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X-RAY OBSERVATIONS OF SPIRAL GALAXIES. I. INTEGRATED PROPERTIES

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ABSTRACT

Fourteen nearby normal spiral galaxies were observed with the *Einstein Observatory*. Thirteen of them were detected with (0.5–3.0 keV) $L_x \sim 10^{38}$–10^{40} ergs s^{-1}. In this paper we report the global properties of the X-ray emission from these galaxies. We find that the X-ray luminosity is correlated with both the optical (blue) and the radio (1.4 GHz) luminosities. However, the functional dependences of the two correlations differ: $l_x \propto l_B^{0.95 \pm 0.07}$, while $l_x \propto l_R^{0.60 \pm 0.10}$. A reexamination of a complete radio sample of spiral galaxies indirectly confirms the X-ray–radio functional relationship. The linear relationship between the X-ray and the optical blue luminosities suggests a relationship between the X-ray luminosity and the stellar content of spiral galaxies responsible for the blue luminosity. This suggests that most X-ray sources in our sample of spiral galaxies are relatively young systems (age $\lesssim 10^9$ yr). The X-ray–radio relationship could have an impact on the current theories of the radio emission in spiral galaxies. A comparison with the sample of peculiar blue galaxies reported by Fabbiano, Feigelson, and Zamorani in 1982 confirms the earlier result of an excess of X-ray emission in those galaxies.

Subject headings: galaxies: evolution — galaxies: structure — radio sources: galaxies — X-rays: sources

I. INTRODUCTION

Only for a handful of nearby normal spiral and irregular galaxies have X-ray data been published so far. High-resolution observations of M31 (Van Speybroeck *et al.* 1979) have shown that the X-ray emission originates from a number of discrete sources distributed throughout the plane of the galaxy, with a concentration in the central bulge and along the spiral arms. The LMC (Long, Helfand, and Grabelsky 1981) and the SMC (Seward and Mitchell 1981) also present a number of discrete fainter X-ray sources, in addition to the well-known very bright variable sources (Clark *et al.* 1978). In these two irregular galaxies a significant number of X-ray sources have been identified with supernova remnants. The galaxies M100 (Palumbo *et al.* 1981) and M33 (Long *et al.* 1981) have also been studied in X-rays. They present structure or multiple X-ray sources. All of the above galaxies have ~(0.5–4 keV) X-ray luminosities in the 10^{39}–10^{40} ergs s^{-1} range.

Although much can be learned from the detailed study of individual galaxies, the X-ray properties of normal galaxies as a class can be derived only from the observations and study of representative samples.

An X-ray survey of peculiar (mainly spiral and irregular) galaxies (Fabbiano, Feigelson, and Zamorani 1982) revealed correlations between the X-ray emission of these galaxies and both the optical (B) and the radio (1.4 GHz) emission. A tendency for galaxies with U excess to be stronger X-ray emitters was also found. These results suggested a relationship between the stellar Population I component and the integrated X-ray emission of late morphological type peculiar galaxies.

In this paper we report the results of the X-ray observations with the *Einstein* satellite of 14 nearby ($D < 30$ Mpc) field spiral and irregular galaxies. Eleven of the galaxies are Sbc or later morphological types. These galaxies were chosen because they do not typically present abnormal colors (see Fig. 1) or peculiar morphologies like those of Fabbiano, Feigelson, and Zamorani (1982). As such, they are representative of "normal" galaxies. Although this sample is quite small, it can be used to uncover relationships that might shed light on the X-ray properties of spiral and irregular normal galaxies. It will also be useful to see how their integrated X-ray properties compare with those of more "active" (in the star formation sense) peculiar galaxies.

