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SEARCH FOR STARBURSTS AMONG X-RAY–SELECTED GALAXIES: OPTICAL SPECTROSCOPY[1]

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ABSTRACT

To establish the nature of X-ray–selected galaxies and to probe the potential contribution of "starburst" galaxies to the X-ray background, we have obtained low-resolution spectra, in the range 3500–7300 Å, of the optical counterparts of 15 X-ray sources selected from the *Einstein Observatory* Extended Medium-Sensitivity Survey and Imaging Proportional Counter Source Catalog. At least three X-ray sources can be classified as starburst galaxies on the basis of line-ratio diagnostics alone. This is consistent with the number expected from recent models which predict that starburst galaxies could account for at least ~15%–20% of the extra-galactic X-ray background at 2 keV.

Subject headings: cosmic background radiation — galaxies: Seyfert — galaxies: X-rays — infrared: sources — line identifications — spectrophotometry — X-rays: general — X-rays: sources

1. INTRODUCTION

X-ray starburst galaxies have recently been proposed as possible contributors to the extragalactic X-ray background (Danese et al. 1987; Persic et al. 1989; Weedman 1990; Griffiths & Padovani 1990; Lonsdale & Harmon 1991; Green, Anderson, & Ward, 1991).[3] In particular, Griffiths & Padovani (1990) developed a model in which starburst galaxies would account for at least ~15%–20% of the X-ray background. According to this model, about six to 40 starburst galaxies (depending on galaxy evolution) should be found in the *Einstein* Extended Medium-Sensitivity Survey (EMSS; Gioia et al. 1990).

The EMSS is a large, statistically complete, flux-limited sample of X-ray sources ($F_X \gtrsim 7 \times 10^{-14}$ ergs cm^{-2} s^{-1} in the band 0.3–3.5 keV) detected serendipitously at or above 4 times the rms noise level in the *Einstein* Imaging Proportional Counter (IPC) fields of high Galactic latitude and long exposure time (Gioia et al. 1990). Nearly 95% of the sources in the EMSS are optically identified. Most of these are active galactic nuclei (AGNs; see Maccacaro et al. 1991 for a detailed study of the properties of X-ray–selected AGNs in the EMSS), and ~2% are galaxies without evidence of an active nucleus. Starburst galaxies have hardly been identified thus far in the EMSS, but several EMSS sources are associated with faint galaxies that cannot be classified unambiguously as AGNs, starburst, or normal galaxies from the optical data available (Stocke et al. 1991). To investigate the presence of starburst galaxies in the EMSS, it is therefore important to establish the nature of the non–AGN and ambiguous X-ray sources in this survey.

In this *Letter* we present the results of low-resolution spectroscopy (in the range 3500–7300 Å) performed on five optical counterparts of EMSS sources with uncertain classification. We have also included in this study a sample of extragalactic X-ray sources detected by the *Einstein* IPC, but not part of the EMSS (see § 2).

2. SAMPLE SELECTION

The sample of X-ray starburst galaxy candidates was selected from the *Einstein* EMSS and IPC Source Catalog as follows.

2.1. *EMSS Sample*

We searched the EMSS for the X-ray sources associated with galaxies with ambiguous classification (i.e., potential starbursts), whose spectral signatures were either unclear or at the borderline between AGNs and normal/starburst galaxies. This led to a total sample of about 50 X-ray galaxies, from which we selected ~40 galaxies observable from the northern hemisphere.

2.2. *IPC–IRAS Sample*

We have also examined the X-ray sources of the IPC Catalog (Harris et al. 1990) that were detected in the IPC fields at a lower signal-to-noise (S/N) level than the EMSS (S/N ≥ 3.5 instead of 4). Since starburst galaxies are expected to have high infrared luminosities, we used infrared emission as a selection criterion for the X-ray sources, i.e., we searched for X-ray starburst galaxy candidates by performing a positional cross-correlation between all the sources in the IPC Catalog and all the infrared sources in the *IRAS* Point Source Catalog (PSC). We used the data base and correlation package of the *EXOSAT* Database System (White & Giommi 1991), and, adopting a correlation radius of 1′ (where the number of real associations is maximized and the number of chance coincidences is minimized), we selected all the IPC sources with a match in the *IRAS* PSC within that distance (Fig. 1). We obtained a sample of 814 X-ray/infrared sources (~4% of these are expected by chance coincidence), of which 171 were not previously classified X-ray stars. After elimination of some other stars still remaining in the sample (recognizable from their infrared fluxes), of sources classified elsewhere as Seyfert 1 and 2 galaxies, and of sources identified with nearby galaxies brighter than 10.0 mag, our final IPC–*IRAS* sample contained 59 X-ray–selected galaxies (observable from the northern

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[3] A "starburst" galaxy is defined here as an object in which the star formation rate is larger than the value which could be maintained in equilibrium over the lifetime of the galaxy (Griffiths & Padovani 1990).

