ISOCAM PHOTOMETRY OF NARROW-LINE X-RAY GALAXIES

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ABSTRACT

Mid-infrared photometry of the hosts of Narrow-Line X-ray Galaxies at 6$\mu$m and 12$\mu$m has been attempted with ISOCAM. No conclusive detections have been made. This implies that these are quiescent objects with little or no active star-formation. Neither X-ray binaries nor starburst-driven superwinds are consistent explanations for the X-ray emission in these objects. We conclude that these NLXGs are predominantly AGN-powered.

INTRODUCTION

The spectrum of the extragalactic X-ray background (XRB) is complex and remains poorly understood. Multiple differing populations of sources are thought to contribute to it — the spectrum differs strongly from that of local AGN in the range 2–20 keV (0.4 vs. 0.7; Boldt & Leiter 1987), suggesting that AGN may not be the dominant contribution.

The cutoff in the X-ray source counts at $\sim 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (Barcons & Fabian 1989) indicates that optically-selected quasars are not sufficient to generate all of the XRB. Several authors (e.g. Hamilton & Helfland 1987, Griffiths & Padovani 1990) have suggested a faint starburst population at moderate $z$ analogous to local IRAS-selected galaxies as a contribution to the XRB. The X-ray emission would be generated by typically $\sim 10 – 100$ massive Population I X-ray binaries (MXRB’s) per galaxy.

Narrow-Line X-ray Galaxies

Several very deep ($S_{\text{lim}} \sim 10^{-14} – 10^{-15}$ erg cm$^{-2}$ s$^{-1}$) X-ray surveys have recently been carried out (Table 1), and have discovered evidence for this X-ray luminous starburst population: narrow emission-line galaxies with X-ray luminosities 10–100 times greater than normal galaxies (Narrow-Line X-ray Galaxies, or NLXG’s).

NLXG’s have narrow (< 1000 km s$^{-1}$) emission lines of [OII], [OIII], Hα, Hβ, [NII] and [SII] in common with many late-type galaxies. The line ratios (especially [OIII]/[OII]) indicate a much higher ionisation state than in field galaxies. The [OII]$\lambda$5007 is often asymmetric to the blue (Boyle et al. 1995) indicating outflow. There is little or no reddening apparent.

Subsamples of NLXG’s appear to consist of roughly similar numbers of starburst and Seyfert galaxies,
Table 1: Selected data for ISO targets. †: Luminosity in Einstein IPC band (0.3–3.5keV). Line flux ratios measured from low-resolution (6 Å) WHT spectra. References: 1: Boyle et al. (1995a). 2: Ciliegi et al. (1995a). 3: Stocke et al. (1991). Where $B$ magnitudes were not available, $B - V = 0.3$ was assumed.

| Source         | Date obs. | $z$  | $m_B$ | $L(0.5–2keV)$ (erg s$^{-1}$) | $I(\text{[OIII]})$ | $I(\text{H}β)$ | $I(\text{[NII]})$ | $I(\text{H}α)$ | ID       | Ref. |
|----------------|-----------|------|-------|------------------------------|-------------------|----------------|----------------|-------------|---------|------|
| MS1414.8–1247  | 1997 Aug 20 | 0.198 | 19.32 | $1.3 \times 10^{44}$†        | 2.08              | 0.33          | HII            | 3           |         |      |
| CRSS1514.4+5627| 1997 Sep 1  | 0.446 | 20.69 | $3.8 \times 10^{43}$         | —                 | —             | Sy2            | 2           | 1       |      |
| CRSS1705.3+6044| 1997 Sep 3  | 0.572 | 19.29 | $4.6 \times 10^{43}$         | $> 2$             | —             | Sy2            | 2           |         |      |
| CRSS1605.6+2543| 1997 Sep 21 | 0.278 | 18.9  | $1.7 \times 10^{43}$         | 0.5               | 0.4           | HII            | 1           |         |      |
| CRSS1605.9+2554| 1997 Sep 21 | 0.151 | 20.55 | $4.4 \times 10^{42}$         | —                 | —             | ?             | 1           |         |      |
| CRSS0030.7+2616| 1997 Dec 3  | 0.246 | 18.70 | $5.9 \times 10^{42}$         | —                 | 0.78          | ?              | 1           |         |      |
| GSGP4X:48      | 1997 Dec 3  | 0.155 | 20.37 | $3.4 \times 10^{42}$         | —                 | —             |       | 4           |         |      |
| GSGP4X:91      | 1997 Dec 3  | 0.416 | 21.33 | $3.1 \times 10^{42}$         | —                 | —             |       | 4           |         |      |
| MS2338.9–1206  | 1997 Dec 13 | 0.085 | 18.99 | $9.1 \times 10^{42}$         | 3.2               | 0.19          | Sy2/HII        | 4           |         |      |
| QSF1X:36       | 1998 Jan 15 | 0.551 | 21.07 | $3.6 \times 10^{43}$         | —                 | —             |       | 4           |         |      |
| MS0423.8–1247  | 1998 Mar 19 | 0.161 | 19.76 | $8.7 \times 10^{43}$         | —                 | 0.34          | Sy2/HII        | 4           |         |      |

