points (BLL96), the five highest luminosity Abell cluster points and the highest luminosity BCS point from Figure 1. We first set $\beta = 1$ in the $M - T$ relation and fit for $c$ and $p$. The fitted value for $p$ is included in Table 1 and examples of two of the fits are shown in Figure 2. The dashed curve in Figure 2a is the best fit when the exponent is kept fixed at the analytic prediction $p = 4/3$. Clearly, the shape of the XLF derived using this prediction is in gross disagreement with the observed function. Figure 2b also shows the importance of the low and/or high-luminosity data points. If only our five Abell cluster data points are used (dotted line), the fitted value of $p$ increases by at least 0.2 in all cases (from $p = 3.18$ to $p = 3.88$ in this case). We get virtually identical results if we redo our fits without the BCS point whereas dropping the poor cluster points results in slightly greater discrepancies.

5. CONCLUSIONS

Starting from an optically-selected, statistical sample of Abell clusters, we have made a new determination of the local XLF to compare to previous work and more distant cluster samples. Our cluster sample is larger than all previous studies, and is contained within a smaller volume. For this reason, we have reduced statistical uncertainties in the local XLF by nearly a factor of two for a limited range in $L_X$ ($L_X > 10^{43} h_{50}^{-2}$ ergs/sec). It is only for $L_X < 10^{43}$ ergs/sec that incompleteness due to the opti-
global selection of our sample is apparent. The observed incompleteness is not a failing in Abell’s catalog, but rather results from the contribution of poor clusters and groups below Abell’s richness limit.

Combined with the poor-cluster XLF of BLL96, we have examined the local XLF over nearly three orders of magnitude in $L_X$. We find that the local XLF is remarkably well represented by a power-law over nearly this entire range in $L_X$. This is significant evidence that hierarchical formation results in similar cluster properties over a large range in $L_X$ and mass. Including the brightest $L_X$ clusters from the BCS sample which fall above the break in the XLF at $L_X > 10^{45.5} \text{ergs/sec}$, we also performed a Schechter-function fit which is in good agreement with other recent surveys to much higher redshift ($z < 0.7$), confirming a lack of significant evolution at these luminosities.

We have used our new local XLF to derive a constraint on $\Omega_0$. This would appear to contradict a common claim that the $\sigma_8 - \Omega_0$ degeneracy can be broken only by including the evolution with redshift (e.g. Bahcall & Fan 1998). In fact, PS mass functions for combinations of $\sigma_8$ and $\Omega_0$ that satisfy a $\sigma_8 - \Omega_0$ constraint differ in shape. Borgani et al. (1999) have recently used the shape of the local XLF in order to constrain $\sigma_8 - \Omega_0$ and the shape of the L-T relation. Including clusters at higher redshift, they concluded that $\Omega_0 = 0.4^{+0.3}_{-0.2}$ for open models, and $\Omega_0 \leq 0.6$ for flat models assuming no evolution in the L-T relation; both of which are consistent with our results. In this work, we have used the shape of the local XLF, the local number density of 7 keV clusters, and the PS formalism in order to constrain the cluster M-L relation; $L_X \propto M^p$. There is a clear trend for $p$ to increase with $\Omega_0$ (see also Mathiesen & Evrard 1998). None of the theoretical models are consistent with the analytic prediction $p = 4/3$ from Kaiser (1986). If we adopt the constant core-entropy model of EH91, and the additional constraint that $\beta = 1$, the shape of the local XLF suggests that $0.1 \leq \Omega_0 \leq 0.4$, with no constraint on $\Lambda$.

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**Table 1**

**Cosmological Model Parameters**

| Model  | Age$^a$ | $H^b$ | $\Omega_0$ | $\Omega_M$ | $\Omega_X$ | $\sigma_8$ | $p$ | $\beta$ |
|--------|---------|-------|------------|------------|------------|-------------|---|--------|
| OCDM1  | 12.5    | 70    | 0.1        | 0.036      | 0.1        | 1.467       | 1.76$^{+0.14}_{-0.13}$ | 0.66$^{+0.07}_{-0.06}$ |
| OCDM2  | 12.7    | 65    | 0.2        | 0.040      | 0.1        | 1.162       | 2.20$^{+0.14}_{-0.13}$ | 0.88$^{+0.07}_{-0.06}$ |
| OCDM3  | 12.2    | 65    | 0.3        | 0.040      | 0.2        | 1.044       | 2.50$^{+0.14}_{-0.13}$ | 1.14$^{+0.07}_{-0.06}$ |
| OCDM4  | 12.7    | 60    | 0.4        | 0.035      | 0.4        | 0.897       | 2.69$^{+0.14}_{-0.13}$ | 1.47$^{+0.07}_{-0.06}$ |
| OCDM5  | 12.3    | 60    | 0.5        | 0.035      | 0.6        | 0.817       | 2.86$^{+0.14}_{-0.13}$ | 1.90$^{+0.07}_{-0.06}$ |
| OCDM6  | 11.6    | 60    | 0.7        | 0.035      | 0.8        | 0.701       | 3.22$^{+0.14}_{-0.13}$ | 4.0$^{+0.07}_{-0.06}$ |
| ACDM1  | 13.1    | 80    | 0.2        | 0.029      | 0.2        | 1.161       | 2.14$^{+0.14}_{-0.13}$ | 0.84$^{+0.07}_{-0.06}$ |
| ACDM2  | 11.8    | 80    | 0.3        | 0.020      | 0.4        | 1.161       | 2.14$^{+0.14}_{-0.13}$ | 1.17$^{+0.07}_{-0.06}$ |
| ACDM3  | 12.4    | 70    | 0.4        | 0.026      | 0.6        | 0.901       | 2.77$^{+0.14}_{-0.13}$ | 1.62$^{+0.07}_{-0.06}$ |
| ACDM4  | 12.5    | 65    | 0.5        | 0.030      | 0.5        | 0.864       | 2.86$^{+0.14}_{-0.13}$ | 1.90$^{+0.07}_{-0.06}$ |
| ACDM5  | 12.2    | 60    | 0.7        | 0.035      | 0.3        | 0.719       | 3.18$^{+0.14}_{-0.13}$ | 3.5$^{+0.07}_{-0.06}$ |

$^a$ current age of universe in Gyrs
$^b$ Hubble constant in units of km/s/Mpc

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