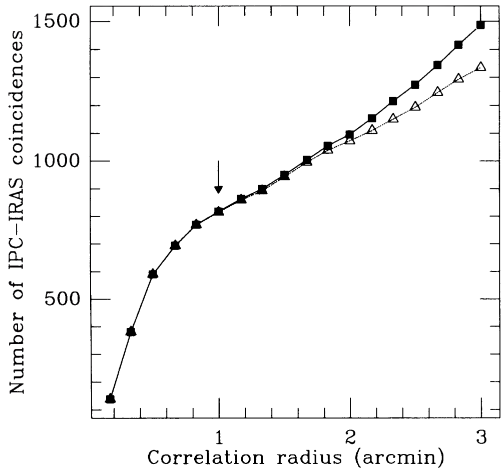

FIG. 1.—Number of positional coincidences between the 5958 IPC sources and the 244,863 *IRAS* point sources, plotted against the radius of the correlation. Filled squares indicate the number of infrared sources with at least a match in the IPC Catalog. Open triangles indicate the IPC sources with at least a match in the *IRAS* PSC. For any radius larger than $\sim 1'$, more than one infrared source is associated with each X-ray source. The arrow marks the chosen correlation radius of $1'$.

hemisphere). Only four of these also belonged to the EMSS. This is because the EMSS is made of the X-ray sources detected with high S/N in a restricted number of IPC fields (Gioia et al. 1990; see also § 1). Among the 59 sources, 27 were IPC targets (usually galaxies with peculiar properties) and were therefore eliminated from the study to avoid biases.

3. OBSERVATIONS AND DATA ANALYSIS

The observations were made during three nights in 1990 September at the Steward Observatory 2.3 m telescope with a Boller and Chivens spectrograph and a TI 800 × 800 pixel CCD. We took ~10 Å resolution spectra of 15 starburst galaxy candidates (four from the EMSS, 10 from the IPC–*IRAS* sample, and one belonging to both samples) in the interval of right ascension 17^h–8^h, north of $-20°$. We oriented the slit along the major axis of the galaxies, and we covered a spectral range of 3500–6500 Å for all the sources, plus 4300–7300 Å for eight of them. The parameters for the observed sources are presented in Table 1 as follows:

Column (1).—Source name. The prefixes MS and IPC pertain respectively to EMSS and IPC–*IRAS* sample sources.

Columns (2) and (3).—Right ascension and declination of the centroid of the X-ray source (1950.0 coordinates).

Column (4).—Soft (0.2–3.5 keV) X-ray flux in units of 10^{-13} ergs cm^{-2} s^{-1} computed from the source count rate quoted in the IPC Catalog, following the same assumptions as Gioia et al. (1990) about the spectrum of the sources. The X-ray fluxes of the EMSS sources, originally computed by Gioia et al. in the 0.3–3.5 keV band, have been recomputed in the 0.2–3.5 keV band for consistency.

Column (5).—Far-infrared flux in units of 10^{-11} ergs cm^{-2} s^{-1} computed from the definition

$$F_{IR} = 1.26 \times 10^{-14}(2.58 f_{60} + f_{100})$$

(Helou et al. 1988). A letter "L" appended to the value indicates an upper limit. The values of the infrared flux densities at 60 μm (f_{60}) and at 100 μm (f_{100}) are from the *IRAS* PSC.

Column (6).—Photographic magnitude of the source (Zwicky et al. 1961–1968). For the EMSS sources the magnitudes are from Stocke et al. (1991).

Column (7).—Other name for the optical counterpart, if previously known.

Column (8).—References to other works.

Column (9).—Classification of the optical counterpart (see § 4 below).

We reduced the data by standard procedures using IRAF packages. Figure 2 shows examples of the resulting spectra. The fluxes in selected emission lines were measured from the spectra using the IRAF task "splot," which also allows us to deconvolve blended lines such as Hα and [N II]. We estimated

