The Luminosity Function Evolution of Soft X–ray selected AGN in the RIXOS survey

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\textbf{ABSTRACT}

A sample of 198 soft X–ray selected active galactic nuclei (AGN) from the \textit{ROSAT} International X–ray Optical Survey (RIXOS), is used to investigate the X–ray luminosity function and its evolution. RIXOS, with a flux limit of $3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ (0.5 to 2.0 keV), samples a broad range in redshift over 20 deg$^2$ of sky, and is almost completely identified; it is used in combination with the \textit{Einstein} Extended Medium Sensitivity Survey (EMSS), to give a total sample of over 600 AGN. We find the evolution of AGN with redshift to be consistent with pure luminosity evolution (PLE) models in which the rate of evolution slows markedly or stops at high redshifts ($z > 1.8$). We find that this result is not affected by the inclusion, or exclusion, of narrow emission line galaxies at low redshift in the RIXOS and EMSS samples, and is insensitive to uncertainties in the conversion between flux values measured with \textit{ROSAT} and \textit{Einstein}. We confirm, using a model independent $< V_c/V_a >$ test, that our survey is consistent with no evolution at high redshifts.

\textbf{Key words:} surveys – galaxies: active – X–rays: galaxies – cosmology: observations.

\section{1 INTRODUCTION}

X–ray properties are becoming an increasingly important tool for selecting samples of AGN, and sample sizes are approaching that of ultraviolet excess (UVX) selected optical samples.

The largest currently available sample of serendipitous X–ray selected AGN comes from the \textit{Einstein} Extended Medium Sensitivity Survey (EMSS, see Stocke et al. 1991), with a sky coverage of 778 deg$^2$. However, the EMSS is dominated by low redshift objects (median $z \sim 0.2$) due to its high limiting flux (typically $> 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the energy range 0.5 to 2.0 keV). Deeper \textit{Einstein} surveys (Primini et al. 1991) identified only 11 AGN. With the arrival of \textit{ROSAT} the possibilities for deeper surveys have been realised: the Cambridge Cambridge \textit{ROSAT} Serendipity Survey covers about 4 deg$^2$ and has a flux limit of $2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ from 0.5 to 2.0 keV (see Boyle et al. 1995); the survey of Boyle et al. (1994) contains 107 broad line AGN and probes to flux levels lower than $4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ (0.5 to 2.0 keV), but is only 70\% complete at this flux limit and covers an area of less than 1.5 deg$^2$ in total. This survey is almost devoid of low redshift objects, with only 3 AGN of $z < 0.4$, and median $z = 1.5$. Even deeper surveys, with even smaller sky coverage, (Hasinger et al. 1993; Branduardi–Raymont et al. 1994) are still in the process of optical identification.

The \textit{ROSAT} International X–ray Optical Survey (hereafter RIXOS, see Mason et al. 1995) occupies a position between the EMSS and the deeper \textit{ROSAT} surveys, with a sky coverage of over 20 deg$^2$ and a limiting flux of $3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ (0.5 to 2.0 keV). It is constructed from 81 long ($> 8000$ seconds) \textit{ROSAT} pointings made with the Position Sensitive Proportional Counter (PSPC) at the focus of the X–ray telescope. The RIXOS AGN sample consists of 198 objects, the largest \textit{ROSAT} selected AGN sample to date, and is particularly useful for investigating evolution models because of its broad sampling of redshifts.
In this paper we present the results of an analysis of the differential X-ray luminosity function (XLF) and its evolution with redshift, using the RIXOS sample. In section 2 we describe briefly the RIXOS survey and present details of the RIXOS AGN sample, while in section 3 we discuss the log $N$ – log $S$ of RIXOS AGN compared to that of the EMSS AGN. In section 4 the methods used in this analysis are explained and in section 5 we present our results, which are discussed in section 6. Our conclusions are presented in section 7.

Throughout this paper a Friedmann model universe has been assumed, and a value of 50 km s$^{-1}$ Mpc$^{-1}$ has been adopted for the Hubble constant $H_0$; two different values for the deceleration parameter, $q_0 = 0$ and $q_0 = 0.5$ have been used.