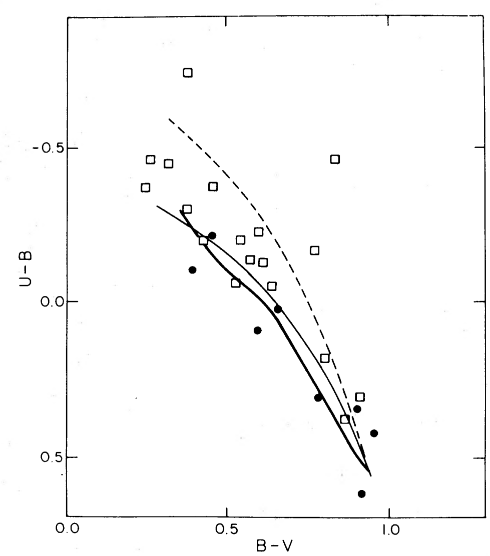

FIG. 1.—The galaxies observed in this survey for which color information is available are plotted in a color-color diagram (*dots*). We also plot the peculiar galaxies from Fabbiano, Feigelson, and Zamorani (1982) (*squares*). The lines across the diagram are from Larson and Tinsley (1978). The heavy line represents the mean colors of the Hubble Atlas sample of normal galaxies. The other solid and dashed lines correspond to models of bursts of star formation ($\tau \sim 10^7$ yr, *dashed line*; $\tau \sim 5 \times 10^8$ yr, *thin solid line*). The normal spiral galaxies discussed in this paper have colors consistent with the heavy solid line.

TABLE 1

X-Ray Data

Galaxy (1)	Right Ascension, Declination (1950) (2)	Date (year, day) (3)	Sequence Number (4)	Time (s) (5)	ΔE (keV) (6)	Radius (arcmin) (7)	Counts/ Error (8)	N_{H_2} (cm^{-2}) (9)	f_x(0.5–3.0 keV) (ergs cm^{-2} s^{-1}) (10)	D (Mpc) (11)	L_x(0.5–3.0 keV) (ergs s^{-1}) (12)
NGC 253	0h45m13, −25°33′7[a]	1979, 186–189	H583	27365	...	12.6	1242.0 / 118.3	1.7×10^{20}	3.7×10^{-12}	5.2	1.3×10^{40}
NGC 628	1 34 0s7, +15 31 55[b]	1980, 10	I7042	6603	0.3–3.1	5.1	75.0 / 16.1	6.1×10^{20}	4.1×10^{-13}	15.9	1.2×10^{40}
NGC 1313[c]	3 17.65, −66 40.7[a]	1980, 2	I7044	8164	0.2–3.2	4.2	422.3 / 28.8	3.0×10^{20}	1.5×10^{-12} (1.2×10^{-12})	4.8	3.8×10^{39} (3.0×10^{39})
IC 342	3 41 58.6, +67 56 36[b]	1980, 228–229	I7045	2130	0.5–3.3	8.9	173.0 / 22.9	1.9×10^{21}	2.8×10^{-12}	4.6	7.1×10^{39}
NGC 1559	4 17.02, −62 54.3[a]	1980, 104	I7046	7195	0.3–3.7	1.6	84.8 / 12.3	3.0×10^{20}	3.1×10^{-13}	20.5	1.5×10^{40}
NGC 2403	7 32 5.5, +65 42 40[b]	1979, 98	I589	5979	0.3–6.0	8.9	352.0[d] / 31.8	5.0×10^{20}	1.4×10^{-12}	5.2	4.6×10^{39}
NGC 2613	8 31.18, −22 48.0[a]	1981, 105–106	I10722	9259	0.5–3.1	3.6	<67.9	$\sim 1.0 \times 10^{22}$	$<4.8 \times 10^{-13}$	28.9	$<4.6 \times 10^{40}$
NGC 2903	9 29 19.9, +21 43 19[b]	1980, 137	I7049	5300	0.3–3.7	6.3	196.0 / 25.5	3.9×10^{20}	9.5×10^{-13}	9.3	9.6×10^{39}
NGC 3031 (M81)	9 51.5, +69 18.3[a]	1979, 123–270	H585	29820	...	12.8	1304.2 / 267.7	5.0×10^{20}	6.5×10^{-12}	2.0	3.2×10^{39} [e]
IC 2574	10 24 41.3, +68 40 18[b]	1980, 111	I7050	6997	0.5–4.0	6.1	92.3 / 26.9	2.8×10^{20}	3.6×10^{-13}	3.7	5.7×10^{38}
NGC 5236 (M83)	13 34.17, −29 36.8[a]	1979, 212–213	I588	7540	0.2–6.0	5.6	900.6 / 40.6	5.0×10^{20}	3.1×10^{-12}	6.7	1.6×10^{40}
NGC 5253	13 37.09, −31 23.4[a]	1980, 363	I7061	7027	0.5–4.8	2.0	35.7 / 11.5	6.1×10^{20}	1.3×10^{-13}	4.0	2.4×10^{38}
NGC 5907[f]	15 14.61, +56 30.4[a]	1980, 2	I7062	2521	0.6–3.0	3.0	23.0 / 7.7	1.7×10^{20}	2.9×10^{-13}	15.6	8.9×10^{39}
NGC 6744	19 5.03, −63 56.3[a]	1980, 270	I7063	27232	0.4–4.1	7.7	766.3 / 69.5	3.0×10^{20}	1.0×10^{-12}	10.4	1.4×10^{40}

