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Chandra Multi-Wavelength Project: Normal Galaxies at Intermediate Redshift

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Abstract We investigate Chandra extragalactic sources, including galaxies with narrow emission line (NELG) and absorption line galaxies (ALG), but excluding broad emission line AGNs and quasars. Based on $f_{\rm X}/f_{\rm O}$, $L_{\rm X}$, X-ray spectral hardness and optical emission line diagnostics, we have conservatively classified normal galaxies. With our ChaMP galaxy sample (extended to include 6 years of Chandra data) and additional normal galaxies found in other X-ray surveys, we discuss their $L_{\rm X}/L_{\rm B}$ evolution, $\log(N)$-$\log(S)$ relationship, off-nucleus ULXs, XBONGs, and E+A galaxies.

Key words: surveys — X-rays: galaxies

1 INTRODUCTION

To understand the formation and evolution of galaxies, it is important to study galaxies at a wide range of redshifts from the time when they form and rapidly evolve. The X-ray observations of normal galaxies at high redshifts provide valuable information that is directly related to the star formation episodes. Ghosh & White (2001) predict that the X-ray luminosity at higher z could be 10–100 times higher than that in the local galaxies.

The Chandra multiwavelength project (ChaMP), with the advantage of wide area coverage (Kim et al. 2007), allow us to investigate a well-defined galaxy sample at redshifts intermediate between distant galaxies found in the Chandra Deep Field (CDF) and the local galaxies (Kim et al. 2006). In addition to the original ChaMP sample selected from the first two years observations (AO1 and AO2), we extend the ChaMP sample up to AO6 (E-ChaMP), but limit to data with SDSS optical coverage, so that there will be no need of additional follow-up observations. The new sample is about a factor 3 larger than the original one. We also utilize normal galaxies from the deep surveys and apply X-ray properties obtained from well-studied local galaxies to address the classification, X-ray luminosity evolution and number density distribution of normal galaxies.

2 CLASSIFICATION

Our sample consists of narrow emission line galaxies (NELG) and absorption line galaxies (ALG). Broad line AGNs/QSOs (with a line width $>$ 1000 km s^{-1}) and galactic stars are excluded. To further separate

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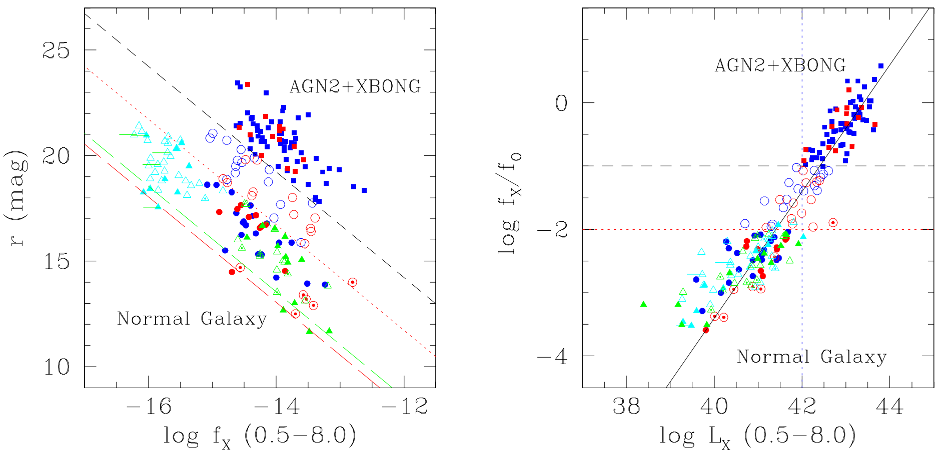

