# MINING *XMM-NEWTON* AND *CHANDRA* FIELDS FOR NORMAL GALAXIES

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## ABSTRACT

We present results from our work on 'normal' X-ray selected galaxies (NGs). The $\log N - \log S$ relation for 46 NG candidates is fitted with a Euclidean power law (slope $-1.46 \pm 0.13$, cumulative number counts). For the largest set of NG candidates in the local Universe (68 galaxies) the best fit Schechter luminosity function (LF) parameters are $L^{\star} = 41.02^{+0.14}_{-0.12}$, $\alpha = 1.76 \pm 0.10$. We discuss the discrepancy with a higher redshift LF at the bright end. We cross-correlated 1XMM and *Chandra*-XASSIST with the *2dFGRS* and found no luminous ($L_X > 10^{42}$) NGs but we found 8 NGs with $\log f_X/f_O > -2$. We complemented this sample with two samples from the literature and concluded that the $\log f_X/f_O < -2$ criterion for separating NGs from AGN mainly selects against massive elliptical NGs.

Key words: *XMM-Newton*; X-rays; galaxies.

## 1. INTRODUCTION

It is a well established fact that galaxies hosting an active galactic nucleus (AGN) give off copious amounts of X-ray emission. On the other hand, galaxies which are 'normal' (NGs), in the sense that they may not be AGN dominated, have only recently been studied in detail in the X-ray band. The likely source of X-ray emission in such systems is diffuse hot gas and/or X-ray binary stars. In the most massive early-type galaxies the X-ray emission is dominated by the hot interstellar medium with temperatures $kT \sim 1$ keV. A smaller fraction of the observed X-ray luminosity is due to low mass X-ray binaries associated with the older stellar population. In late-type galaxies, the X-ray emission originates in hot gas with temperature $kT \sim 1$ keV, which is heated by supernova remnants, as well as in a mixture of low and high-mass X-ray binaries (see Fabbiano, 1989, for a review). The diffuse hot gas contributes significantly in the soft X-ray band ($< 2$ keV) while the X-ray binary systems are responsible for the bulk of the emission at harder energies (e.g. Stevens et al., 2003). The integrated X-ray emission of 'normal' galaxies is believed to be a good indicator of the star-formation activity in these systems (e.g. Gilfanov et al., 2004).

The X-ray luminosity of NGs is usually weak, $\lesssim 10^{42}$ erg s$^{-1}$, i.e. a few orders of magnitude below that of powerful AGN (Moran et al., 1999; Zezas et al., 1998). As a result, observed X-ray fluxes are faint and, until recently, only the very local systems ($< 100\,\mathrm{Mpc}$) were accessible to X-ray missions. With the new generation of X-ray missions, *Chandra* and *XMM-Newton*, the situation has changed dramatically. The *Chandra* Deep Fields North and South (CDF-N, CDF-S; Alexander et al., 2003; Giacconi et al., 2002) have reached fluxes $f(0.5 - 2.0$ keV$) \sim 10^{-17}$ erg cm$^{-2}$ s$^{-1}$, thus providing the first ever X-ray selected NG sample. Using the 2 Ms CDF-North, Hornschemeier et al. (2003) provided a sample of 43 NG candidates for which optical spectroscopic observations are available. These galaxies have X-ray–to–optical flux ratios $\log f_X/f_O < -2$, which these authors use as an empirical boundary, separating NGs from AGN. Norman et al. (2004) extended this study and identified over 100 NG candidates in the combined CDF-N and CDF-S, although optical spectroscopic data are available only for a fraction of these objects. However, these authors have identified NGs with $\log f_X/f_O > -2$. On the other hand, Georgakakis et al. (2003) and Georgakakis et al. (2004a) have identified NGs with $\log f_X/f_O \approx 2$. Here, we present some recent results and address possible selection caveats.

## 2. THE NEEDLES IN THE HAYSTACK SURVEY

The 'Needles in the Haystack Survey' (NHS) was a long-term project aiming to identify X-ray selected NGs in the local Universe. Within the framework of the NHS project (Georgakakis et al., 2004b; Georgantopoulos et al., 2005), 70 *XMM-Newton* fields have been used in total. These cover an area of 11 square degrees and overlap with the Sloan Digital Sky Survey Data Release-2 (SDSS DR-2). The SDSS dataset is complete down to $g \approx 23$ (imaging) and $r \approx 17.7$ (spectroscopy). Using a search radius $r < 7''$ we identified optical counterparts for X-ray sources, from which NGs were selected according to the following selection criteria:

1. Galaxies should be resolved, i.e. have an extended optical light profile,
2. $\log f_X/f_O < -2$,
3. hardness ratios (HRs) *not* indicative of large amounts of absorption,
4. optical spectrum (where available) consistent with star-forming galaxies, based on diagnostic emission-line ratios and lack of broad emission lines.