2.1 Observations and Data Reduction

The X-ray sources in RIXOS were found in a total of 81 ROSAT PSPC pointings. The target of each observation and a small region around it have been excluded from the analysis so that RIXOS consists entirely of serendipitously discovered sources. Sources more than 17 arcminutes offaxis have also been excluded due to their larger positional uncertainty and possible masking by the detector window support structure. Furthermore, only sources detected in the harder ROSAT energy band 0.4 to 2.4 keV are included; the poorer point spread function, interstellar absorption, diffuse Galactic X-ray emission, and the increased contribution of Galactic stars complicate the detection of extragalactic sources in the 0.1 to 0.4 keV band. Using finding charts from the automatic plate measuring (APM) facility at the Royal Greenwich Observatory, Cambridge, optical spectra were taken for all optical counterparts within the one- sigma error circle of each X-ray source. If no likely counterpart was found, the optical counterparts within the one- sigma error circle of each X-ray source position were examined. If no optical counterpart was identified, the X-ray sources within the one- sigma error circle were investigated. The APM finding charts were not sufficient (for example if no optical counterparts appeared near the X-ray source position) CCD images were obtained using the Nordic Optical Telescope (NOT), or the Isaac Newton Group of telescopes (ING) on La Palma. Full details of the optical imaging and spectroscopic observations and data reduction are given in Mason et al. (1995).

In this analysis, the term AGN is used to refer to approximately the same range of objects as in Maccacaro et al. (1991), that is objects with at least one broad (>1000 km/s) emission line and/or [OII]5007 > [OII]3727. Hence the RIXOS AGN sample does include some narrow line objects. These criteria have been deliberately chosen to avoid any significant difference between the RIXOS and EMSS optical selection, allowing the two samples to be meaningfully compared and combined. The effect of excluding narrow line objects is discussed in section 6.

Table 1. RIXOS cumulative sky coverage corrected for incompleteness

| Flux Limit (erg s$^{-1}$ cm$^{-2}$) | Corrected Area (deg$^2$) | Optically Identified Fraction | Number of Fields |
|-------------------------------------|--------------------------|------------------------------|-----------------|
| 3.0 × 10$^{-14}$                   | 14.16                    | 93%                          | 62              |
| 3.5 × 10$^{-14}$                   | 14.36                    | 95%                          | 62              |
| 5.0 × 10$^{-14}$                   | 14.73                    | 97%                          | 62              |
| 6.0 × 10$^{-14}$                   | 15.09                    | 99%                          | 62              |
| 8.4 × 10$^{-14}$                   | 20.04                    | 99%                          | 81              |

2.2 Construction of the AGN sample used in this analysis

A limiting X-ray flux of 3 × 10$^{-14}$ erg s$^{-1}$ cm$^{-2}$ (0.5 to 2.0 keV) was chosen for RIXOS, well above the detection threshold for all the ROSAT fields used. Owing to the constraints of optical telescope scheduling some X-ray sources remain unobserved and/or unidentified. In the interests of keeping incompleteness and optical selection effects to a minimum, the entire RIXOS survey has not been used. In 62 of the 81 RIXOS fields, all objects have been identified or observed spectroscopically to the intended flux limit of 3.0 × 10$^{-14}$ erg s$^{-1}$ cm$^{-2}$ (0.5 to 2.0 keV), while in each of the other 19 fields some, but not all, of the X-ray sources have been observed to this limit; these 19 fields are, however, fully observed to a flux of 8.4 × 10$^{-14}$ erg s$^{-1}$ cm$^{-2}$ (0.5 to 2.0 keV) and are included in the RIXOS AGN sample with this flux limit. Overall spectroscopic completeness of the fields used in the RIXOS AGN sample is 93%; the remaining 7% of sources which are unidentified are those for which the optical counterpart(s) were too faint for us to obtain reliable optical spectra. We have made the assumption that the fraction of unidentified sources which are AGN is the same as that for the identified sources. Accordingly, the sky area used for this analysis has been corrected, in a similar fashion to that of Boyle et al. (1994), by multiplying the area by the fraction of sources identified; as the unidentified fraction is small, this has only a small effect on our results. Since optical completeness is a function of flux limit we have calculated the effective sky area at 3.0 × 10$^{-14}$ erg s$^{-1}$ cm$^{-2}$, 8.4 × 10$^{-14}$ erg s$^{-1}$ cm$^{-2}$, and three intermediate fluxes corresponding to significant changes in spectroscopic completeness. Again, the high level of completeness in RIXOS makes this a small correction, which has only a small effect on our results. The number of ROSAT fields, corrected sky coverages and identified fractions at their respective limiting fluxes are listed in Table 1.