Fig. 1 (a) The optical r magnitude against f_{X} and (b) the X-ray-to-optical flux ratio ($f_{\mathrm{X}}/f_{\mathrm{O}}$) against L_{X}. NELGs and ALGs are distinguished by blue and red colors, respectively. Normal galaxies (with $f_{\mathrm{X}}/f_{\mathrm{O}} < 0.01$) and AGNs (with $f_{\mathrm{X}}/f_{\mathrm{O}} > 0.1$) are marked by filled circles and filled squares, respectively. Open circles mark those unclassified objects with intermediate $f_{\mathrm{X}}/f_{\mathrm{O}}$. Also plotted are normal galaxies identified in CDF-N (Hornschemeier et al. 2003) and XMM-Newton NHS (Georgantopoulos et al. 2005), marked by cyan and green triangles, respectively. The black dashed line and the red dotted line indicate $f_{\mathrm{X}}/f_{\mathrm{O}}$=0.1 and 0.01, respectively. The diagonal solid line in Figure 1(b) indicates the best-fit linear relation for objects with $f_{\mathrm{X}}/f_{\mathrm{O}} > 0.01$.

the obscured AGNs (Type 2 or XBONGs) from normal galaxies, we apply several diagnostics: the X-ray luminosity, X-ray-to-optical flux ratio, X-ray spectral hardness and optical line ratios. We find that $f_{\mathrm{X}}/f_{\mathrm{O}}$ is the most efficient way to distinguish normal galaxies and AGNs when applied conservatively, i.e., normal galaxy if $f_{\mathrm{X}}/f_{\mathrm{O}} < 0.01$ and AGN if $f_{\mathrm{X}}/f_{\mathrm{O}} > 0.1$ (see Fig. 1). We note that in most cases classification by $f_{\mathrm{X}}/f_{\mathrm{O}}$ also satisfies other selection criteria. For example, all galaxies with $f_{\mathrm{X}}/f_{\mathrm{O}} < 0.01$ are less luminous than $L_{\mathrm{X}} = 10^{42}$ erg s^{-1} and all AGNs with $f_{\mathrm{X}}/f_{\mathrm{O}} > 0.1$ are more luminous than $L_{\mathrm{X}} = 10^{42}$ erg s^{-1} (see Fig. 1b). However, with our conservative classification scheme, we can not classify objects with intermediate $f_{\mathrm{X}}/f_{\mathrm{O}}$. Their X-ray spectral hardness and optical line ratios indicate that these intermediate objects indeed consist of mixed types of AGNs and galaxies.

3 NORMAL GALAXIES

In Figure 1, we also plot normal galaxies identified from the Chandra Deep Field-North (CDF-N; Hornschemeier et al. 2003) and the XMM-Newton Needle in the Haystack Survey (NHS; Georgantopoulos et al. 2005). Our sample consists of galaxies at redshifts $z = 0.01 - 0.3$, intermediate between the CDF ($z = 0.1 - 1.0$) and nearby local galaxies, and covers an intermediate flux range. Our sample is similar to the NHS ($z = 0.005 - 0.2$), but extends to a slightly higher z and a fainter X-ray flux. Combining all three samples allows us to cover a wide parameter space and to increase the statistical confidence. While galaxies from three different samples are distinct in their X-ray flux ranges due to the different observation depths, they are well mixed in the $f_{\mathrm{X}}/f_{\mathrm{O}}$ - L_{X} space (or in the L_{O} - L_{X} space) with $L_{\mathrm{X}} = 10^{38} - 10^{42}$ erg s^{-1} and $\log f_{\mathrm{X}}/f_{\mathrm{O}} = -3.5 \sim -2$ (Figure 1).

While we impose a maximum $f_{\mathrm{X}}/f_{\mathrm{O}}$ ($\log f_{\mathrm{X}}/f_{\mathrm{O}} = -2$), there is no lower limit imposed in our selection. Therefore, this minimum $f_{\mathrm{X}}/f_{\mathrm{O}}$ must be real for normal galaxies and appears to remain the same in all three samples. It is interesting to note that the observed minimum $f_{\mathrm{X}}/f_{\mathrm{O}}$ is consistent with the lower limit of L_{X} - L_{B} relationship of early type galaxies (red dashed line; Kim and Fabbiano 2004) and of spirals (green dashed line; Colbert et al. 2003). Those galaxies with the minimum $f_{\mathrm{X}}/f_{\mathrm{O}}$ represent X-ray faint (LMXB-dominant, gas-poor) early type galaxies, or quiescent (non-starburst) spiral galaxies. This indicates that the X-ray emission from X-ray binary populations in our X-ray selected galaxies is similar to that expected from local normal galaxies.