[a] RCBG2 (de Vaucouleurs, de Vaucouleurs, and Corwin 1976).

[b] Dressel and Condon 1976.

[c] The number of counts and the derived fluxes and luminosities might be contaminated by a strong X-ray source to the south of NGC 1313. The quantities in parentheses are derived from the central point source.

[d] Background from template (see text) was used. Using the count rate from a 6′.7–8′.0 annulus, which is consistent with the value from the template, we obtain 392.2 ± 59.4 counts.

[e] Elvis and Van Speybroeck 1982 give a (0.5–4.5 keV) $L_x = 1.7 \times 10^{40}$ ergs s^{-1} for the nuclear source. This is higher than the (0.5–3.0 keV) luminosity here quoted for the entire galaxy. The discrepancy is due to the wider energy band, different spectral assumptions, and an assumed distance of 3.5 Mpc. The count rate for the nuclear source is 0.031 counts s^{-1} in Elvis and Van Speybroeck (1982), smaller indeed than we find for the entire galaxy (0.044 counts s^{-1}).

[f] Using a galaxy radius of 6′.1 (from D_{25}) we do not have a significant detection. The 3 σ upper limit on the count rate is <75.0, giving $f_x < 9.6 \times 10^{-13}$ ergs cm^{-2} s^{-1} and $L_x < 2.9 \times 10^{40}$ ergs s^{-1}.

We will study here the integrated X-ray properties of the sample. In a following paper (Fabbiano *et al.* 1984*b*, hereafter Paper II), we will discuss the distribution of the X-ray surface brightness in these galaxies.

II. X-RAY OBSERVATIONS AND RESULTS

The 14 galaxies discussed in this paper were all observed with the *Einstein Observatory* (for a description of the observatory, see Giacconi *et al.* 1979) as part of the Harvard-Smithsonian Center for Astrophysics survey. Twelve of them were observed with the Imaging Proportional Counter (IPC). Two of these were also observed at higher angular resolution with the High Resolution Imager (HRI). In this paper we will use only the IPC image for these twelve galaxies. For two galaxies, only HRI observations were available to us, and they are used in this study.

The galaxies in our sample and the results of the *Einstein* observations are listed in Table 1. Column (1) list the galaxy names; column (2) gives their right ascension and declination. Whenever possible we list the position from Dressel and Condon (1976); otherwise, we use those of the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976, hereafter RCBG2). Columns (3)–(5) give the dates of the X-ray observations, the *Einstein* sequence number, and the exposure time in the image. The HRI observations are identified by an H in front of the sequence number, and the IPC observations, by an I. The time in the image is the time during which the instrument was operative and an aspect solution was available. It excludes the portions of the orbit during which the bright Earth or the South Atlantic Anomaly were in the field of view. Moreover, since the background of sequence I7046 appeared particularly noisy, this image was analyzed using a high background rejection procedure (D. Fabricant 1982, private communication).