from the line ratio diagnostics (e.g. Filippenko & Terlevich 1992). Individual NLXGs are quite similar in other characteristics (e.g. optical and X-ray luminosities, redshift, optical line shapes). The population evolves strongly with redshift, apparently as $L_X(z) = L_X(0)(1 + z)^C$; $C = 2.5 \pm 1$ (Boyle et al. 1995a, Pearson et al. 1997), similar behaviour to that for radio galaxies and radio-loud quasars, optically-selected QSOs and X-ray selected AGN. NLXGs may contribute 15-35 per cent of the XRB, dependent on the extrapolated shape of the luminosity function and effects of metallicity.

The existence of X-ray luminous ($L_X > 10^{42}$ erg s$^{-1}$) starbursts is still controversial, however. Moran et al. (1996) find that NLXG’s in the EMSS (Stocke et al. 1991) with ambiguous classifications have faint broad wings in their Hα lines, and argue that they are intermediate-type Seyferts (1.8 or 1.9) where the broad-line emission is heavily-reddened and possibly variable. Line diagnostics of composite galaxies may be problematic. We clearly need additional constraints on the starburst/AGN nature of NLXG’s, and so we have conducted a deep imaging survey of several NLXG’s with ISO, in order to constrain their SED’s in the mid-infrared.

**OBSERVATIONS**

Our ISO targets were chosen from three deep X-ray surveys: EMSS (Stocke et al. 1991), CRSS (Boyle et al. 1995a), and the deep ROSAT survey of Griffiths et al. (1996). Subsets of the brightest X-ray targets were selected. Within the scheduling constraints of the ISO mission, 13 targets were chosen, and 11 were actually observed. Each target was observed with ISOCAM (Césarsky et al. 1996) using the LW2 (5.5–8.5μm) and LW10(8.0–15.0μm) filters. The image scale was chosen as 3″ per pixel. The observations were microscanned in a 2×2 raster, offsetting 6″ between each point. The integration time was set as 20.16 s per frame. A total of 20 frames were taken at each position to allow the detectors to stabilise, then a further 20 frames for target data. The images were processed with the CAM Interactive Analysis (CIA) software — frames were corrected for dark current, glitches in both spatial and temporal domains were searched for and removed using the Multiresolution Median Transform algorithm, transients were removed using the IAS algorithm, and the frames were flat-fielded, registered and stacked to form the final mosaics.
Table 2: Results of ISOCAM photometry of Narrow-Line X-ray Galaxies. Limits are conservative 5σ upper limits, where σ is the pixel-to-pixel RMS scatter in the ISOCAM frames. $L_{\text{IR}}$: Far-IR luminosity, calculated using Soifer et al. (1987). $SFR$: Star formation rate, extrapolated from FIR luminosity by $SFR \sim 26L_{\text{IR,11}}M_{\odot} \text{ yr}^{-1}$ (Hunter & Gallagher 1987). $L_X$(superwind): X-ray emission expected from superwind driven by starburst with observed parameters. $N_{\text{HMXRB}}$: number of HMXRB’s expected based on IR emission from OB stars.

| Source           | $S(6\mu m)$ (µJy) | $S(12\mu m)$ (µJy) | $L_{\text{IR}}$ (erg s$^{-1}$) | $SFR$ ($M_{\odot} \text{ yr}^{-1}$) | $L_X$(superwind) (erg s$^{-1}$) | $N_{\text{HMXRB}}$ |
|------------------|-------------------|-------------------|-----------------|-----------------|-----------------|----------------|
| CRSS1514.4+5627  | < 240             | < 290             | < $1.3 \times 10^{37}$ | < 0.9           | < $1.1 \times 10^{39}$ | < 2.6           |
| CRSS1605.6+2543  | < 190             | < 290             | < $5.5 \times 10^{32}$ | < 0.4           | < $5.0 \times 10^{39}$ | < 1.1           |
| CRSS1605.9+2554  | < 190             | < 260             | < $1.7 \times 10^{32}$ | < 0.1           | < $1.7 \times 10^{39}$ | < 0.3           |
| CRSS1705.3+6044  | < 220             | < 310             | < $3.7 \times 10^{33}$ | < 2.5           | < $3.0 \times 10^{40}$ | < 7.4           |
| MS1414.8-1247    | < 330             | < 770             | < $6.3 \times 10^{42}$ | < 0.4           | < $5.7 \times 10^{39}$ | < 1.3           |

