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The X-ray luminosity function of local galaxies

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ABSTRACT

We present an estimate of the local X-ray luminosity function and emissivity for different subsamples of galaxies, namely Seyferts, LINERS, star-forming and passive (no-emission-line) galaxies. This is performed by convolving their optical luminosity function, as derived from the Ho et al. spectroscopic sample of nearby galaxies with the corresponding L_x/L_B relation. The local galaxy emissivity is $\approx 1.6 \times 10^{39}\, h\, \mathrm{erg\, s^{-1}\, Mpc^{-3}}$ in agreement with the results from a number of cross-correlation analyses using large-area surveys. From our analysis, it becomes evident that the largest fraction of the galaxy emissivity comes from galaxies associated with active galactic nuclei (Seyferts but also LINERS) while the contribution of star-forming and passive galaxies is small. This independently supports the view that most of the yet unidentified X-ray sources in deep *ROSAT* fields which are associated with faint optical galaxies do harbour an active galactic nucleus.

Key words: galaxies: evolution – quasars: general – galaxies: starburst – diffuse radiation – X-rays: galaxies – X-rays: general.

1 INTRODUCTION

The launch of the X-ray satellite *ROSAT* has brought great progress in understanding the origin of the X-ray background (XRB) (for a review see Fabian & Barcons 1992). Deep X-ray surveys have resolved about 70 per cent of the XRB at soft energies (0.5–2 keV) (Hasinger et al. 1998). Spectroscopic follow-up observations have demonstrated that the majority of these sources are broad-line, luminous active galactic nuclei (QSOs) e.g. Shanks et al. (1991), Georgantopoulos et al. (1996), McHardy et al. (1998), Schmidt et al. (1998). The QSO luminosity function (LF) derived on the basis of these surveys (Boyle et al. 1993, 1994; Page et al. 1996; Jones et al. 1997) suggests that QSOs cannot contribute the bulk of the XRB at these energies. Indeed, at faint X-ray fluxes there are many sources associated with optical galaxies which present narrow emission lines (Boyle et al. 1995; Griffiths et al. 1996; McHardy et al. 1998). Roche et al. (1995, 1996), Almaini et al. (1997) and Soltan et al. (1997) quantified the contribution of these NELGs by cross-correlating optically selected galaxies with *ROSAT* XRB fluctuations. They found that NELGs can easily contribute the bulk of the XRB together with QSOs at soft energies. Similar attempts were made by Refregier, Helfand & McMahon (1997) using *Einstein* data and also in the hard band (2–10 keV) by Lahav et al. (1993) and Miyaji et al. (1994) who cross-correlated nearby *IRAS* galaxy catalogues with *HEAO-1* data. Although there is mounting evidence that most of these galaxies do present either high-excitation lines or broad wings and thus they are associated with AGN activity (e.g. Schmidt et al. 1998), their exact nature and contribution to the XRB remains unclear. Here, we provide an independent estimate of the local galaxy X-ray LF and emissivity. More importantly, we assess the contribution of different classes of galaxies (Seyferts, LINERS, star-forming and passive galaxies) to the galaxy X-ray emissivity. This is done by convolving the optical LF as derived from the Ho et al. (1995) sample of nearby galaxies with the corresponding L_x/L_B relation (Section 2). The same method has been employed using *IRAS* data (Griffiths & Padovani 1990; Treyer et al. 1992; Barcons et al. 1995). Schmidt, Boller & Voges (1996) also present a preliminary analysis of the local galaxy luminosity function using *ROSAT* all-sky survey data. However, the use of the Ho et al. sample presents the advantage that excellent quality nuclear spectra exist for each galaxy; thus it provides us with one of the less biased samples against low-luminosity active galactic nuclei (AGN). Moreover, the use of an optical sample may introduce less bias against passive galaxies and LINERS most of which are associated with early-type galaxies and thus are probably under-represented in IR-selected samples. Our findings are compared with both the cross-correlation (e.g. Soltan et al. 1997) as well as the *IRAS* LF (e.g. Barcons et al. 1995) results in Section 3.

