Searching for X-ray Luminous Starburst Galaxies

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Abstract.

The existence or otherwise of X-ray luminous star-forming galaxies has been an open question since the era of the Einstein satellite. Various authors have claimed the discovery of X-ray luminous star-forming galaxies but in many cases more careful spectroscopic studies of these objects have shown that many of them are in fact obscured AGN. In order to investigate the possibility that such a class of galaxies do exist, we have carried out a cross-correlation between optical and IRAS samples of galaxies which are known to contain large numbers of star-forming galaxies and catalogs of sources detected in X-ray surveys. The selection criteria for the optical follow-up observations was based on their X-ray and infrared (IRAS) colors and their X-ray luminosities. We note that this sample is by no means complete or uniformly selected and hence cannot be used for statistical studies, but nevertheless confirmation of the existence of such a class of objects would be an important step, and would require us to understand the physical process responsible for such powerful X-ray emission.

We have initiated an optical spectroscopic survey in order to obtain accurate spectroscopic classifications for all the objects which are claimed to be starburst galaxies. Here we present preliminary results from this survey. We have discovered a number of starburst galaxies with X-ray luminosities above $\sim 10^{41}$ erg s$^{-1}$ (for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$). We investigate possible origins for the X-ray emission in individual cases.

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1. Introduction

It has been suggested by several authors (e.g., Bookbinder et al. 1980; Griffiths & Padovani 1990; McHardy et al. 1998) that X-ray luminous ($L_X > 10^{41-42}$ erg s$^{-1}$ in the 0.5 – 2.5 keV band for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$) starburst galaxies may make a significant contribution to the extragalactic X-ray background (XRB). However there is still a considerable debate as to whether significant numbers of these objects exist (e.g., Moran et al. 1994, 1996; Wisotzki & Bade 1997). Major
contributions are known to result from unobscured AGN, and reprocessed emission from obscured AGN (Fabian et al. 1990). Moran et al. (1994) defined the lower limit for the X-ray luminosity of X-ray luminous star-forming galaxies at $10^{42}$ erg s$^{-1}$, however for our study, we will take $L_X = 10^{41}$ erg s$^{-1}$ as the lower limit. From recent X-ray studies of nearby galaxies (Read et al. 1997) the highest observed X-ray luminosity for starburst galaxies is $\sim 10^{41}$ erg s$^{-1}$; the only exception is Arp 299 which has $L_X = 5 \times 10^{41}$ erg s$^{-1}$ in the 0.5 – 2.5 keV band (Zezas et al. 1998). A luminosity of $\sim 10^{41}$ erg s$^{-1}$ is still $10^{\sim 100}$ times greater than the typical luminosity for nearby star-forming galaxies.

In recent deep ROSAT X-ray surveys (e.g., Georgantopoulos et al. 1996; McHardy et al. 1998), a population of faint soft X-ray sources ($f_X \sim 10^{-14} - 10^{-15}$ erg cm$^{-2}$ s$^{-1}$) with relatively high X-ray luminosities has been identified with narrow emission line galaxies (NELGs). The typical X-ray luminosities of these objects are about $10^{42}$ erg s$^{-1}$ or even higher. Modeling of the various classes of objects (QSOs, clusters, NELGs) which contribute to the XRB (Pearson et al. 1997; McHardy et al. 1998) has shown that depending on their evolution, NELGs may contribute up to 50% in the 0.5 – 2.0 keV range at fainter fluxes ($f_X < 10^{-15}$ erg cm$^{-2}$ s$^{-1}$). Optical spectroscopy of these objects has shown that there is a significant fraction of bona-fide starburst galaxies together with a number of objects lying on the borderline between starbursts and AGN (Griffiths et al. 1996; McHardy et al. 1998). However, there has been a poor record in the past, with many misclassified starbursts, which after a careful spectroscopic classification turned out to be AGN (e.g., Halpern et al. 1995; Moran et al. 1996). Moreover, very recently Georgantopoulos et al. (1999) using the X-ray luminosity function of nearby starbursts and AGN estimated that the contribution of star-forming galaxies to the XRB is less than $\sim 10\%$. Indeed based on recent very deep ROSAT observations of the Lockman Hole region (Hasinger et al. 1998) it has been claimed that essentially all of the XRB can explained by various types of AGN.