TABLE 1

OBSERVED STARBURST GALAXY CANDIDATES

Name (1)	R.A. (2)	Decl. (3)	F_X[a] (4)	F_{IR}[b] (5)	m_{pg} (6)	Other Name (7)	References (8)	Classification (9)
MS 00378+2917	$00^h37^m50^s.7$	+29°17′08″	69.98	...	16.1[c]	...	1, 2	No emission lines
IPC 01072−0348......	01 07 12.0	−03 48 14	1.00	4.67L	...	...		AGN
IPC 01105+0201......	01 10 35.9	+02 01 45	1.86	3.75	15.4	UGC 00768		Ambiguous classification
MS 01291−2237	01 29 09.5	−22 37 46	7.11	...	16.5[c]	...		Broad emission lines
IPC 04001−1811......	04 00 10.4	−18 11 08	2.23	15.48	14.2[d]	ESO 549–G49		Starburst galaxy
IPC 04290+1815......	04 29 04.1	+18 15 04	1.58	10.32L	...	...		Star
IPC 05366+6921......	05 36 38.6	+69 21 18	1.73	49.26	12.2	NGC 1961	3, 4	Starburst galaxy[e]
MS 08340+6517[f]......	08 34 02.7	+65 17 38	1.72	28.15	14.2[c]	...	5, 6	Starburst galaxy
IPC 17549+6521......	17 54 58.7	+65 21 05	13.36	1.16	...	...		Broad emission lines
IPC 18101+2152......	18 10 08.4	+21 52 18	6.79	6.23	14.9	Zw 1810.1+2153		AGN
IPC 20560+2953......	20 56 05.5	+29 53 16	45.95	11.21L	...	...		Ambiguous classification
IPC 21302−0233......	21 30 12.9	−02 33 14	6.39	3.13	...	...		Broad emission lines
MS 23061−2236	23 06 09.4	−22 36 06	22.82	...	16.0[c]	...		No emission lines
MS 23486+1956	23 48 40.8	+19 56 54	6.31	...	17.1[c]	...	7	Starburst galaxy
IPC 23488+1950......	23 48 49.9	+19 50 05	5.03	107.86	13.1	NGC 7771	3, 4, 8	Starburst galaxy[e]

[a] In units of 10^{-13} ergs cm^{-2} s^{-1} in the band 0.2–3.5 keV.
[b] In units of 10^{-11} ergs cm^{-2} s^{-1}.
[c] *V* magnitude.
[d] *B* magnitude (from Lauberts 1982).
[e] Classification by Condon et al. 1991.
[f] Source in the IPC–*IRAS* sample also.

REFERENCES.—(1) de Griip, Miley & Lub 1987; (2) Hill et al. 1988; (3) Condon & Broderick 1988; (4) Condon et al. 1991; (5) Margon et al. 1988; (6) Wiklind 1989; (7) Gioia et al. 1984; (8) Kazaryan & Kazaryan 1989.

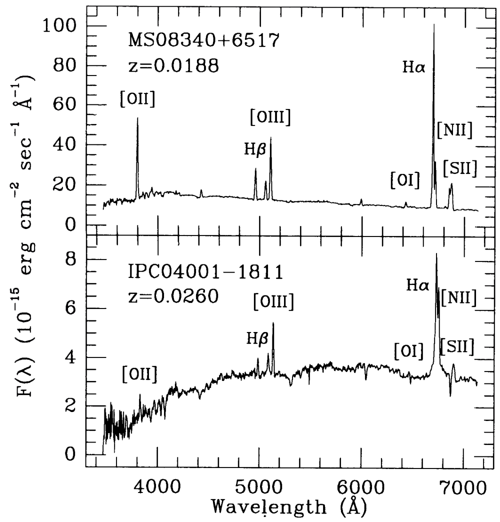

FIG. 2.—Spectra of the starburst galaxies MS 08340+6517 and IPC 04001−1811. The spectra have been wavelength- and flux-calibrated and corrected for Galactic extinction.

an average 20% uncertainty in the flux determination for all lines in all galaxies, from a mean 10% error in the flux calibration of the standard stars and by comparing repeated measurements of the same lines. We computed the redshift z of each source by measuring the centroid of a Gaussian centered on the [O III] λ5007 emission line (Table 2).

4. GALAXY CLASSIFICATION

We used the ratios of selected emission lines to classify the observed galaxies. This method, based on the relative strength of the lines, allowed us to distinguish into two broad categories of narrow-line objects: those in which the emitting gas is photoionized by a population of OB stars (as in starburst galaxies and giant H II region–like galaxies) and those in which the gas is photoionized by a nonthermal power-law continuum source (as in QSOs, Seyfert galaxies, and LINERs) (Baldwin, Phillips, & Terlevich 1981; Veilleux & Osterbrock 1987).