The redshift distribution, $N(z)$, of the RIXOS AGN sample is shown in Fig. 1. The sample has a significantly higher median redshift, 0.6, than the EMSS (0.2).

To obtain the largest possible working sample of AGN, the RIXOS and EMSS surveys have been combined coherently (Avni & Baccall 1980) to give a total of over 600 AGN. This combined sample will be referred to as ‘RIXOS + EMSS’ hereafter. To correct the EMSS sample for incompleteness, the EMSS ‘expected’ AGN (see Maccacaro et al. 1991) have been included in the EMSS and EMSS + RIXOS samples. Throughout this analysis a power law X-ray spectrum has been assumed, $f_v \propto \nu^{-\alpha x}$. 
Figure 1. Redshift Distribution, $N(z)$, of RIXOS. The solid histogram is the actual distribution while the dashed and dotted lines are the $N(z)$ relations predicted by the power law with redshift cutoff and polynomial models respectively, for $q_0 = 0$.

Figure 2. X-ray Luminosity and redshift of RIXOS AGN (closed squares) and EMSS AGN (open triangles). Luminosities have been calculated using $q_0 = 0$.

Figure 3. Integral log $N$ – log $S$ of RIXOS AGN (closed squares) and EMSS AGN (open triangles).

For comparison of the results presented in this paper with those of Boyle et al. (1994) and Maccacaro et al. (1991), the analysis has been performed using $\alpha_X = 1$. The first results from X-ray colour analysis (see Mittaz et al. 1995) indicate that this is quite representative of the RIXOS AGN, which have a median $\alpha_X \sim 1.01$. The scatter of $\alpha_X$ around the value 1.0 appears to be larger in the RIXOS sample than was found by Macaccaro et al. (1988) for EMSS AGN, although the hardening of source spectra with redshift (see Francis 1993) does not appear to be significant in the RIXOS sample and has not been included in this analysis. The X-ray luminosity - redshift ($L_X$, $z$) distribution for the RIXOS and EMSS AGN are compared in Fig. 2. As expected from a deeper survey, the RIXOS AGN typically have lower luminosity and/or higher redshift than the EMSS AGN.

3 LOG $N$ – LOG $S$

The survey of Boyle et al. (1994) contains a larger number of AGN than would be predicted by extrapolating the EMSS log $N$ – log $S$ to lower fluxes; these authors suggested that this may be partly due to an error in their conversion from ROSAT to Einstein fluxes. In practice there are a number of factors which might affect the relative source counts and/or fluxes of the two samples, including differences in the source detection and parameterisation algorithms, uncertainties in the detector response matrices used to transform count rates to fluxes, uncertainties
in the spectral form used to convert from fluxes in the Einstein 0.3 to 3.5 keV band to the ROSAT 0.5 to 2.0 keV band and the effects of incompleteness or other biases.

To assess these effects Figure 3 compares the integral \( \log N - \log S \) for the RIXOS and EMMSS AGN. This plot is derived using a conversion factor (CF) of 1.8 between the fluxes in the two bands which is appropriate for a powerlaw spectrum of \( \alpha_x = 1 \) if we use the standard published response matrices for ROSAT and Einstein. It is clear that RIXOS has a larger number of sources than the EMMSS by about 30% at almost all fluxes when using this conversion. Although RIXOS samples a larger area than EMMSS by about 30% at almost all fluxes when using this conversion, there is significant overlap in the fluxes of objects found in the two samples, and there is thus no physical reason why the log \( N - \log S \) relations of the two surveys should be different.