To improve the signal-to-noise ratios, the data from the first and last few IPC spectral channels were not included in the final image. The background level tends to be particularly high in these channels. Column (6) lists the energy band used for each of the IPC observations.

The source counts were derived after background subtraction using circular areas of diameter corresponding to the photometric diameter D_{25} of RCBG2. The galaxies in our sample are extended in angular scale over many instrument resolution elements. The X-ray emission also tends to be extended (Paper II). Particular care was therefore taken in the subtraction of the IPC background. The IPC background is not uniform over the whole $1^\circ \times 1^\circ$ field and varies as a function of the instrumental gain (D. Fabricant 1982, private communication). We therefore built a template for the background using two long IPC exposures of deep survey fields in the energy band used for the galaxy fields. This template shows that the background is basically constant within the central 10′ of the IPC fields. Since most of the galaxies are smaller in angular scale than 10′, we calculated the background locally from source-free areas surrounding the "galaxy circle." In all cases we compared a radial projection of the galaxy field with the background template to make sure of the accuracy of our background determination.

A different approach was used for the two galaxies observed with the HRI. The HRI background is fairly well defined and uniform in the instrumental plane. Therefore, we did not resort to complicated subtraction techniques. In both cases we used rectangular boxes (49 arcmin^2 for NGC 253 and 100 arcmin^2 for M81) including all of the galaxy emission. The background was calculated from a similar area in an empty part of the field.

The galaxy radii and the background subtracted counts with their statistical errors are listed in columns (7) and (8). NGC 2613 was not detected at or above the 3 σ limit. A 3 σ upper limit on the source counts is given. In the case of NGC 5907 a source was found using a 3′ circle. The detection was not significant using a circle of standard "galaxy radius," because of the inclusion of more background counts and consequent increasing of the statistical error. We list both detection and upper limit in Table 1.

The X-ray fluxes were derived using the standard *Einstein* software. Column (10) lists the X-ray fluxes in the (0.5–3.0 keV) band corrected for galactic absorption in the line of sight ($N_{\rm H}$ from Heiles 1975 are given in col. [9]) and for an assumed thermal spectrum with $kT = 10$ keV. We chose this spectrum for consistency with our earlier paper (Fabbiano, Feigelson, and Zamorani 1982). We estimate that the uncertainty in the instrumental gain and in the spectral parameters will give a systematic error of $\sim 30\%$ to the X-ray fluxes.

Column (11) lists the distances in megaparsecs. For uniformity we derived these distances from RCBG2 using an $H_0 = 50$ km s^{-1} Mpc^{-1}. The distances in Table 1 are typically within a factor of 2 or less of the estimates of Sandage and Tammann (1974*a*, *b*) for some of our galaxies. The use of the Sandage and Tammann distances will not change any of the results on the correlations that we discuss in the following section. Column (12) lists the X-ray luminosities in the (0.5–3 keV) energy range.

Thirteen of the 14 galaxies observed in this survey were detected, with X-ray fluxes ranging from 1.3×10^{-13} to 6.5×10^{-12} ergs cm^{-2} s^{-1}. The X-ray luminosities range from 2.4×10^{38} to 1.6×10^{40} ergs s^{-1}.

In Table 2 we list the logarithms of the monochromatic fluxes and luminosities at 1.4 GHz (f_R, l_R) (reference in Table 2), in the blue (f_B, l_B) (from the $B_T{}^0$ of the RCBG2) and at 2 keV (f_x, l_x) for the 14 galaxies.