To classify our galaxies between these two categories, we compared the ratio of [O III] λ5007 to Hβ with the ratios of [O I] λ6300, [N II] λ6583, and [S II] λλ6716, 6731 to Hα. These ratios are reliable indicators of the nature of the ionizing radiation (Veilleux & Osterbrock 1987). In Table 2 we list the observed line ratios for the galaxies in our sample. We also indicate the values corrected for interstellar extinction in the objects. The amount of intrinsic reddening was estimated by comparing the observed Balmer decrement $I_{obs}(H\alpha)/I_{obs}(H\beta)$ to the value in the dust-free case (e.g., Osterbrock 1989), using the reddening curve parameterized by Miller & Mathews (1972).[4] Table 2 shows that the reddening corrections are so small that they do not at all affect the classification of the galaxies.

We plot in Figure 3 the reddening-corrected ratios of [N II], [S II], and [O I] to Hα against the ratio of [O III] to Hβ. The thick lines are adopted from Veilleux & Osterbrock (1987) and separate the domains of H II region galaxies and AGNs. Hence, the position of a galaxy's line ratios in these three diagrams determines whether it is more likely to be a starburst galaxy or an AGN. We obtained the following classification for the X-ray sources in the two samples.

4.1. *EMSS Sample*

Two objects (MS 08340+6517 and MS 23486+1956) can be classified as H II region–like galaxies from the line-ratio diagnostics. MS 08340+6517 (which also belongs to our IPC–*IRAS* sample) is a "normal" galaxy under the classification scheme of the EMSS, but had already been recognized as a very bright starburst nucleus by Margon et al. (1988). Our observations confirm their classification. MS 23486+1956 is listed in the EMSS with uncertain classification between a normal spiral and an AGN. No emission lines were detected from MS 23061−2236 and MS 00378+2917, while MS 01291−2237 shows broad emission lines.

4.2. *IPC–IRAS Sample*

The galaxies IPC 04001−1811 and MS 08340+6517 (see above) can be classified as H II region–like galaxies from the line-ratio diagrams. Two objects (IPC 01072−0348 and IPC 18101+2152) can be classified as AGNs, but the classification of IPC 20560+2953 remains ambiguous because the galaxy is present only in two diagrams and in two different domains. Three IPC galaxies (IPC 01105+0201, IPC 05366+6921, and IPC 23488+1950) could not be plotted in Figure 3 because either Hα or Hβ was not measured in their spectra. However, IPC 05366+6921 and IPC 23488+1950 have been classified as starburst galaxies by Condon, Frayer, & Broderick (1991) on the basis of radio and infrared data. We detected broad

[4] For objects without Hα/Hβ measurement, we adopted the mean observed Balmer decrement. Note that the Balmer decrement in the dust-free case is about 9% higher for AGNs than for H II region galaxies (Gaskell & Ferland 1984). Although this is much lower than the typical 20% uncertainty in the observed line ratios, the appropriate value was used to compute the corrected ratios in Table 2.

TABLE 2

MEASURED AND CORRECTED EMISSION-LINE RATIOS

	log ([O III]/Hβ)		log ([N II]/Hα)		log ([S II]/Hα)		log ([O I]/Hα)		
NAME	Measured	Corrected	Measured	Corrected	Measured	Corrected	Measured	Corrected	z
IPC 01072−0348......	1.16	1.14	−0.33	−0.33	−0.69	−0.70	−1.14	−1.12	0.0537
IPC 04001−1811......	0.57	0.54	−0.29	−0.29	−0.92	−0.94	−1.57	−1.54	0.0260
IPC 05366+6921......	−0.81	−0.84	...	...	...	...	...	...	0.0124
MS 08340+6517	0.30	0.27	−0.55	−0.56	−0.42	−0.44	−1.57	−1.54	0.0188
IPC 18101+2152......	0.16	0.11	−0.16	−0.16	−0.30	−0.33	−0.95	−0.90	0.0179
IPC 20560+2953......	−0.21	−0.21	−0.21	−0.21	−1.03	−1.03	...	...	0.0324
IPC 22522+1126......	...	...	0.09	0.09	−0.43	−0.44	−1.86	−1.84	0.0280
MS 23486+1956	0.47	0.44	−0.53	−0.53	−0.60	−0.62	−1.45	−1.42	0.0423
IPC 23488+1950......	−1.06	−1.09	...	...	...	...	...	...	0.0134