Further investigation of the reasons for this discrepancy is beyond the scope of this paper. Instead we adopt an approach whereby we parameterise the discrepancy empirically, and investigate to what extent the uncertainty in this number affects the results on AGN evolution when we combine the RIXOS and EMMSS samples. The device we use for this empirical parameterisation is to find the CF for which the two log \( N - \log S \) relations are consistent. At the flux limits of the EMMSS and RIXOS the \( N(S) \) relation is well fit by a power law. Using maximum likelihood, the two samples have been fitted simultaneously with a single power law slope but different normalisations.

\[
\frac{dN}{dS} = k_E S^{-\gamma} \quad \text{EMSS objects, } S(0.3 - 3.5\text{keV}) \\
\frac{dN}{dS} = k_R S^{-\gamma} \quad \text{RIXOS objects, } S(0.5 - 2.0\text{keV})
\]

There are two free parameters in this fit, the power law slope \( \gamma \) and the difference between the two normalisations \( (k_E/k_R) \); the actual normalisations are found by requiring that the number of objects predicted by the log \( N - \log S \) for the sky coverage of RIXOS plus the sky coverage of the EMMSS is equal to the total in RIXOS plus the total in the EMMSS. The normalisation difference should be related simply to the empirical CF from ROSAT to Einstein fluxes by

\[
\text{CF} = (k_E/k_R)^{1/(\gamma-1)}
\]

We assumed upper flux limits of 2 \( \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \) (0.3 to 3.5 keV) and 10 \( \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \) (0.5 to 2.0 keV) for the EMMSS and RIXOS respectively, to reflect the selection against very bright sources in these surveys. This has only a small effect on the results; changing the upper flux limits to any reasonable value (or removing them) changes the best fit by only a fraction of the 1 \( \sigma \) statistical errors quoted below. The best fit slope \( \gamma \) is found to be 2.56, consistent with the slopes found when the two samples are fit independently, 2.61 \( \pm 0.06 \) for the EMMSS and 2.45 \( \pm 0.11 \) for RIXOS, where errors are 1 \( \sigma \). Since the slope of the EMMSS log \( N - \log S \) curve is actually steeper than (although consistent with) that of RIXOS, there is no evidence from this comparison to support previous claims about incompleteness in the EMMSS (e.g. Franceschini et al. 1994) in which incompleteness is thought to be a problem at low fluxes. The best fit CF is found to be 1.47 \( \pm 0.11 \); again errors are 1 \( \sigma \). The standard conversion factor of 1.8 is thus significantly different (rejected at \( >99.0\% \)) from that found by matching the log \( N - \log S \) curves. There is, however, no evidence from the RIXOS and EMMSS log \( N - \log S \) that the CF should be as small as 1.0, a possibility considered in Boyle et al. (1994).

To assess the impact of the different conversion factors on AGN evolutionary models, values of 1.47 and 1.8 have both been used in the subsequent analysis and the results compared. Note that all fluxes and luminosities quoted in this paper are 0.5 to 2.0 keV, i.e. the Einstein fluxes have been converted to the ROSAT flux band.

4 THE LUMINOSITY FUNCTION

The techniques that we have applied to the data are discussed in this section, while the results of the analysis are described in section 5.

A flux limited survey samples different luminosity ranges at different redshifts. The AGN population as a function of luminosity and redshift is represented by the XLF, \( \phi(L, z) \), which is defined as the number of objects detected per unit comoving volume per unit luminosity interval, i.e.

\[
\phi(L, z) = \frac{d^2N}{dVdL}(L, z)
\]

Evolution in the space density or luminosity of AGN with redshift is seen as a change in the XLF.

The two simplest forms for evolution are pure density and pure luminosity evolution (PLE). In pure density evolution, the number of AGN per unit comoving volume is assumed to evolve while the distribution of luminosities remains constant. In PLE, the number of AGN per unit comoving volume remains constant, while the luminosity of each AGN evolves.

Pure density evolution models do not predict the flattening at low fluxes which is seen in the best log \( N - \log S \) curves currently available, in both the optical (Boyle et al. 1988) and X-ray bands (Branduardi - Raymont et al. 1994, Hasinger et al. 1993). For this reason, recent evolutionary models have been based on luminosity evolution of some form. Only PLE models are considered in this paper.

