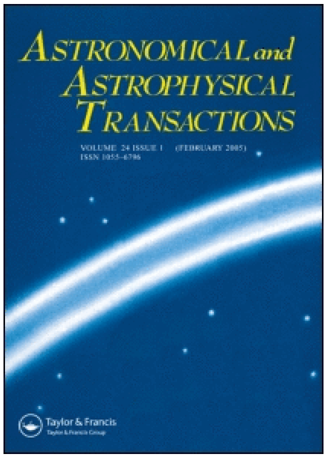

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A. L. Zezas [a]; I. Georgantopoulos [b]; M. J. Ward [a]
[a] Department of Physics and Astronomy, University of Leicester, Leicester
[b] National Observatory of Athens, Lofos Koufou, Palaia Penteli, Athens, Greece

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X-RAY LUMINOUS STAR-FORMING GALAXIES

A. L. ZEZAS[1], I. GEORGANTOPOULOS[2], and M. J. WARD[1]

[1] *Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH*
[2] *National Observatory of Athens, Lofos Koufou, Palaia Penteli, 15236, Athens, Greece*

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We present results from the cross-correlation of the spectroscopic atlas of Ho *et al.* (1995) with the *ROSAT* All-Sky Survey Bright Source Catalogue, in an attempt to understand the X-ray emission mechanisms in nearby galaxies. The resulting sample of 45 galaxies consists predominantly of AGN. However, there are several star-forming galaxies spanning a wide range of X-ray luminosities ($\sim 10^{38}$–10^{42} erg s^{-1}). We have analysed *ROSAT* and *ASCA* data for the two most luminous star-forming galaxies, namely NGC 3310 and NGC 3690. We find that their 0.1–10 keV X-ray spectra can be fitted by a soft thermal plasma of $kT \sim 0.8$ keV and a harder component with $kT \sim 10$–15 keV or a power-law with $\Gamma \sim 1.6$. These are very similar to the spectra of the archetypal star-forming galaxies NGC 253 and M 82.

KEY WORDS Galaxies: NGC 3310, NGC 3690, starburst galaxies, X-rays

1 INTRODUCTION

A large number of faint ($B < 23$) galaxies has been found in deep *ROSAT* surveys (e.g. Boyle *et al.*, 1995; Georgantopoulos *et al.*, 1996). These galaxies have high X-ray luminosities ($L_x > 10^{42}$ erg s^{-1}) and present narrow emission lines in their optical spectra. Despite the high probability of chance coincidences (i.e. field galaxies lying accidentally in the error box of the X-ray source), cross-correlations of the X-ray positions with deep optical images have proved the existence of this population at a high level of significance (e.g. Roche *et al.*, 1995; Almaini *et al.*, 1997). Schmidt *et al.* (1998) obtained Keck spectra for 50 X-ray sources in the Lockman hole. They find that the large majority of these host an AGN although some fraction of galaxies cannot be excluded.

Now, we have the opportunity to study the properties of such luminous galaxies in the local universe, using the *ROSAT* All-Sky Survey (RASS). Boller *et al.* (1992) cross-correlated the *IRAS* Point Source Catalogue with the *RASS*. Preferential spectroscopic follow-up observations of the highest X-ray luminosity objects (Moran *et* *al.*, 1997) show that the vast majority of galaxies with $L_x > 10^{42}$ erg s^{-1} are AGN. Here instead, we have carried out a cross-correlation of the sample of Ho *et al.* (1995, 1997) and the *ROSAT* All-Sky Survey Bright Source Catalogue (RASS-BSC). The spectroscopic sample of Ho *et al.* contains moderate resolution, high-signal-to-noise spectra of *all* northern galaxies with $B < 12.5$ providing a complete sample of the galactic activity in the nearby universe. The important advantage of the Ho *et al.* sample is the pre-existing, very good quality spectra which give us unambiguous classifications for all the galaxies. The RASS-BSC contains almost 18 000 sources found in the all-sky survey carried out during the first years of the *ROSAT* mission. Our aim is to understand the X-ray emission mechanisms in the nearby galaxies and to test whether a class of X-ray luminous ($L_x \sim 10^{41-42}$ erg s^{-1}) star-forming galaxies exists.

2 THE CROSS-CORRELATION

The results of the cross-correlation are presented in Table 1. There are 45 coincidences within 1 arcmin distance from the optical galaxy. On the basis of the sky density of the RASS-BSC sources, we expect less than one to be by chance. Columns 1, 2 and 3 contain the names and the coordinates of the objects; the X-ray luminosities calculated using the RASS-BSC count rates and a power-law of $\Gamma = 2$ are listed in column 4 (we use $H_0 = 65$ km s^{-1} Mpc^{-1}); finally, in column 5 we give the spectroscopic classifications from Ho *et al.* (1997). We note that the sample is by no means statistically complete, due to the non-uniform coverage of the sky in the RASS.