In order to obtain more insight into this problem and investigate the importance of the class of X-ray luminous starbursts to the XRB, we have initiated an optical spectroscopic survey of a large sample of candidate for X-ray luminous starburst galaxies. We present preliminary results from the first observing campaign and report the discovery of three galaxies belonging to this class.
Table I. The cross-correlations.

| Sample 1  | Sample 2     | Result | Chance-coincidences |
|-----------|--------------|--------|---------------------|
| Markarian | RASSBSC      | 26     | 0 ± 0               |
| Markarian | WGAcat       | 40     | 2 ± 1               |
| IRAS FSC  | RASSBSC      | 1776   | 19 ± 3              |
| IRAS FSC  | WGAcat       | 1514   | 66 ± 5              |
| Kiso      | RASSBSC      | 58     | 2 ± 1               |
| Kiso      | WGAcat       | 76     | 5 ± 1               |

2. The Sample

Our sample was selected by cross-correlating suitable optically and infrared selected lists of galaxies with a potentially high content of starburst galaxies, with the ROSAT X-ray catalogues. We have used the Markarian (Mazzarella & Balzano 1986) and Kiso-Schmidt (Takase & Miyauchi-Isobe 1984) catalogues of UV-excess galaxies and the IRAS Faint Source Catalogue (IRAS FSC, Moshir 1991). These have been cross-correlated against the ROSAT bright source catalogue (RASSBSC, Voges et al. 1996) and the WGAcat (White et al. 1995). The RASSBSC was constructed after the All Sky Survey carried-out in the first phase of the service of ROSAT. It contains 18,811 X-ray sources down to a count rate of 0.5 counts s\(^{-1}\) in the 0.1 – 2.4 keV band. However, because of the non-uniform coverage of the sky and the effective sensitivity changes due to variations in the hydrogen column density, this sample is neither uniform nor complete. The WGAcat contains all the sources detected in all the ROSAT PSPC pointed observations that became public prior to 1994 March. The WGAcat is not uniform, but it contains much fainter sources than the RASSBSC as the exposures of the pointed observations are much deeper than the snapshots used to construct the RASSBSC.

We used a search radius of 30″ which gives an association likelihood greater than 95% (the typical error radius in the WGAcat coordinates is ~ 20″). We assessed the chance coincidence probability by shifting the coordinates of one catalogue by a few degrees and cross-correlating the catalogues again (this test was done five times with different shifts to improve the statistics of the chance coincidences). The results from the cross-correlations together with the number of chance coincidences are presented in Table 1.
From the cross-correlated lists we first excluded all the Galactic objects. We found 150, 126 and 447 X-ray emitting galaxies in the Markarian, Kiso lists and the IRAS FSC respectively. In order to exclude AGNs from the IRAS FSC sample we applied a further selection criterion which uses the $L_X/L_{IR}$ ratio to distinguish between broad-line objects (Seyfert 1s and QSOs) and NLEGs (Seyfert 2s, LINERs and starbursts see Green et al. 1992). After the application of this selection criterion, this catalogue was reduced to a total of 310 entries. Finally, we excluded all the known AGNs based on classifications available in the literature. The result is a list of $\sim$ 100 potential X-ray luminous star-forming galaxies.

3. Observations and Activity Classification

We have initiated an optical spectroscopic survey of the final sample using the University of Arizona 2.3-m telescope on Kitt Peak. Observations were obtained during two observing runs in May and September 1998. Intermediate resolution optical spectra covering the wavelength range 3900–7100 Å with a resolution of 8 Å FWHM (which corresponds to $\sim$ 400 km s$^{-1}$ at 5500 Å) have been obtained for 49 galaxies from our sample. We used a slit width of 2.5" and the plate scale is 1.6"/pixel.

The data have been reduced following the standard procedures (bias subtraction, flat-fielding and cosmic ray removal). Standard stars from the list of Massey et al. (1988) were used for both removal of the atmospheric absorption features and flux calibration. One-dimensional spectra with an optimum aperture were extracted from the two-dimensional data.

We have measured line fluxes and redshifts for all the galaxies observed in the first observing run. To assess the activity class, we made use of the standard diagnostic line ratios [O III]λ5007/Hβ, [O II]λ6300/Hα, [N II]λ6584/Hα, and [S II]λλ6713,6731/Hα (e.g., Veilleux & Osterbrock 1987). Out of the 19 objects analyzed so far, we have found three X-ray luminous star-forming galaxies. These three galaxies lie well within the starburst locus of the diagnostic diagrams. The names of the X-ray luminous starburst galaxies together with their distances$^1$ are presented in Table 2. The optical line ratios and the visual extinctions derived from the Balmer decrement are also given in Table 2.