As shown by Maccacaro et al. (1991), the XLF can be modeled as two power laws with a break luminosity, \( L_{\text{break}} \), such that

\[
\phi = K_1 L^{-\gamma_1} \quad L < L_{\text{break}} \\
\phi = K_2 L^{-\gamma_2} \quad L > L_{\text{break}}
\]

where \( K_1 \) and \( K_2 \) are normalisations of the two power laws. Since we require the luminosity function to be continuous, the two normalisations are not independent. A single normalisation \( K_1 \) is adequate, since

\[
K_2 = K_1/L_{\text{break}}^{\gamma_1 - \gamma_2}
\]

In the framework of a PLE model the XLF retains its shape at all redshifts, hence the XLF at any redshift depends on only the evolution law and the XLF at zero redshift (hereafter \( z = 0 \) XLF).

4.1 Maximum likelihood and 2D K.S. testing

The maximum likelihood method (Marshall 1984) has been used to obtain best fit evolution parameter(s) and \( z = 0 \) XLF for each evolution model, utilising the full RIXOS + EMMSS sample of AGN. This technique involves
simultaneously fitting the evolution and the $z = 0$ XLF. There are four or five free parameters (three from the $z = 0$ XLF, $\gamma_1$, $\gamma_2$, and $L_{break}$, plus either one or two from the evolution model) in fitting the models considered in this paper. The normalisation of the $z = 0$ XLF is set so that the total number of objects predicted by the model is equal to the number in the sample, and is not a free parameter in the fit.

To test the acceptability of evolutionary models, the two dimensional Kolmogorov-Smirnov (2D K.S.) test has been used. Two alternatives have been used in the literature, the test described by Peacock (1983), and the test of Fasano & Franceschini (1987), which is also described in Press et al. (1992). It is important to use the test most effective at rejecting poor models and accepting good models for the RIXOS and EMSS datasets, to ensure confidence in the results. To assess the most appropriate test to use, both were applied to simulated data as follows:

The two best fit XLFs and evolution models (see section 5.1) from Maccacaro et al. (1991) were used to produce 200 simulated samples of AGN, 100 from each evolution model. Each sample was constructed using two completeness limits, appropriate to the RIXOS and EMSS samples respectively. The number of objects in each simulated sample was between 400 and 600, similar to the number of objects in the combined RIXOS + EMSS sample, and the tests were performed over exactly the same plane as those used on the real sample (see below). In this way, the 2D K.S. tests were evaluated under very similar conditions to those under which they were actually to be applied. Each sample was tested once against its own parent XLF and evolutionary model, and once against the other, so that 200 tests were performed with correct models and 200 with incorrect models. The Peacock test rejected 100 incorrect models (50%) at the 95% level and 6 correct models, while the Fasano & Franceschini test rejected 84 incorrect models (42%) and 10 correct models. This indicates that the 2D K.S. test of Peacock is more efficient at distinguishing between good and bad models of our data. Because the EMSS and RIXOS contain a very large range of sky coverage at different completeness limits, the combined RIXOS + EMSS sample has a slightly lower redshift - de-evolved luminosity correlation coefficient (typically 0.43, but dependent on cosmological and evolutionary model) than the simulation models (typically 0.5 to 0.7). According to Fasano & Franceschini (1987), their test reaches maximum efficiency when compared to that of Peacock (1983) at higher correlation coefficients, and so it is reasonable to assume the results obtained from our simulations should hold for the actual data to be tested. The test of Peacock (1983) has therefore been used in this paper.

Models have been tested in the redshift and de-evolved luminosity plane over a range that includes all parameter values found in RIXOS and the EMSS, $(0 < z < 3.5, 10^{40} < L_0 < 10^{47})$ where $L_0$ is the de-evolved 0.5 - 2.0 keV luminosity in erg s$^{-1}$; note that $L_0$ is model dependent. Since there is no selection criterion in this analysis, based on observed X-ray luminosity, which would correspond to the $M_{B} < -23$ requirement often used in optical QSO surveys, the test has not been performed over an interval in observed luminosity. Imposing a lower limit to observed luminosity in this way would introduce implicit density evolution to a PLE model (see Kassiola and Mathez 1990), and is hence undesirable.