We postpone any discussion of the X-ray spectral properties to a later time, when the data will be reprocessed with the final IPC calibrations. We will discuss the spatial distribution of the X-ray emission in Paper II. Here we look at the global properties of the sample galaxies.

III. THE DISTRIBUTION OF X-RAY LUMINOSITIES AND OF X-RAY/RADIO/OPTICAL FLUX RATIOS

Although our sample is not complete in any way, it can be still instructive to look at its average properties and to compare them with those of the blue peculiar galaxies in Fabbiano, Feigelson, and Zamorani (1982). The histogram of the (0.5–3.0 keV) X-ray luminosities for our sample of 14 galaxies is shown in Figure 2*a*. The distribution is peaked at $L_x \sim 10^{40}$ ergs s^{-1} but tails off down to $\sim 10^{38}$ ergs s^{-1}. The histogram of L_x for the peculiar galaxies is shown in Figure 2*b*. Although a few of these galaxies have been detected with L_x in the order of $\sim 10^{41}$ ergs s^{-1}, given the large number of upper limits, the two distributions could be consistent.

Figures 2*c* and 2*d* shows the histograms of f_x/f_B for the 14 spiral and irregular galaxies, to which we have added M31 (Van Speybroeck *et al.* 1979), and for the peculiar galaxies, respectively. The "normal" galaxies present a narrow distribution of f_x/f_B ranging from $\sim 2 \times 10^{-7}$ to $\sim 2 \times 10^{-8}$ and peaking at about $\sim 10^{-7}$. The peculiar galaxies instead can have f_x/f_B considerably in excess of 10^{-7}. Given the many

TABLE 2

X-Ray, Radio, and Optical Properties

Galaxy (1)	T^a (2)	B_T^{0a} (3)	$\log f_R$ (mJy), $\log l_R$ (ergs s^{-1} Hz^{-1}) (4)	$\log f_B$ (mJy), $\log l_B$ (ergs s^{-1} Hz^{-1}) (5)	$\log f_x$ (mJy), $\log l_x$ (ergs s^{-1} Hz^{-1}) (6)	$\log (f_x/f_B)$, $\log (f_x/f_R)$ (7)
NGC 253	5	7.40	3.75, 29.26[b]	3.69, 29.20	−3.28, 22.23	−6.96, −7.02
NGC 628	5	9.48	2.34, 28.62[b]	2.86, 29.34	−4.23, 22.25	−7.09, −6.56
NGC 1313	7	8.95	2.62, 28.06[c]	3.07, 28.51	−3.70, 21.74	−6.77, −6.32
IC 342	6	7.86	3.44, 28.85[d]	3.50, 28.91	−3.39, 22.02	−6.90, −6.83
NGC 1559	6	10.36	2.66, 29.36[c]	2.50, 29.20	−4.36, 22.34	−6.85, −7.02
NGC 2403	6	8.30	2.48, 27.99[e]	3.33, 28.84	−3.69, 21.82	−7.02, −6.16
NGC 2613	3	10.13	1.90, 28.90,[f]	2.60, 29.60	< −4.16, < 22.84	< −6.77, < −6.07
NGC 2903	4	9.05	2.60, 28.62[e]	3.03, 29.05	−3.88, 22.06	−6.92, −6.48
NGC 3031	2	7.24	2.70, 27.38[e]	3.75, 28.43	−3.03, 21.65	−6.77, −5.74
IC 2574	9	10.45	< 1.85, < 27.07[f]	2.47, 27.69	−4.31, 20.91	−6.77, > −6.16
NGC 5236	5	7.85	3.40, 29.13[b]	3.51, 29.24	−3.38, 22.35	−6.90, −6.78
NGC 5253	0	10.37	1.74, 27.04[g]	2.50, 27.78	−4.71, 20.57	−7.22, −6.45
NGC 5907	5	10.08	2.38, 28.85[h]	2.61, 29.08	−4.37, 22.10	−7.00, −6.76
NGC 6744	4	8.30	2.46, 28.57[b]	3.33, 29.44	−3.85, 22.26	−7.17, −6.31

[a] RCBG2.
[b] Mathewson and Rome 1963.
[c] Tovmassian 1966.
[d] van der Kruit 1973*b*.
[e] van der Kruit 1973*a*.
[f] Hummel 1980.
[g] Harnett 1982 (from flux at 408 MHz, with spectral index $\alpha = 0.7$).
[h] deJong 1965.