As the star formation rate peaks at $z = 2-3$, the fossil record of past star formation imprinted on X-ray binaries could be detected by observing galaxies at high redshifts (e.g., Ghosh and White 2001; Ghosh in this conference). The X-ray luminosity could be 10–100 times higher than that in the local galaxies with HMXB peaking at $z = 1-2$ while LMXB at $z = 0.5-1.0$. We note that the average quantity of $f_{\rm X}/f_{\rm O}$ or $L_{\rm X}/L_{\rm O}$ as a function of z (as often used in the literature) could be seriously affected by selection effects (e.g., the upper limit of $f_{\rm X}/f_{\rm O}$) and/or AGN contamination. Instead, we test the X-ray luminosity evolution using the minimum of $f_{\rm X}/f_{\rm O}$ and $L_{\rm X}/L_{\rm O}$ as a function of z (as described in the previous section).

The combined sample is complete up to $z = 0.1$ and becomes incomplete at higher z due to the flux limit. Within this limited z range (z <0.1 or look back time of ∼1 Gyr), the minimum value of $L_{\rm X}/L_{\rm r}$ (or $f_{\rm X}/f_{\rm O}$) remains constant, indicating that no significant change in the X-ray properties of normal galaxies, hence no luminosity evolution in the X-ray binary population up to $z = 0.1$. It is critical to include galaxies at higher z ($z = 0.5-1.0$), but that will require the next generation X-ray mission such as Gen X.

In Figure 2, we plot the $\log(N)$-$\log(S)$ relation of the ChaMP normal galaxies. Our $\log(N)$-$\log(S)$ relations in the soft (0.5–2.0 keV) and broad (0.5–8.0 keV) bands appear to have the same shape, with the Euclidean slope of –1.5± 0.15 (the best-fit power-low distribution is plotted in the figure.) This is not surprising, because we are dealing with a homogeneous sample of galaxies with a relatively small amount of obscuration. This is in contrast to AGN-dominated cosmic background sources, where obscured and unobscured X-ray sources contribute differently in different energy bands (e.g., Kim et al. 2004). We also note that unlike the broken power-law distribution of cosmic background AGNs with a break at $f_{\rm X}$ (0.5–2.0 keV) = 6×10^{-15} erg cm^{-2} s^{-1} (e.g., Kim et al. 2004), the $\log(N) - \log(S)$ of normal galaxies is well reproduced by a single power-law over a wide range of $f_{\rm X}$ (see also Tajer et al. 2005). Also plotted in Figure 3 are those previously determined with the CDF sample in the S-band (Hornschemeier et al. 2003) and the NHS sample in the B-band (Georgakakis et al. 2004). It appears that our S-band $\log(N)$-$\log(S)$ can be connected to that of the CDF, if extrapolated. However, the CDF data point at the faintest $f_{\rm X}$ ($\sim 3 \times 10^{-17}$ erg s^{-1} cm^{-2}) is slightly higher than the extrapolated value and their best-fit slope, -1.74, is slightly steeper than ours. Our B-band $\log(N)$-$\log(S)$ is statistically identical to that of the NHS, except our data extend to lower fluxes with smaller error bars. Since the $\log(N)$-$\log(S)$ relation of normal galaxies is considerably steeper than that of AGN-dominated cosmic background sources (with a slope of 0.6–0.7), we determine that normal galaxies will exceed in number over the AGN population at $f_{\rm X} < 10^{-18}$ erg s^{-1} cm^{-2}. which is slightly fainter than previous estimates by Hornschemeier et al. (2003) and Bauer et al. (2004).