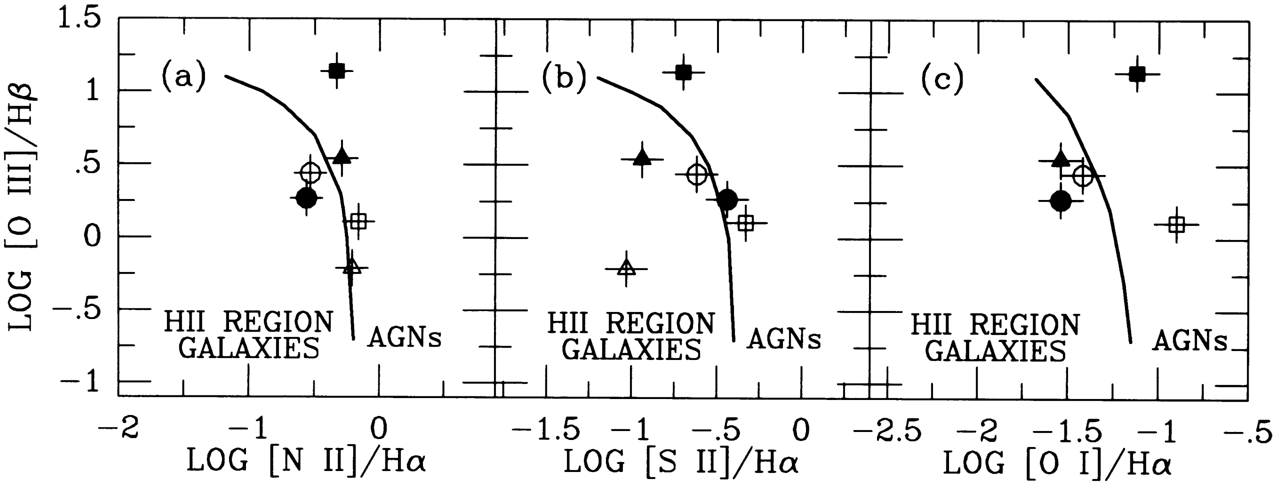

FIG. 3.—Reddening-corrected intensity ratios of [O III] λ5007/Hβ against (*a*) [N II] λ6583/Hα, (*b*) [S II] (λ6716 + λ6731)/Hα, and (*c*) [O I] λ6300/Hα. In each panel, the solid curve (adapted from Veilleux & Osterbrock 1987) divides H II region–like galaxies from AGNs. The error bars correspond to the mean 20% uncertainty in the flux measurements. The galaxies shown are MS 23486+1956 (*open circles*), MS 08340+6517 (*filled circles*), IPC 18101+2152, (*open squares*), IPC 01072−0348 (*filled squares*), IPC 20560+2953 (*open triangles*), IPC 04001−1811 (*filled triangles*).

emission lines from IPC 17549+6521 and IPC 21302−0233, while IPC 04290+1815 is a star.

5. DISCUSSION AND CONCLUSIONS

We have collected and analyzed spectroscopic data for 15 optical counterparts of X-ray sources selected from the *Einstein* EMSS and IPC Catalog (cross-correlated with the *IRAS* PSC). So far, we have classified five of them on the basis of line-ratio diagnostics.

Two EMSS X-ray sources, among the five observed, can be classified as starburst galaxies. This result is consistent with the suggestion by Griffiths & Padovani (1990) that about six to 40 starburst galaxies should be found in the entire EMSS. If present, these galaxies have to be found among the ∼50 EMSS galaxies with ambiguous classification (see § 2). We found two starburst galaxies out of five EMSS sources, i.e., in ∼10% of the total sample of X-ray starburst candidates in the EMSS. This agrees well with the approximately one to four sources expected in the same fraction of the EMSS.

We have identified two starburst galaxies (four, if we consider also the two classified by Condon et al. 1991) among the 11 IPC–*IRAS* sources observed, i.e., in ∼19% of the whole IPC–*IRAS* sample. From Figure 5 of Griffiths & Padovani, we expect to find about five to 30 starburst galaxies in the whole IPC–*IRAS* Catalog (which covers 10% of the sky) brighter than a few times 10^{-13} ergs cm^{-2} s^{-1} (i.e., the average X-ray luminosity of the IPC–*IRAS* sources in our sample). Accordingly, there should be approximately one to six starburst galaxies among 11 IPC–*IRAS* candidates. Our finding of at least two starburst galaxies is consistent with this prediction.

Our observations support the hypothesis that starburst galaxies may account for at least ∼15%–20% of the extragalactic X-ray background at 2 keV (more if there is galaxy evolution; Griffiths & Padovani 1990). However, we have observed so far only a fraction of the EMSS and IPC–*IRAS* samples of X-ray starburst candidates and are collecting additional spectra to improve the statistics and classify the remaining sources. The spectroscopic analysis of 15 more X-ray sources will be presented in a forthcoming paper (Fruscione & Griffiths 1991). Moreover, a parallel study is underway to confirm the spectroscopic identifications presented here with the help of near-infrared imaging (Griffiths et al. 1991).

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