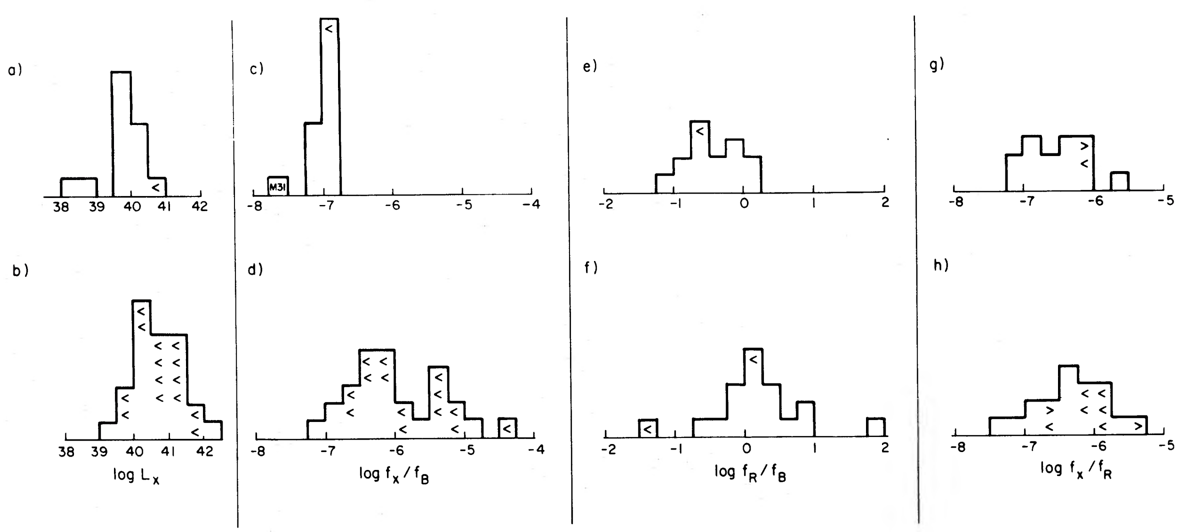

Fig. 2.—(*a*) and (*b*) Histograms of the X-ray luminosities for the 14 normal spirals here surveyed and the peculiar galaxies of Fabbiano, Feigelson, and Zamorani (1982). (*c*) and (*d*) Histograms of the X-ray to blue flux ratios f_x/f_B for normal and peculiar spiral and late-type galaxies. (*e*) and (*f*) Histograms of the X-ray to 1.4 GHz radio flux ratios f_R/f_B for normal and peculiar galaxies for which radio measurements are available. (*g*) and (*h*) Histograms of the radio to blue flux ratios f_x/f_R for normal and peculiar galaxies.