The NG sample thus compiled comprises 28 galaxies. For only 5 of these are there no optical spectra. 16 of the galaxies have either a narrow emission-line optical spectrum or a spectral energy distribution (SED) consistent with a late-type spectrum. 12 of the galaxies have either exclusively absorption lines or a SED consistent with an early-type spectrum. The median redshift is 0.05.

A comparison of the luminosity-redshift relation for this sample with the NG samples from the CDF-N and S (Figure 1) shows that the NHS and CDF samples are complementary. After combination with 18 local galaxies from CDF-N and S, a local NG X-ray luminosity function was constructed.

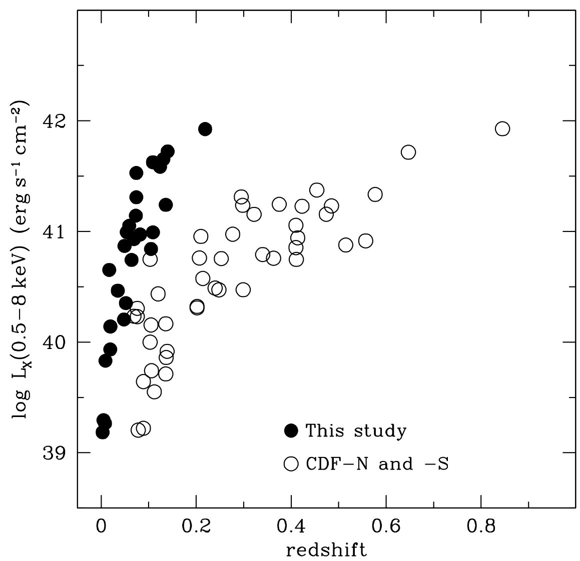


*Figure 1.* *$L_X$ (0.5-8.0 keV) against redshift, from Georgantopoulos et al. (2005). Filled circles are from the NHS NG candidate sample. Open circles are from the CDF samples. The two surveys cover complementary regions of $L_X - z$ space.*

## 3. NORMAL GALAXIES IN 1XMM

The above work has been extended in Georgakakis et al. (2005) by using the First *XMM-Newton* Serendipitous Source Catalogue (1XMM). The sample covers an area of $\approx 6$ square degrees to a flux limit $\approx 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. The galaxy selection criteria were as above with optical counterparts identified using the U.S. Naval Observatory Catalog (USNO), version A2.0. Follow-up spectroscopy was performed at the Guillermo Haro 2-m class telescope in Cananea, Mexico, and was complemented with the SDSS and the literature. A sample of 28 NGs was thus obtained, with optical spectra for 26 of these.

The inlet plot in Figure 2 shows the '$\log N - \log S$' relation for our NG candidates. For the main plot, we combined the 1XMM and NHS samples into a new sample comprising a total of 46 NGs covering $\approx 15$ square degrees. This can be fitted with a power law, obtaining a slope of $-1.46 \pm 0.13$ (cumulative number counts, Euclidean), in excellent agreement with Hornschemeier et al. (2003) at faint fluxes and Tajer et al. (2005) at the very bright end.