From Table 1 we see that the large majority of the X-ray galaxies are AGN (Seyferts but also some LINERS). However, there are seven star-forming galaxies while there is also a large fraction (six galaxies) of late-type or normal galaxies. From the seven star-forming galaxies of our sample two are well-studied dwarf star-forming galaxies (NGC 5204, NGC 4449) with X-ray luminosities of $\sim 10^{38}$–10^{39} erg s^{-1} (Della Ceca, Griffiths and Heckman, 1997). The archetypal star-forming galaxy M 82 (7.5×10^{40} erg s^{-1}) is also in our sample. An interesting finding is the presence of two star-forming galaxies with luminosities above 10^{41} erg s^{-1} reaching the luminosities of low-luminosity AGN. A peculiar object is NGC 5905 which, although it has a very high luminosity of 1.5×10^{42} erg s^{-1} in the RASS, has shown a significant decline in X-ray flux in subsequent observations (Bade *et al.*, 1996). However, its optical spectrum has no signatures of AGN activity.

3 NGC 3690 AND NGC 3310

From the starburst galaxies in this sample we present here results on the two most luminous ones, NGC 3310 and NGC 3690. Both are nearby galaxies at distances of 19.6 Mpc and 63.2 Mpc, respectively. Both galaxies appear to be in interacting

Table 1. The resulting sample

Name	*RA* ($B1950$)	*Dec* ($B1950$)	L_X $erg\ s^{-1}$	*Classification*
NGC 221	00 39 57.77	+40 35 26.0	37.7	E.T.
NGC 224	00 40 00.13	+40 59 42.7	38.6	Normal
NGC 410	01 08 12.79	+32 52 46.0	42.03	T2:
NGC 507	01 20 50.70	+32 59 45.0	42.46	Normal
NGC 598	01 31 01.67	+30 24 15.0	38.6	H
NGC 777	01 57 21.20	+31 11 22.0	42.10	Sy2/L2::
NGC 1275	03 16 29.57	+41 19 51.8	44.16	Sy 1.5
NGC 2300	07 15 45.10	+85 48 31.0	41.08	E.T.
NGC 2832	09 16 44.05	+33 57 42.0	42.52	L2::
NGC 3031	09 51 27.30	+69 18 08.3	39.84	Sy 1.5
NGC 3034	09 51 43.60	+69 55 00.0	40.88	H
NGC 3147	10 12 39.30	+73 39 02.0	41.83	Sy2
NGC 3227	10 20 46.78	+20 07 06.1	40.85	Sy1.5
NGC 3310	10 35 39.08	+53 45 42.6	40.89	H
NGC 3516	11 03 22.84	+72 50 20.2	41.65	Sy1.2
NGC 3627	11 17 38.40	+13 15 47.0	40.08	T2/S2
NGC 3690	11 25 43.24	+58 50 12.3	41.62	H
NGC 3998	11 55 20.93	+55 43 54.6	41.69	L1.9
NGC 4051	12 00 36.40	+44 48 34.8	42.01	S1.2
NGC 4125	12 05 36.30	+65 27 06.0	40.95	T2
NGC 4151	12 08 01.05	+39 41 01.8	41.11	Sy1.5
NGC 4203	12 12 33.87	+33 28 29.0	41.60	L1.9
NGC 4235	12 14 36.74	+07 28 08.9	41.44	Sy1.2
NGC 4258	12 16 29.39	+47 34 53.2	40.31	Sy1.9
NGC 4261	12 16 49.94	+06 06 06.1	41.25	L2
NGC 4291	12 18 06.00	+75 38 59.0	41.04	E.T.
NGC 4449	12 25 45.94	+44 22 16.0	39.24	H
NGC 4472	12 27 13.90	+08 16 22.0	41.24	Sy2::
NGC 4579	12 35 12.01	+12 05 34.4	41.26	Sy1.9/L1.9
NGC 4594	12 37 22.80	−11 21 00.0	40.62	L2
NGC 4636	12 40 16.60	+02 57 43.0	41.65	L1.9
NGC 4639	12 40 21.50	+13 31 52.2	40.46	Syl
NGC 4649	12 41 08.44	+11 49 34.5	41.00	E.T.
NGC 4736	12 48 31.90	+41 23 32.2	39.90	L2
NGC 5005	13 08 37.66	+37 19 29.1	40.63	L1.9
NGC 5033	13 11 09.23	+36 51 30.6	41.20	Sy1.5
NGC 5055	13 13 34.90	+42 17 34.0	39.80	T2
NGC 5204	13 27 43.80	+58 40 32.0	39.54	H
NGC 5194	13 27 45.98	+47 27 21.5	40.20	Sy2
NGC 5813	14 58 38.90	+01 53 57.0	41.83	L2:
NGC 5846	15 03 56.92	+01 47 53.1	41.72	T2:
NGC 5905	15 14 02.80	+55 42 06.0	42.18	H
NGC 5982	15 37 38.50	+59 31 03.0	41.30	L2::
NGC 6482	17 49 43.60	+23 05 00.0	42.00	T2/S2::
NGC 7331	22 34 46.66	+34 09 20.9	40.35	T2