It is interesting to note that Hickox and Markevitch (2007) reported that the unresolved (at 1–2 keV) 20% cosmic X-ray background requires a faint-end $\log(N)$-$\log(S)$ relation steeper than that of AGNs, suggesting that normal galaxies significantly contribute to the unresolved soft X-ray background.

4 OFF-NUCLEUS ULX

Ultra luminous X-ray sources with $L_X > 2 \times 10^{39}$ erg s^{-1} (exceeding Eddington $L_{\rm X}$ of stellar mass black holes) are often found in star burst galaxies in the local universe (Fabbiano 2006) and are therefore known to be correlated with star formation rate (e.g., Gilfanov et al. 2004; Swartz et al. 2004). Because of their high luminosity, ULX can be used to probe the SFR and its evolution as a function of z. Ptak and Colbert (2004) found 12% of RC3 spirals and irregular galaxies with one or more ULX candidates. Lehmer et al. (2006) identified 24 ULX candidates from the CDF data at $z = 0.05-0.3$ and reported a suggestive increase of the ULX fraction by a factor of 1.9 from the local value (∼ 80% confidence).

Using the E-ChaMP data, we searched 2740 galaxies ($R_{25} > 20''$ and $r = 15-19$ mag and $z = 0.01-0.13$). Of these, 835 galaxies have a limiting flux corresponding to the ULX luminosity. Correcting for different detection limits in different galaxies and for contamination by cosmic background sources (mostly by AGNs), we find the fraction of galaxies with ULX candidates to be 10% within 0.5 R_{25}. The number of ULX candidates found in R between 0.5 R_{25} and R_{25} is similar to that expeced from the background sources. Our ULX fraction is similar to that in the local universe (Ptak and Colbert 2004), suggesting no change up to $z = 0.13$. We also find that the ULX fraction depends on the galaxy luminosity, being 50% higher in bigger galaxies ($M_r < -20$ mag) than in smaller ($M_r > -20$ mag) galaxies. We note that

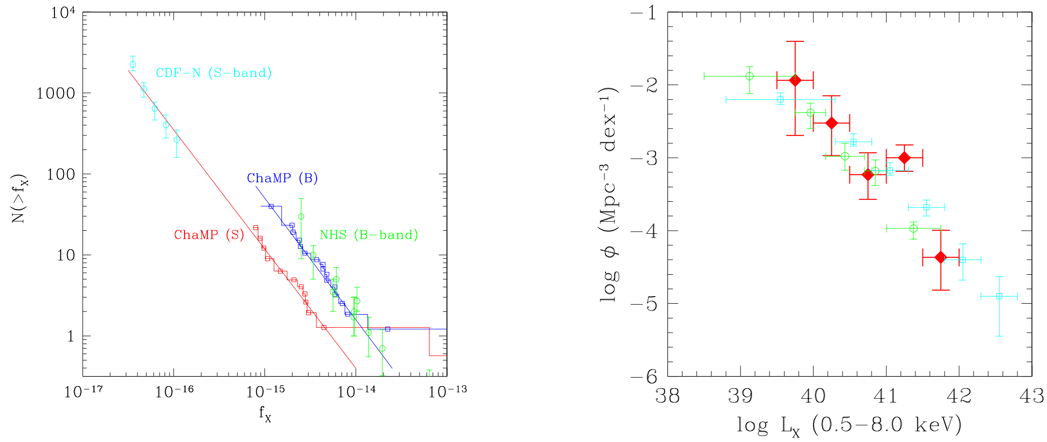

Fig. 2 (a) $\log(N)$-$\log(S)$ relation of normal galaxies determined in S (0.5–2 keV) and B (0.5–8 keV) energy bands. Also plotted for comparison are those determined with the CDF-N (Hornschemeier et al. 2003) and NHS sample (Georgantopoulos et al. 2005) (b) X-ray luminosity function of ChaMP normal galaxies (red diamonds). Also plotted are XLFs by Georgantopoulos et al. (2005; green circles) and by Norman et al. (2004; cyan squares).