4.2 $1/V_a$ and $< V_e/V_a >$

An estimate of the behaviour of the XLF can be gained in a model-independent way using the $1/V_a$ statistic (Avni & Bahcall 1980) and plotting the XLF in distinct redshift bins, as in Maccacaro et al. (1991). Of course, any evolution occurring within these distinct bins will not be apparent in this type of treatment.

A more quantitative treatment can be made using the $< V_e/V_a >$ statistic (Avni & Bahcall 1980). To investigate single parameter PLE models, without simultaneously modelling the $z = 0$ XLF, we have carried out $< V_e/V_a >$ tests in distinct redshift shells. In this case the test is used to obtain acceptable evolution parameters for the given model, and the bins have been chosen so that within each shell the evolution parameter has a 68% confidence region of about ±20% its value over the entire redshift range; this is a good compromise between resolution in redshift and constraint of the evolutionary properties of each bin. The practical aspects of the $< V_e/V_a >$ test within redshift shells are described in Della Ceca et al. (1992).

We have also used the $< V_e/V_a >$ test to examine evolution at high redshift in a model independent way. In this case the $< V_e/V_a >$ test has been applied in the redshift interval $z_b < z < 3.5$ where $z_b$ is varied. Here, the test is used with no evolutionary model, and capable of determining whether the data are consistent with the no evolution hypothesis between $z_b < z < 3.5$, and if not, whether the luminosity function is increasing with redshift ($< V_e/V_a > > 0.5$), or decreasing with redshift ($< V_e/V_a > < 0.5$). This use of the $< V_e/V_a >$ test is described in Dunlop and Peacock (1990).

5 RESULTS

The best fit evolution parameters and luminosity functions have been obtained from the combined RIXOS + EMSS sample. As a check for consistency between the two samples they have been tested for goodness of fit both individually and in combination. Table 2 shows the results for the maximum likelihood and 2D K.S. tests applied to the models that have been investigated. Errors quoted were obtained using the method of Lamppton, Margon and Bowyer (1976), and correspond to $\Delta \chi^2 = 1$, i.e. 68% confidence intervals for one interesting parameter.

5.1 The simplest models

The two simple PLE models used by Maccacaro et al. (1991), are power law evolution

$L = L_0 \times (1 + z)^C$

and evolution which is exponential with look back time

$L = L_0 \times e^{C \tau}$

where $C$ is the evolution parameter and $\tau$ is look back time.
overpredicts evolution at high redshift, \( z > 1 \), with parameter lies below any value which would be consistent with the model fails because it requires unacceptably rapid evolution models derived from the exponential evolution model luminosity functions. Figs 6 and 7 shows evolution parameters acceptable at 68\% for these models in redshift shells against the best fit power law and exponential model curves in Fig. 4 lie well above the data). Evolution is slower at high redshift in the exponential model than in the power law model, and hence in Fig. 5 the exponential model appears less discrepant at \( z > 1.5 \) than the power law model in Fig. 4. Figs 4 to 7 have been constructed using \( q_0 = 0 \), \( CF = 1.8 \).

### 5.2 Two Parameter Evolution Models

As both single parameter models are rejected by the 2D K.S. test, more complex models have been investigated. From Figs 4 and 5 it appears there is little difference in the slope of the luminosity function in different redshift bins, so models in which the luminosity function changes slope with redshift have not been considered. A power law model with a redshift cutoff, \( z_{\text{cut}} \), where\[ L = L_0 \times (1 + z)^\gamma \quad z < z_{\text{cut}} \]
and alternatively, a polynomial evolution of the form\[ L = L_0 \times 10^{(C_z + C_{z^2})} \]
both have two free parameters for the evolution (plus three for the luminosity function). Both of these models are accepted at the 95\% level by the 2D K.S. test for the combined RIXOS + EMSS samples for both values of \( q_0 \) and \( CF \); there is little justification, from the 2D K.S. probabilities obtained, to prefer one of the models. The similarity of the two models for \( z < 1.5 \) is illustrated by the pre-
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5.3 Evolution at high redshift

It is seen in the previous section that PLE models in which evolution ceases or changes direction at high redshift are found more acceptable than models where evolution continues, for both values of $q_0$ and CF, indicating that evolution at $z > 2$ must be absent or slow compared to that at low redshift. As further evidence, the results of the $< V_e/V_a >$ test from $z = z_b$ to $z = 3.5$ for the combined

dicted $N(z)$ relations plotted in Fig. 1. The two evolution models are however radically different in shape beyond this redshift; in the polynomial evolution model luminosity declines after $z \sim 2$, and at $z = 3.5$ the expected number of objects differs by a factor of 5 for the two models. A larger sample of $z > 2$ objects would have the potential to discriminate between the two models.