Note. The symbols in the last column refer to the classification of Ho *et al.*: Syl–Sy2.0, Seyfert 1 to Seyfert2; L, LINER; T, Transition object; H, Starburst galaxy; E.T., Early type galaxy. The colons indicate uncertain classifications. We refer the reader to the original paper of Ho *et al.* (1997).

pairs/mergers. NGC 3690 forms an interacting pair with IC 694. Their separation is 21″ which translates to ~ 6 kpc at the assumed distance. For NGC 3310 there is also strong evidence that it is the remnant of a recent merger, according to anomalies found in its rotation curve (Mulder and van Driel, 1996), and its disturbed morphology (Ballick and Heckman, 1981). Evolutionary synthesis modelling of the optical and infrared spectra of these galaxies has shown that the age of the starburst is about 10 Myr (Pastoriza *et al.*, 1993 and Nakagawa *et al.*, 1989 for NGC 3310 and NGC 3690 respectively). In the particular case of the latter, Nakagawa *et al.* find that the two bursts have different properties, implying either different ages or different initial mass functions (IMF).

3.1 X-Ray Data Analysis

We have obtained the *ROSAT* (PSPC and HRI) and *ASCA* observations of these galaxies from the archive. After following the standard screening procedure, we extracted PSPC and *ASCA* SIS and GIS spectra along with HRI images. The HRI images show that the soft X-ray emission is extended in NGC 3310. In NGC 3690 the emission comes from three distinct components (two correspond to the nuclei of NGC 3690 and IC 694) which again appear to be spatially resolved.

Table 2. Spectral fitting results for NGC 3310 and NGC 3690

Parameter	*NGC 3310* Double temperature Raymond Smith	Raymond Smith + power-law	*NGC 3690* Double temperature Raymond Smith	Raymond Smith + power-law
kT (keV)	$0.80^{+0.07}_{-0.04}$	$0.81^{+0.09}_{-0.12}$	$0.83^{+0.03}_{-0.03}$	$0.83^{+0.02}_{-0.04}$
	$14.98^{+13.52}_{-4.88}$		$10.3^{+5.9}_{-2.4}$	
Γ		$1.44^{+0.20}_{-0.11}$		$1.56^{+0.11}_{-0.11}$
$N_H (10^{20}\ \mathrm{cm}^{-20})$	$1.37^{+0.50}_{-0.32}$	$1.74^{+0.68}_{-0.40}$	$1.60^{+0.42}_{-0.40}$	$2.42^{+0.63}_{-0.46}$
χ^2/d.o.f.	168.7/165	170.2/165	287.8/235	291.5/235

We fitted the *ROSAT* and *ASCA* spectra together. The spectral fitting results are presented in Table 2. We found that they are fitted with an optically thin thermal plasma of temperature ~ 0.8 keV and either a hot thermal plasma ($kT \sim$ 10–15 keV), or a power-law with $\Gamma \sim$ 1.5–1.6. The spectral fits for the soft band are suggestive for a thermal origin of the X-ray emission, arising from diffuse hot gas, probably associated with a galactic super-wind (Heckman *et al.*, 1996). However, the origin of the hard X-rays is still unclear as there is more than one possible mechanism which can produce the observed spectrum. A power-law spectrum can be produced either by X-ray binaries or inverse Compton scattering of the starburst infrared photons by the supernova generated relativistic electrons, while hot gas (and X-ray binaries) give a thermal plasma spectrum. These results are similar to the results found for the prototypical starburst galaxies M 82 and NGC 253 (Ptak *et al.*, 1997, Moran and Lehnert, 1997), suggesting a common X-ray emission mechanism in star-forming galaxies spanning a wide range of luminosities. Better signal-to-noise ratio and higher energy X-ray spectra but mainly high-resolution X-ray imaging are needed in order to draw any conclusions on the origin of the hard X-ray emission in these galaxies.

4 CONCLUSION

We have presented our results on the cross-correlation of the sample of Ho *et al.* (1995) with the RASS-BSC. Our intent was to search for X-ray luminous star-forming galaxies and to probe X-ray content of the nearby universe. The cross-correlation gives 45 objects within a radius of 1 arcmin. Although this sample is dominated by AGN (mainly Seyferts), there are seven star-forming galaxies spanning a large range X-ray luminosities ($\sim 10^{38}$–10^{42} erg s^{-1}) rivalling the luminosities of low-luminosity AGN. We have analysed archival observations of the two most luminous star-forming galaxies in our sample, namely NGC 3690 and NGC 3310. We find that their soft spectra are fitted by an optically thin thermal plasma of temperature ~ 0.8 keV. The hard X-ray emission can be fitted either with a high-temperature thermal plasma ($kT \sim 10$–15 keV) or a flat power-law ($\Gamma \sim 1.6$). These results are similar to those found for the prototypical starburst galaxies M 82 and NGC 253, suggesting a common X-ray emission mechanism in star-forming galaxies over a large range of luminosities. The combination of AXAF and XMM observations will shed more light on the origin of the hard X-ray emission which currently remains unknown in all star-forming galaxies.

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