2 METHOD AND RESULTS

The X-ray galaxy LF can be obtained by convolving the optical LF with the L_x/L_B relation (see Avni & Tananbaum 1986) i.e. by deriving the bivariate optical/X-ray LF:

$$\Phi(l_x) = \int \Phi(l_B)\, \phi(l_x | l_B) \mathrm{d}l_B$$

where l_x and l_B denote the logarithms of the X-ray (0.2–4 keV) and the optical (B) luminosity respectively; $\Phi(l_B)$ is the optical luminosity function per unit logarithmic luminosity interval and $\phi(l_x|l_B)$, is the conditional probability function i.e. it gives the distribution of l_x around the average X-ray luminosity $\langle l_x \rangle$ at a given optical luminosity l_B. We have used $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$ throughout the paper.

We have used the Ho et al. (1995, 1997a) spectroscopic sample of nearby galaxies in order to derive the optical LF for various classes of galaxies. The above is a magnitude-limited sample ($B < 12.5$) of 486 galaxies above $\delta > 0$. Excellent nuclear spectra (high signal-to-noise ratio, medium resolution) and thus bona-fide spectroscopic identifications exist for each galaxy (Ho et al. 1997a). 14 per cent of the galaxies do not present emission lines in their nuclei and hence can be classified as passive galaxies or 'early-type galaxies' on the basis of spectroscopy rather than on morphology. At least 40 per cent of the galaxies have AGN-like spectra: Seyfert, LINERS or transition objects i.e. with composite LINER/H II spectra. The remaining nuclei can be classified as star-forming (H II) (Ho et al. 1997b). The use of the above sample offers the possibility to construct a LF for various spectroscopic subsamples of galaxies and therefore to distinguish the relative contribution of AGN and normal galaxies to the XRB. The magnitudes listed in Ho et al. (1997a) are corrected for both Galactic and intrinsic reddening. The distances have been corrected according to the Virgo infall model of Tully & Shaya (1984). We have used only galaxies with $|b| > 20°$ in order to minimize the effects of Galactic reddening. We are then left with 416 galaxies with $B < 12.5$. We derive the optical LF using the classical $1/V_{max}$ method (Binggeli, Sandage & Tammann 1988). The $1/V_{max}$ points are then fitted with a Schechter function in order to obtain a parametric expression for the LF:

$$\Phi(M) = \phi_\star\, 10^{[0.4(M_\star - M)(\alpha+1)]}\, \exp[-10^{0.4(M_\star - M)}]$$

The results are presented in Table 1: column (1) gives the type of galaxies; column (2) gives the normalization $\phi_\star$ in units of $\mathrm{Mpc^{-3}\,mag^{-1}}$; columns (3) and (4) give the slope α and characteristic magnitude $M_\star$ of the LF together with the associated 1σ error bars; finally column (5) lists the reduced χ^2. Note that the best-fitting LF for all galaxies together, yields $\phi_\star = 1.8\times 10^{-2}\,\mathrm{Mpc^{-3}\,mag^{-1}}$, $\alpha = -1.2^{+0.04}_{-0.13}$ and $M_\star = -19.7^{+0.05}_{-0.50}$, with a reduced χ^2 of 0.5. The galaxy LF derived by Loveday et al. (1992) from the APM sample yields $\phi_\star = 1.4\times10^{-2}$, $\alpha = -1.0$ and $M_\star = -19.5$. Therefore, the Loveday et al. (1992) fit is in good agreement with our results suggesting that our crude approach provides a good approximation to the true galaxy LF. We have also verified that excluding a 10° region around Virgo does not change our results appreciably. In Fig. 1 we present the LF for the different subsamples of galaxies. Henceforth, we include the 'transition' class of objects in the LINERS sample.

Next, we derive the L_x/L_B relation for the above subclasses of galaxies. Many galaxies from the Ho et al. sample are listed in the

Table 1. The best-fitting results for a Schechter optical LF.

Type	$\phi_\star$	α	$M_\star$	χ^2/dof
Seyferts	0.001	$-1.2^{+0.3}_{-0.5}$	$-20.1^{+0.3}_{-0.1}$	0.27
LINERS	0.005	$-1.0^{+0.2}_{-0.3}$	$-19.7^{+0.2}_{-0.3}$	0.73
H II	0.009	$-1.3^{+0.2}_{-0.1}$	$-19.5^{+0.2}_{-0.4}$	0.62
passive	0.002	$-1.5^{+0.4}_{-0.6}$	$-19.8^{+0.3}_{-0.4}$	3.0