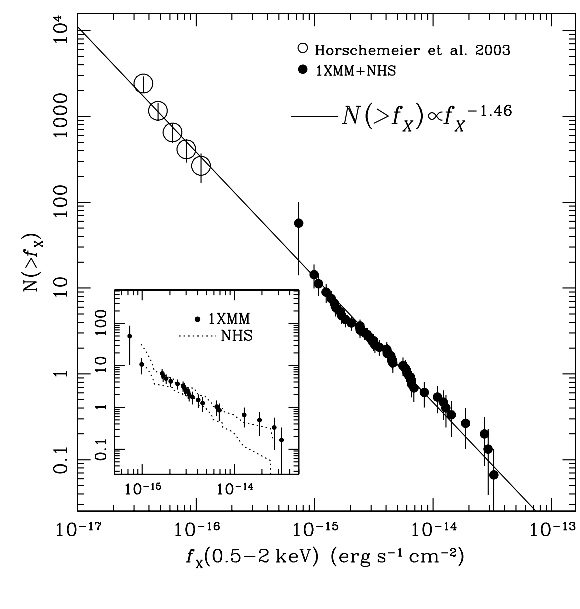


*Figure 2.* *Cumulative normal galaxy counts in the 0.5-2.0 keV spectral band from Georgakakis et al. (2005). Filled circles are the combined sample of NG candidates from the NHS and 1XMM studies. Open circles are source counts from Hornschemeier et al. (2003). The continuous line is the best fit to the $\log N - \log S$ relation at bright fluxes from the combined NHS and 1XMM samples. The inlet plot shows the $\log N - \log S$ for galaxies in the 1XMM study only, compared with counts from the NHS.*

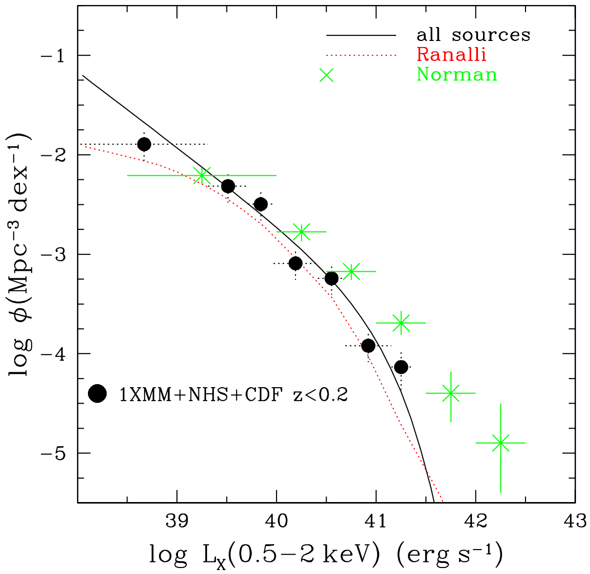


*Figure 3. The $0.5-2.0$ keV LF for the combined sample 1XMM, NHS and CDF of $z<0.2$ NGs (adapted from Georgakakis et al., 2005). Filled circles are from the 68 NG sample described in the text. The solid line shows the maximum likelihood fit. The dashed line shows the IRAS LF (Ranalli et al., 2005) corrected to the X-ray band. The crosses are from Norman et al. (2004).*

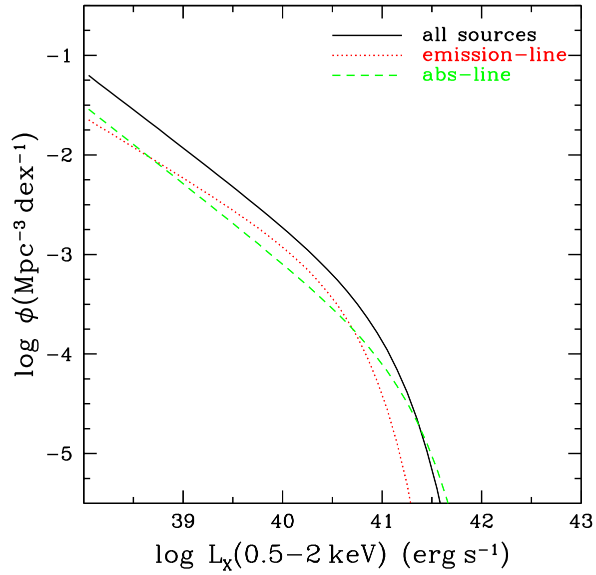


*Figure 4. LFs for early and late type NGs. Solid line: best fit to all NGs. Dashed line: best fit to absorption line NGs. Dotted line: best fit to emission line NGs. LFs for the two categories are comparable. Adapted from Georgakakis et al. (2005).*

### 3.1. Luminosity Functions

We combined the 46 1XMM+NHS NGs with 22 local ($z<0.2$) galaxies from the CDFs to obtain the *largest sample of NGs in the local Universe*, comprising 68 galaxies. As described in Georgantopoulos et al. (2005), we derived both the binned X-ray luminosity function (LF, Page & Carrera, 2000) and a parametric Maximum Likelihood fit (Tammann et al., 1979) adopting a Schechter (1976) form for the LF.