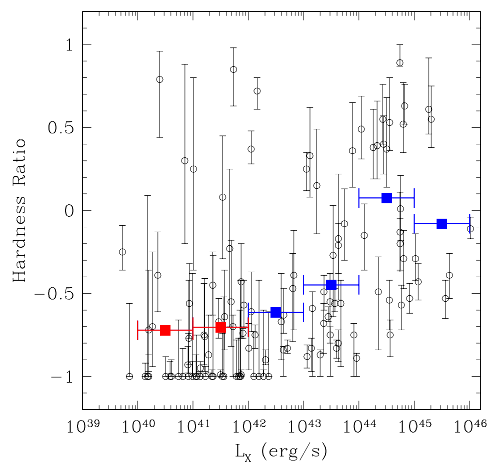

Fig. 3 Hardness ratio of absorption line galaxies (S-band from 0.5–2.0 keV and H-band from 2.0–8.0 keV). The squares indicate the average HR in each L_X bin.

the galaxy luminosity dependency must be taken into account, because bigger galaxies are preferentially selected in the higher z sample. This may partly explain the difference between ours and the CDF result.

5 XBONG

XBONG (X-ray bright, optically normal galaxies) is defined as an X-ray luminous object ($L_X > 10^{42}$ erg s^{-1}) with no obvious spectroscopic signature of AGN (ALG with no emission line). While the existence of such an unusual population has been known since the Einstein mission (Elvis et al. 1981), its nature is still not clear.

Kim et al. (2006) identified 21 XBONG candidates among the ALG sample with $L_X = 10^{42} - 5 \times 10^{43}$ erg s^{-1}. In the E-ChaMP sample, we find 66 candidates with $L_X < 10^{46}$ erg s^{-1}. As seen in the previous sample where only 2 of 21 XBONGs exhibit significant X-ray absorption, most XBONG candidates with $L_{\rm X} = 10^{42} - 10^{44}$ erg s^{-1} do not appear to be obscured (see Fig. 3). However, we find that almost half of luminous XBONGs ($L_{\rm X} > 10^{44}$ erg s^{-1}) are heavily obscured with ($N_{\rm H} > 10^{22}$ cm^{-2}), indicating that a large number of luminous XBONGs are indeed AGNs with their emission line regions hidden and that the fraction of obscured XBONGs depends on $L_{\rm X}$.

6 E+A GALAXIES

Kim et al. (2006) identified 2 E+A galaxy candidates with strong Balmer absorption lines but no [O II] emission line. Both galaxies have stronger X-ray emission for their optical flux than those of typical normal galaxies, suggesting the E+A phenomena may enhance the X-ray emission. Both galaxies are also distinct in their soft X-ray spectra. This rules our the dusty absorption hypothesis for the origin of the E+A phenomena.

We cross-correlate our E-ChaMP galaxy sample with a new E+A galaxy sample (Goto 2007) and find one more E-A candidate (CXOMP J092316.3+311431). This galaxy also shares the same properties as the above two E+A candidates in the strong X-ray luminosity and soft X-ray spectrum, confirming our previous conclusions.

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DISCUSSION

JIM BEALL: The continuity between the normal galaxies and AGN in log $f_{\rm X}/f_{\rm O}$ vs. $L_{\rm X}$ is remarkable. Can you comment on what this implies for micro-quasars and their relationships to AGN?

DONG-WOO KIM: Although it is possible that low-luminosity AGNs exist in all normal galaxies, their X-ray contribution is not significant in normal galaxies where the hot gas and LMXBs dominate their X-ray emission. While the relationship is indeed tight among AGNs (i.e., $\log f_{\rm X}/f_{\rm O} > -1$ in Figure 1), normal galaxies (i.e., $\log f_{\rm X}/f_{\rm O} < -2$) actually deviate from this simple relation with more scatter.