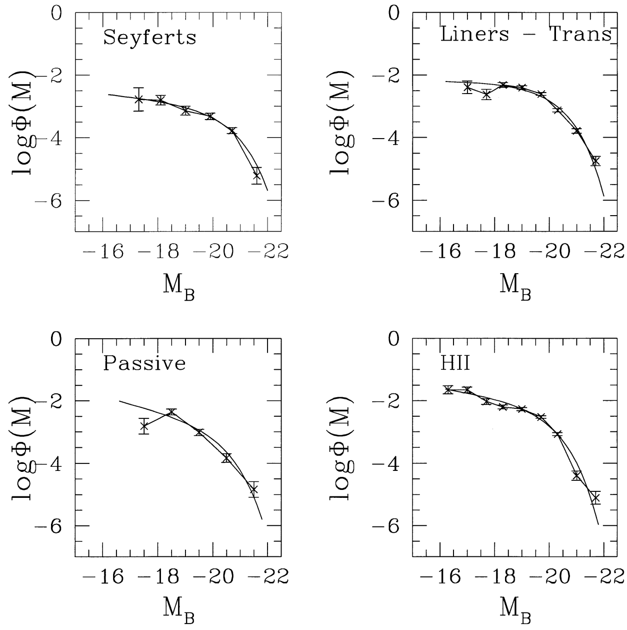

Figure 1. The optical LF of the different subsamples of galaxies in the Ho et al. sample: Seyferts, LINERS, H II and passive galaxies. The solid line denotes the best-fitting Schechter function to the $1/V_{max}$ points (crosses).

Table 2. The regression results for the $\log L_{0.2-4\mathrm{keV}}$ versus $\log L_B$ relation.

Type	slope	Intercept	dispersion	$\langle l_x \rangle$
Seyferts (22)	1.62	-30.10	0.78	41.0
LINERS (59)	0.90	0.54	0.74	39.9
H II (54)	0.89	0.65	0.47	39.3
passive (29)	1.81	-39.2	0.78	39.2

X-ray catalogue of galaxies of Fabbiano, Kim & Trinchieri (1992). This catalogue contains *Einstein* detections and 3σ upper limits of nearby galaxies in the 0.2–4 keV band. After excluding objects where the X-ray emission may not be associated with the galaxy (see Fabbiano et al. 1992 for details) we are left with 164 objects (of which 69 are upper limits). We have performed a regression analysis [$\log L_x(0.2-4\mathrm{keV})$ against $\log L_B$] using the EM algorithm of the ASURV survival analysis package (Isobe, Feigelson & Nelson 1986). The results are presented in Table 2: column 1 gives the galaxy type together with the number of galaxies used; columns (2) (3) and (4) list the slope, intercept and the dispersion σ (assuming a Gaussian distribution around the best-fitting line) of the $\log L_x$ versus $\log L_B$ relation while column (5) gives the mean X-ray luminosity. In our analysis there is the inherent assumption that the above 164 galaxies represent an unbiased subsample of the Ho et al. survey. As our sample consists mainly of targets rather than serendipitously observed sources, there may be possible biases in the derived L_x/L_0 relation. Therefore, we have attempted to test the validity of the 'fair sample' assumption by dividing our original sample into two subclasses on the basis of the off-axis angle of the galaxy, θ: sources with $\theta < 5$ arcmin mostly consisting of targets and objects with $\theta > 5$ arcmin, which are mostly serendipitous sources. The L_x/L_0 results for the above two subsamples are found to be statistically equivalent.