The X-ray fluxes are calculated from the point spread function (PSF) and vignetting corrected WGACat count rates. We used a Raymond & Smith (1977) thermal plasma model with a temperature $kT =

$^1$ we report the first measurement for the redshift of IRAS F16419+8213
Figure 1. Low luminosity end of the soft (0.5 – 2.5 keV) X-ray luminosity versus the Hα luminosity correlation (the two lines represent different fits to the correlation for X-ray luminosities ranging from $10^{40}$ erg s$^{-1}$ to $10^{46}$ erg s$^{-1}$, Koratkar et al. 1995) found for AGN (squares). The star symbols are our new X-ray luminous starbursts. For comparison we also plot three nearby luminous starforming galaxies (open circles).

0.8 keV, which is found to adequately describe the soft X-ray (0.5 – 2.5 keV) spectra of star-forming galaxies (Read et al. 1997). For the absorbing column density we used the Galactic from 21 cm radio observations (Stark et al. 1992).

4. Results

In Table 3 we give the Hα luminosity (corrected for extinction), the FIR luminosity (42.5 – 112.5 μm band) estimated using the expression of David et al. (1992) and the soft X-ray luminosity for the three X-ray luminous starbursts. We can obtain an estimate of the star formation rate (SFR) for massive stars ($M > 10 M_\odot$) using the calibration in terms of the Hα luminosity given in Kennicutt (1983). Somewhat surprisingly the derived SFRs are moderate, comparable to the values found for nearby starburst galaxies.

Figure 1 shows the low luminosity end of the soft X-ray versus the Hα correlation found for AGN (filled squares, Koratkar et al. 1995). We
Table II. Spectroscopic properties of the galaxies.

| Galaxy         | vel  | [N ii]/Hα | [S ii]/Hα | [O i]/Hα | [O iii]/Hβ | A_V |
|----------------|------|-----------|-----------|----------|-----------|-----|
| NGC 6013       | 4508 | 0.49      | 0.38      | 0.04     | 1.78      | 3.0 |
| IRAS F16400+3944 | 8934 | 0.35      | 0.35      | 0.05     | 0.63      | 2.6 |
| IRAS F16419+8213 | 11993 | 0.28     | 0.27      | 0.12     | 0.68      | 2.6 |

Columns (2) is the recession velocity in km s\(^{-1}\). Columns (3), (4), (5) and (6) are the observed optical line ratios. Column (7) is the visual extinction.

plot our X-ray luminous starbursts as star symbols and other nearby starbursts as open circles (Read et al. 1997; Zezas et al. 1998; Alonso-Herrero et al. 1999). It is clear that the three X-ray luminous galaxies present an excess of H\(\alpha\) emission with respect to the X-ray emission when compared with low-luminosity AGNs, but they seem to be similar to the nearby X-ray luminous starbursts. If we estimate the X-ray luminosities from the number of massive X-ray binaries (using the total number of ionizing photons obtained from the extinction-corrected H\(\alpha\) luminosity, or the FIR luminosity) we find that the observed X-ray luminosities cannot be reproduced. The estimated X-ray luminosities are low by a factor of \(\sim 10 - 100\) even if we add a contribution from a superwind (e.g., Heckman et al. 1995). This discrepancy may be due either to the presence of a highly obscured AGN component or another mechanism which makes the production of X-rays from a starburst more efficient (e.g., subsolar metallicities Griffiths & Padovani 1990).

Table III. Luminosities and SFRs for the X-ray luminous starbursts.

| Galaxy         | \(L_{H\alpha}\) \((10^{41}\text{ erg s}^{-1})\) | \(L_{\text{FIR}}\) \((10^{43}\text{ erg s}^{-1})\) | \(L_X\) \((10^{44}\text{ erg s}^{-1})\) | Total SFR \((M_\odot\text{ yr}^{-1})\) |
|----------------|---------------------------------|-----------------|-----------------|------------------|
| NGC 6013       | 2.0                            | 2.5             | 2.8             | 0.2              |
| IRAS F16400+3944 | 13.2                           | 30.4            | 1.5             | 2.0              |
| IRAS F16419+8213 | 6.6                            | 9.5             | 8.9             | 1.0              |

Column (2) is the extinction-corrected H\(\alpha\) luminosity. Column (3) is the FIR luminosity. Column (4) is the star formation rate (for stars with \(M > 10 M_\odot\)) from H\(\alpha\) luminosity. Column (5) is the 0.5 – 2.5 keV X-ray luminosity.
5. Conclusions

We present preliminary results from an on-going spectroscopic survey which has the main goal of identifying examples of X-ray luminous star-forming galaxies. Our results suggest that such galaxies DO exist in the local universe. This may have important implications for the study of the extragalactic X-ray background and for understanding the mechanisms responsible for their high X-ray luminosity. Future observations will enlarge the current sample and help answer the question first raised by Bookbinder et al. (1980) more than 15 ago years, of whether X-ray luminous starburst galaxies make a significant contribution to the XRB.

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