The $0.5-2.0$ keV LF for the combined sample is shown in Figure 3. The best fit Schechter parameters are $L^{\star}=41.02^{+0.14}_{-0.12}$, $\alpha=1.76\pm0.10$. Also shown are the IRAS LF of Ranalli et al. (2005) and the LF data points from the higher redshift sample of Norman et al. (2004). We note the good overall agreement with the IRAS LF. There is good agreement with the Norman et al. (2004) as well, except for the bright end. This may suggest (i) contamination of the Norman et al. (2004) sample by AGN, (ii) bias in our sample against luminous systems ($L_X\gtrsim10^{42}$ erg s$^{-1}$) because of the $\log f_X/f_O<-2$ cut or (iii) evolution of the NG LF.

In Figure 4 we are showing best fit LFs for all sources, as well as separately for emission line and absorption line NGs from our sample. The LFs are comparable.

## 4. NORMAL GALAXIES IN *2DFGRS*

We have searched the Two Degree Field Galaxy Redshift Survey (*2dFGRS*) database for X-ray selected NGs (Tzanavaris et al., 2006). The $b_J=19.45$ faint limit of this survey allows detection of galaxies up to $\log f_X/f_O\sim1$ for X-ray fluxes of a few $\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

We cross-correlated the 1XMM catalogue with the *2dFGRS* and obtained 18 X-ray/optical pairs within a $6''$ matching radius. We also cross-correlated the *Chandra*-XASSIST catalogue with the *2dFGRS* and obtained 20 X-ray/optical pairs within a $3''$ matching radius. We used selection criteria similar to those described above to separate NGs from AGN. Our aim was to look for NGs which were (i) 'luminous' ($L_X>10^{42}$ erg s$^{-1}$), and/or (ii) had $\log f_X/f_O>-2$. We did not find any luminous NGs in our sample. However, we found 8 NGs (H II nuclei and absorption-line galaxies) with $\log f_X/f_O>-2$.

We complemented our results with data from the literature. Specifically, we used the nearby star-forming galaxy sample compiled by Zezas (2001). This comprises 44 galaxies detected by *ROSAT* PSPC, spanning the luminosity range $L_X(0.1-2.4\text{keV})\approx4\times10^{37}-3\times10^{41}$erg s$^{-1}$. Galaxies in this sample have been classified on the basis of high quality nuclear spectra from Ho et al. (1997). Further, we used the nearby galaxy sample of Fabbiano et al. (1992). Galaxies in this sample have been observed with the *Einstein* observatory and comprise all morphological types. Galaxies flagged as AGN