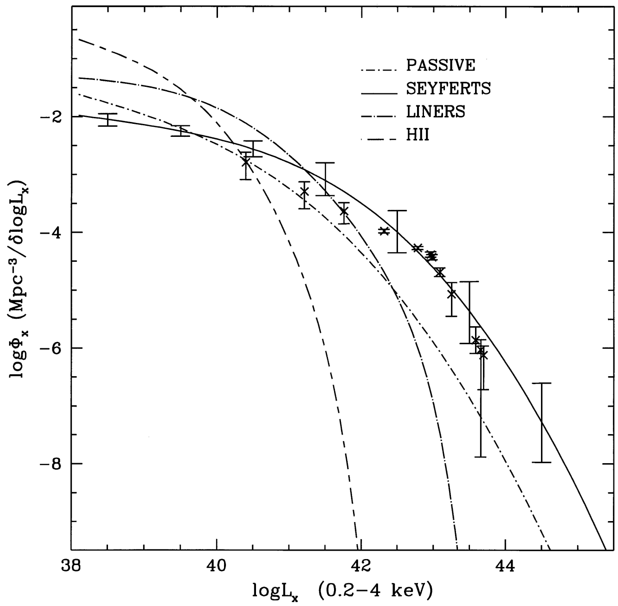

Figure 2. The X-ray LF, for different subsamples of galaxies (Seyferts, Liners, star-forming and passive). The 1σ errors on the Seyfert LF are also shown. The crosses denote the local QSO X-ray LF derived from the *RIXOS* sample (Page et al. 1996).

Table 3. The X-ray local galaxy emissivity and fractional contribution to the 0.2–4 keV XRB in the case of no evolution.

type	emissivity ($10^{39}\ h\,\mathrm{erg\,s^{-1}\,Mpc^{-3}}$)	fraction
Seyferts	0.80 (±0.18)	0.20
LINERS	0.46 (±0.05)	0.11
H II	0.16 (±0.02)	0.04
passive	0.17 (±0.02)	0.04

The derived X-ray LFs for various subclasses of galaxies are presented in Fig. 2. We plot the 1σ error bars only for the Seyferts in order to avoid confusion. The errors were derived by varying the optical LF slope α and the L_x/L_B relation within their 1σ confidence limits. For comparison we also plot the *RIXOS* QSO X-ray LF from Page et al. (1996). Using the LF derived above, we estimate the local volume emissivity and the contribution of galaxies to the 0.2–4 keV XRB. The derived contribution sensitively depends on the cut-off redshift, z_{max}, the rate of evolution as well as the X-ray spectral index (e.g. Lahav et al. 1993). Here, we choose $z_{max} = 4$. We use a spectral index of $a_x = 0.7$ comparable to the X-ray spectrum of NELGs in the *ROSAT* band (Almaini et al. 1996; Romero-Colmenero et al. 1996). We first adopt a simple no-evolution model. We choose the lower limit of integration in luminosity, L_{min}, to be as low as $L_x = 10^{38}$ erg s^{-1}, i.e. the luminosity of a solar mass X-ray binary radiating at the Eddington limit. Our results do not critically depend on the lower limit of integration. When we increase the limit of integration to $L_x = 10^{40}$ erg s^{-1}, the Seyfert emissivity reduces by 5 per cent. Note, however, that our derived LF depends sensitively on the dispersion of the L_x/L_0 relation, in the sense that the larger the dispersion the higher the number density of bright objects and thus the emissivity. If the dispersion is systematically over-estimated, then our results should be viewed only as upper limits to the emissivity. This may be the case in the Seyfert subsample where the presence of intrinsic absorption especially in low-luminosity objects may broaden the L_x/L_0 distribution (see Franceshini, Gioia, Maccacaro 1986). The results are presented in Table 3: j denotes the emissivity in units of $10^{39}\ h$ erg s^{-1} Mpc^{-3} while f denotes the fractional contribution to the 0.2–4 keV XRB, assuming no evolution. The observed XRB intensity in the above band was estimated integrating the expression $9 \times E^{-0.4}$ keV cm^{-2} s^{-1} sr^{-1} keV^{-1} (Gendreau et al. 1995). In a strong evolution scenario i.e. $j \propto (1+z)^k$ with the evolution parameter $k = 3$, in accordance to the results of Almaini et al. (1997) for the *ROSAT* NELGs, the Seyferts alone would produce 90 per cent of the XRB intensity.