Figure 4. Binned $< 1/V_a >$ XLF of the RIXOS + EMSS sample and best fit power law evolution model XLF (dashed lines) for $q_0 = 0$ and CF = 1.8.

Figure 5. Binned $< 1/V_a >$ XLF of the RIXOS + EMSS sample and best fit exponential evolution model XLF (dashed lines) for $q_0 = 0$ and CF = 1.8.

Figure 6. Power law evolution parameter C in redshift bins using the $< V_e/V_a >$ test for $q_0 = 0$ and CF = 1.8.

Figure 7. Exponential evolution parameter C in redshift bins using the $< V_e/V_a >$ test for $q_0 = 0$ and CF = 1.8.
RIXOS + EMSS sample are shown in Figs 8 and 9. Both were constructed using a CF of 1.8; when 1.47 is used, \( < V_e/V_a > \) is a few percent lower; note that above \( z_b = 2.4 \) there are only 4 objects included in the test. From \( z_b = 1.67 \), with 30 AGN, the \( < V_e/V_a > \) test shows the data to be consistent at the 68% level with no evolution for both values of \( q_0 \) and CF. The \( < V_e/V_a > \) test used in this way is model independent, and this result is not restricted to PLE models.

6 DISCUSSION

Although changing the ROSAT to Einstein CF from 1.8 to 1.47 does not appear to affect the choice of model, (i.e. the power law with evolution cutoff and polynomial models are both significantly more acceptable than the simple power law and exponential models), it does have a significant effect on the best fit evolution parameter(s) and the \( z = 0 \) XLF. In all cases the best fit parameters for CF = 1.47 are outside the 90% confidence region of the parameters for CF = 1.8; evolution is slower, and the steep part of the XLF is less steep if the CF of 1.47 is used. The slope of the low luminosity region of the XLF is affected little by the choice of CF.

The evolution parameter, \( C \), for the exponential model is consistent at 68% with the EMSS value \( (C = 4.18 \pm 0.35 \text{ for } q_0 = 0) \) only for CF = 1.47, and its low K.S. probability confirms the result of Della Ceca et al. (1991) that this model is a poor description of AGN evolution. For the power law model, the value of \( C \) obtained here is consistent with that found by Maccacaro et al. (1990) \( (2.56 \pm 0.17 \text{ for } q_0 = 0) \) for both values of CF. The introduction of a cutoff in evolution at \( z = 1.8 \) significantly improves the 2D K.S. probability of the power law model for the RIXOS + EMSS sample; the last column of Table 2 shows that the EMSS data alone is also better fit with the evolution cutoff. Including an evolution cutoff at \( z = 1.8 \) in a \( < V_e/V_a > \) test to the EMSS data with a power law evolution model and \( q_0 = 0 \) gives \( C = 2.74 \pm 0.20 \), almost identical to the RIXOS+EMSS value for CF = 1.47 and still consistent for CF = 1.8.

Comparing the CF = 1.8, \( q_0 = 0 \) evolution parameters and \( z = 0 \) XLFs from the RIXOS+EMSS sample with those of Boyle et al. (1994), we find similar values for all but the exponential evolution model which evolves faster in Boyle et al. (1994). For \( q_0 = 0.5 \), there is less agreement, with the \( z = 0 \) XLFs of the exponential, power law, and polynomial evolution laws having significantly lower values for \( \gamma_1 \) (i.e. flatter slopes at low luminosity) in Boyle et al. (1994). The best fit \( q_0 = 0.5 \) power law with evolution cutoff model in Boyle et al. (1994), whilst having a similar \( z = 0 \) XLF and evolution rate \( C \), has a much higher cutoff redshift \( (z_{cut} = 1.7) \), than the value found here, \( z_{cut} = 1.4 \) for \( q_0 = 0.5 \).