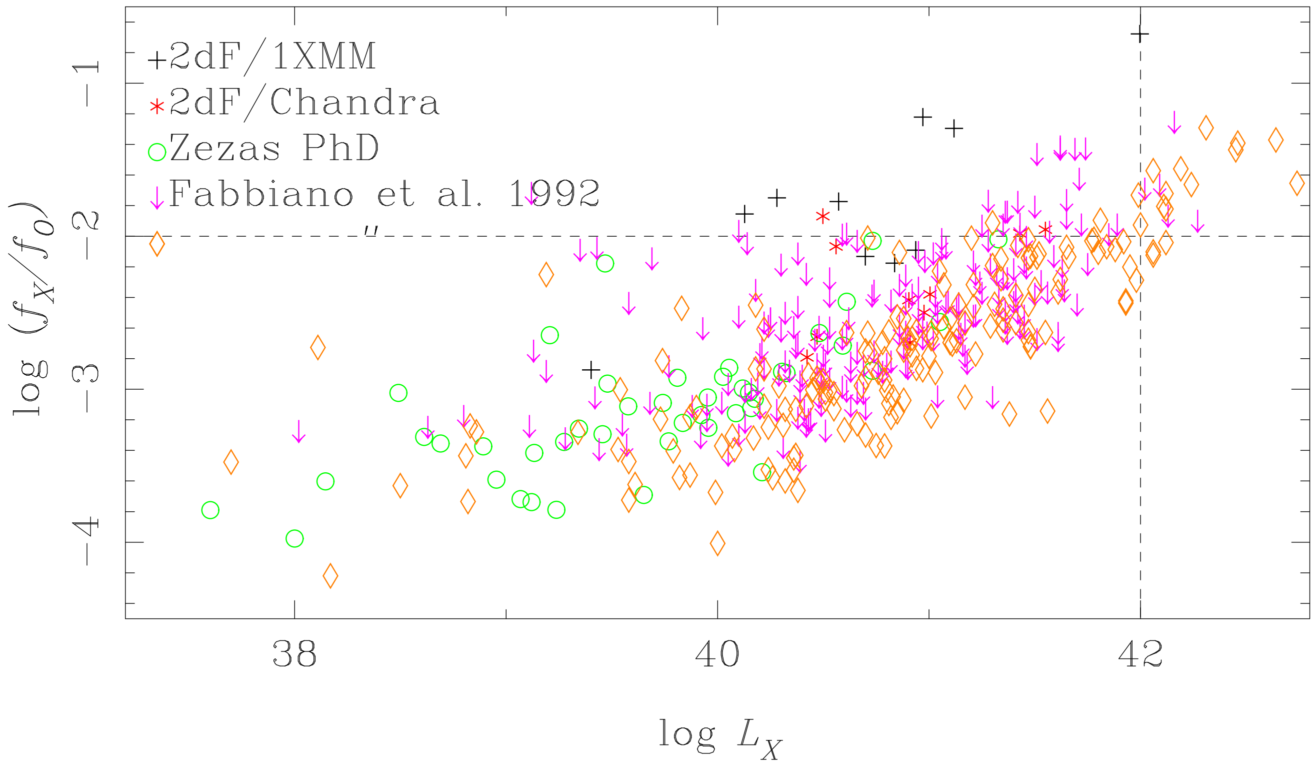


*Figure 5. Plot of* $\log f_X/f_O$ *versus* $\log L_X$*. Plotted here are values calculated from our XMM-Newton and Chandra data, as well as from the literature (see legend in the plot). For all samples only galaxies which are classified as non-AGN are plotted. The two dashed lines demarcate the regions of* $\log f_X/f_O - L_X$ *space which may be inhabited mainly either by NGs (*$\log L_X < 42$, $\log f_X/f_O < -2$*) or by AGN.*

*Table 1. NGs with* $\log f_X/f_O > -2$*. Groups of rows separated by horizontal lines correspond to the sample indicated in the first column. 2dFGRS stands for the combined correlation samples 2dFGRS–XMM-Newton and 2dFGRS–Chandra. Each row corresponds to the NG type indicated in the second column.* H II *stands for* H II *nucleus, A for absorption-line spectrum, S for spiral, E for elliptical, Irr for irregular. Each of the last three columns gives the fraction of NGs with* $\log f_X/f_O > -2$ *in the* $\log L_X$ *region indicated at the top of the column. Galaxies for which only upper limit information is available have not been taken into account. Empty entries indicate that no NGs of this type have been found.*

| Sample | NG type | $\log L_X < 42$ | $41 < \log L_X < 42$ | $\log L_X \geq 42$ |
|---|---|---|---|---|
| *2dFGRS* | H II | 4/26 | | |
| | H II? | 1/26 | | |
| | A | 2/26 | 2/10 | 1/12 |
| Zezas (2001) | any | 0 | 0 | 0 |
| Fabbiano et al. (1992) | S/H II | 1/194 | 1/75 | 1/40 |
| | Irr | 1/194 | 1/75 | |
| | E | 1/194 | 1/75 | 13/40 |

hosts in the original sample have been excluded. We have also carried out a further literature search to exclude more AGN from the final sample.

The combined samples are plotted in Figure 5. The observed correlation follows from the $L_X \sim L_B^{1.8}$ (Fabbiano et al., 1992). Results *for galaxies with* $\log f_X/f_O > -2$ are tabulated in Table 1. Note that in the Zezas (2001) sample there are no luminous or $\log f_X/f_O > -2$ galaxies, unlike the Fabbiano et al. (1992) sample. The latter sample clearly suggests that the $\log f_X/f_O < -2$ criterion selects against massive elliptical NGs. This sample and our *2dFGRS* sample also suggest some selection against star-forming NGs. However, the *2dFGRS* results are more tentative, because they are largely based on diagnostic emission-line ratios, without previous stellar template subtraction. Reliable stellar-template subtraction is not possible for *2dFGRS* fibre spectra, so the question remains open until better spectra are available.

## 5. FUTURE PROSPECTS

We are further expanding the 68-galaxy sample described above by using *Chandra*-SDSS fields, in order to reach fainter fluxes and luminosities. We are also in the process of obtaining higher-quality spectra for further assessing the effect of the $\log f_X/f_O < -2$ criterion on galaxy selection.

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