RESULTS

This paper discusses only those five NLXGs for which data had been received at the time of writing. Regrettably, none of the resulting ISOCAM frames studied so far shows any statistically reliable detections. The upper limit on source detections is given by Table 1 as 5σ, where σ is the pixel-to-pixel RMS scatter in flux values. In cases of possible source detection (≥ 3σ) the temporal behaviour of the raw data was investigated, and found to be consistent with detector glitching (sudden sharp rise followed by exponential recovery).

The upper limits on integrated FIR luminosities were calculated using the method of Soifer et al. (1987), using the relations between X-ray luminosity and IR colours found by Green et al. (1992). We then followed Zezas et al. (1998) in estimating a number of the starburst properties from the overall IR luminosity, and testing whether they were consistent with the X-ray emission (Table 2).

The global star formation rate $SFR$ was determined by $SFR = 26L_{\text{IR,11}}M_{\odot} \text{ yr}^{-1}$ (Hunter et al. 1987). The NLXGs appear to be quiescent galaxies, with SFR’s < $2.5M_{\odot} \text{ yr}^{-1}$ (cf. M82: 4–9 and luminous starbursts ≥ $50M_{\odot} \text{ yr}^{-1}$). The IR luminosity was used to estimate the kinetic energy deposition rate from supernovae and stellar winds, and hence the X-ray luminosity of the gas which is associated with the starburst-driven superwind (Heckman et al. 1996). A starburst age of 10 Myr and ambient density of 1 cm$^{-3}$ was assumed. The ratio of these superwind luminosities to the observed X-ray luminosities is typically very small ($L_{X,\text{superwind}}/L_{X,\text{obs}} \sim 10^{-4}$), and we conclude that superwinds are not a viable source for the soft X-ray emission in these NLXG’s.

The typical hard X-ray luminosity of high mass X-ray binaries is $10^{37–38}$ erg s$^{-1}$. We do not have definitive hard X-ray spectral fits on these sources, but we estimate their hard X-ray luminosities to be $\sim 10^{32–43}$ erg s$^{-1}$. This translates into $10^4$ to $10^6$ HMXRBs per galaxy. This can then be compared with the number of ionising OB stars per galaxy, assuming that it is mostly these stars which heat the dust, generating the FIR luminosity. We estimate between 1500 and $3.5 \times 10^4$ per galaxy. If ~ 0.2 percent of these are massive X-ray binaries (Fabbiano et al. 1992), we obtain the (very low) numbers given in Table 2. HMXRB’s are not a viable source for the soft X-ray emission in these NLXG’s.

The presence of broad components in the Hα lines remains unclear from existing optical spectra, but from the above it seems that the most likely explanation for the X-ray emission in these sources is low-luminosity AGN activity (as in NGC 3628; Yaqoob et al. 1995).
Fig. 1: (A: Left:) Comparison of NLXGs and sources from the Extended 12-Micron Sample (Rush, Malkan & Spinoglio 1993). ROSAT 0.1–2.4 keV fluxes for 12 Micron sources taken from Rush et al. (1996). Luminosities assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$. (B: Right:) Colour-colour plots showing ratios of $B$ magnitude to 6µm and 12µm flux for one NLXG (CRSS1605.6+2543). Tracks represent colours of starbursts from GISSEL96 stellar evolution library (Bruzual & Charlot 1993).

In principle, we should be able to constrain the properties of possible starburst components by comparison of the observed limits on optical-MIR colours with synthetic stellar evolution models, such as those of Bruzual & Charlot (1993). Figure 1(B) shows a first crude attempt at this, showing optical/MIR tracks described by “instantaneous” starbursts as a function of burst age. The hatched area shows the region within the observed optical colour limits — in most cases the colours are not consistent with “old” stellar populations $t \geq 1$ Gyr.

We expect to obtain the data for the remaining ISOCAM frames shortly. Calibration of the ISO instruments is being continuously improved in post-mission analysis. Improvements in the data-processing may well allow the flux limits to be improved. Starburst models will explore a range of metallicity, and AGN contributions.

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