It is notable that almost all of the models considered in this paper are found more acceptable to the 2D K.S. test than in Boyle et al. (1994), in which almost all models are rejected at > 99%. Boyle et al. used the test of Fasano & Franceschini (1987), while we have used that of Peacock (1983). However we have also tested our models against the RIXOS + EMSS dataset using the test of Fasano & Franceschini, and do not find them to be rejected at > 99%. In Boyle et al. (1994), the inclusion of narrow line objects gave significantly increased 2D K.S. probabilities, (i.e. a better fit). However, narrow line objects which would be classified by Stocke et al. as AGN have been included throughout this analysis. If we exclude these objects, which occur in both the EMSS and RIXOS, we do find lower 2D K.S. probabilities, although the polynomial and power law with evolution cutoff models are still acceptable at the 95% level while the simple power law and exponential evolution models are not. For the \( z = 0 \) XLF, typically \( \gamma_1 \) is reduced by about 0.1 and \( L_{break} \) is
increased by 25% to 50% depending on the specific PLE model and choice of cosmology; the best fit values of $\gamma_2$ and $z_{\text{cut}}$ change by no more than 0.02 and the evolution parameters remain within the errors quoted in table 2. There are no broad line objects with $L_0 < 2 \times 10^{43} \text{erg s}^{-1}$.

The poor model fits of Boyle et al. (1994) may be attributable to the conversion between ROSAT and Einstein measured fluxes; the ROSAT sample of Boyle et al. (1994) combined with the EMSS AGN using a CF of 1.8 shows an evolution rate too high to be consistent with the EMSS sample alone. As we have discussed in section 3, the effective CF from ROSAT to Einstein fluxes may be significantly lower than 1.8, and as seen in table 2 a lower CF has the potential to reduce the evolution rate of combined ROSAT and Einstein data, and hence could improve the self consistency and model fits of Boyle et al. (1994).

The log $N - \log S$ at faint fluxes derived from the CF = 1.8 models tested above, and extended to $z = 4$ are shown in Fig. 10. None of the model curves exceed the total faint X-ray log $N - \log S$ obtained by fluctuation analysis in Hasinger et al. (1993), or Barcons et al. (1994). Notably, the log $N - \log S$ curves at faint fluxes for PLE are separated strongly by the value of $q_0$ used, while the specific choice of PLE model has a comparatively minor effect. In a $q_0 = 0.5$ universe, AGN undergoing PLE should represent between 30% and 45% of all sources with $S > 10^{-15} \text{erg s}^{-1} \text{cm}^{-2}$; in contrast, in a $q_0 = 0$ universe AGN evolving in this way would be expected to constitute between 55% and 100% of these sources. Above $3 \times 10^{-14} \text{erg s}^{-1} \text{cm}^{-2}$ the log $N - \log S$ curves from the PLE models are all very similar and represent the data well.

The AGN contribution to the 1 - 2 keV X-ray background has been calculated for $0 < z < 4$, $10^{40} < L_0 < 10^{47}$ (where $L_0$ is the de-evolved 0.5 - 2 keV luminosity in erg s$^{-1}$) for all the models tested in section 5 and is shown in table 2 (column entitled $S_{XRB}$). As expected from the log $N - \log S$ predictions, the contribution of AGN to the X-ray background from these models has a stronger dependence on the value of $q_0$ than the choice of PLE model. The values for the AGN X-ray background intensity given in table 2 are in good agreement with those of Boyle et al. (1994). A recent measurement of the X-ray background (Chen, Fabian and Gendreau 1996) using both ASCA and ROSAT found an intensity of $1.46 \times 10^{-8} \text{ergs}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ (1 - 2 keV). Using this value, our acceptable models (power law with evolution cutoff and polynomial) predict that AGN account for between 44% and 50% ($q_0 = 0$) or 29% and 32% ($q_0 = 0.5$) of the 1 - 2 keV X-ray background, where these ranges include the uncertainty in CF. Taking the value of $1.25 \times 10^{-8} \text{ergs}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ for the 1 - 2 keV X-ray background (Hasinger 1992) used by Boyle et al. (1994), the contribution from AGN rises to between 52% and 60% ($q_0 = 0$) or 33% and 38% ($q_0 = 0.5$).

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