3 DISCUSSION & SUMMARY

We have estimated the local galaxy X-ray LF and volume emissivity for different spectroscopic subsamples of galaxies: Seyferts, LINERS, star-forming and passive galaxies. This was carried out by combining the optical LF derived from the Ho et al. spectroscopic sample of nearby galaxies with the L_x/L_0 relation derived from the Fabbiano et al. atlas of X-ray galaxies. The local emissivity is $j \approx 1.6 \pm 0.2 \times 10^{39}\ h$ erg s^{-1} Mpc^{-3} in the 0.2–4 keV band, translating to a contribution of 40 per cent to the extragalactic X-ray background, assuming no evolution. Our result is consistent with that of Soltan et al. (1997) who find $j \sim 2 \times 10^{39}\ h$ erg s^{-1} Mpc^{-3} (0.2–4 keV) from a cross-correlation of bright galaxy catalogues with the *ROSAT* all-sky survey background maps. In the hard 2–10 keV X-ray band, cross-correlations of local optical and *IRAS* galaxy catalogues with *HEAO-1* and *Ginga* data, yield similar results: Lahav et al. (1993), Miyaji et al. (1994) and Barcons et al. (1995) find local emissivities ranging from $j \sim 1.0 - 1.7 \pm 0.6 \times 10^{39}\ h$ erg s^{-1} Mpc^{-3}, in the 0.2–4 keV band, where we assumed for the conversion a spectral index of $\Gamma = 1.7$. Interestingly, cross-correlations of optical plates with deep *ROSAT* pointings yield lower emissivities $j \sim 0.5 \pm 0.07 \times 10^{39}\ h$ erg s^{-1} Mpc^{-3}(0.2-4 keV) locally, (Roche et al. 1995, 1996; Almaini et al. 1997). However, as the median redshift of the galaxies in Almaini et al. (1997) is $z = 0.45$ while in our sample is z=0.004, cosmological evolution may play an important role. The largest contribution to our derived galaxy emissivity comes from AGN, i.e. the Seyfert galaxies and LINERS. Our Seyfert galaxy emissivity is in good agreement with that of Barcons et al. (1995), $j \sim 1.1 \pm 0.2 \times 10^{39}\ h$ erg s^{-1} Mpc^{-3}(0.2–4 keV), derived on the basis of *IRAS* 12 μm and *HEAO-1* data. Unfortunately, owing to the small number statistics we are unable to distinguish between different Seyfert subclasses. Note that, our Seyfert LF is in good agreement with the local QSO LF of the *RIXOS* survey (Page et al. 1996), at bright luminosities ($L_x \gtrsim 10^{42}$ erg s^{-1}) where the Seyfert LF is dominated by the Seyfert 1 population (see Fig. 2). At fainter luminosities our Seyfert LF is systematically above the *RIXOS* QSO LF. A new result from our analysis is that LINERS appear to contribute substantially to the local volume emissivity. From Fig. 2 it is evident that Seyferts dominate the bright luminosities while LINERS play an important role at luminosities $\lesssim 10^{42}$ erg s^{-1}. Indeed, the cross-correlation of the *ROSAT* all-sky survey Bright Source Catalogue with the Ho et al. sample yields 45 coincidences within 1 arcmin (Zezas, Georgantopoulos & Ward 1999). The majority of these sources are LINERS (15) and Seyferts (13) while four objects are intermediate between Seyferts and LINERS according to the Ho et al. (1997a) classification. The above result is marginally consistent with previous analyses: Miyaji et al. (1994) set up an upper limit to the non-Seyfert population (e.g. star-forming galaxies and LINERS) emissivity of $j \approx 0.4 \times 10^{39}\, h\,\mathrm{erg\,s^{-1}\,Mpc^{-3}}$ while Barcons et al. (1995) derive an 2σ upper limit of $j \approx 0.7 \times 10^{39}\, h\,\mathrm{erg\,s^{-1}\,Mpc^{-3}}$. This may be partly explained by the fact that LINERS are mainly associated with early-type galaxies (Ho et al. 1997b) which have low-IR emission and are thus under-represented in *IRAS* galaxy samples. The galaxy population which present no AGN activity such as passive and star-forming galaxies, contribute only a small fraction (four per cent for each class) of the XRB intensity in the 0.2–4 keV band. This is somewhat higher than the star-forming galaxy emissivity derived from the the *IRAS* galaxy LF (Treyer et al. 1992).

In conclusion, the extragalactic X-ray light appears to be dominated by accretion processes rather than star-forming activity, in agreement with previous predictions by Miyaji et al. (1994), Barcons et al. (1995). Star-forming and passive galaxies produce less than 10 per cent of the XRB intensity in the 0.2–4 keV band assuming no evolution. This independently suggests that the vast majority of the galaxies detected in deep *ROSAT* and *ASCA* fields are associated with AGN (Seyferts but also LINERS). Future large effective area missions such as *XEUS* will be able to probe the faint tail of the galaxy LF up to high redshifts and thus to detect large numbers of non-AGN, normal galaxies in a similar fashion to deep optical surveys.

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