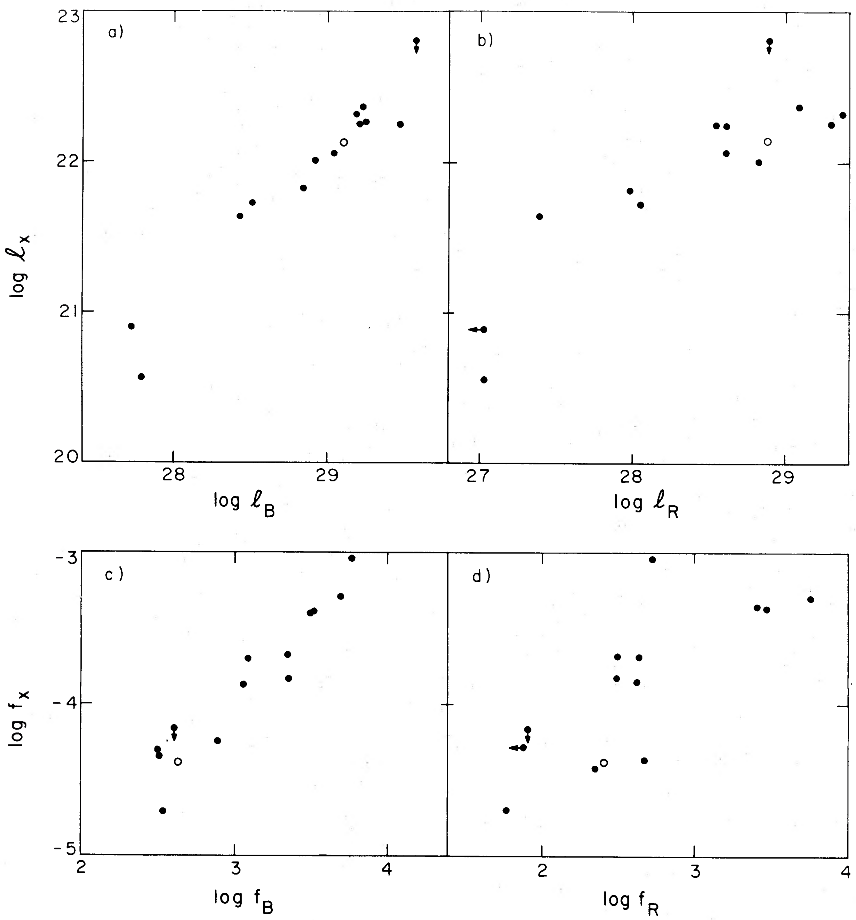

FIG. 3.—Correlations between X-ray and blue and between X-ray and radio monochromatic luminosities for the galaxies in our sample (Figs. 3*a* and 3*b*); the correlations between fluxes are shown in Figs. 3*c* and 3*d*. The empty dot identifies NGC 5907 (see text).

upper limits, also here it is difficult to quantify the differences. However, if the normal galaxies were distributed like the peculiar ones, then by scaling the number of galaxies in the two samples, we would expect between five and six "normal" galaxies to have $\log f_x/f_B > -6.75$, whereas none is detected. The "normal" galaxies thus do seem to lack high X-ray to optical ratios.

The peculiar galaxies also tend to have larger f_R/f_B than the 14 normal galaxies in our sample (Figs. 2*e* and 2*f*). This effect had been noticed and discussed previously by Biermann (1976). However, the f_x/f_R ratios are similarly distributed in the two samples (Figs. 2*g* and 2*h*).

IV. CORRELATIONS BETWEEN X-RAY EMISSION AND OTHER INTEGRATED QUANTITIES

a) l_x *versus* l_B *and* l_R

In Figures 3*a* and 3*b* we plot $\log l_x$ versus $\log l_B$ and $\log l_R$, respectively. In Figures 3*c* and 3*d* we plot the corresponding fluxes. Correlations are evident in all cases. Using the nonparametric Spearman rank correlation test (Kendall and Stuart 1976), we calculated the probabilities that the correlations might arise by chance under the null hypothesis of uncorrelated samples (Table 3). Given the presence of one radio upper limit and one X-ray upper limit in our sample of 14 spiral galaxies, we used two different approaches in the calculation of the Spearman rank coefficients. First, we ignored the one X-ray upper limit, but we used the radio upper limit as a detection. Given the position of the radio upper limit, this is a conservative approach. This gives very small probabilities that the correlations between the luminosities arise by chance. Second, we took a worst possible rank approach for the upper limits. This corresponds to treating all the upper limits as detections in the two flux/flux correlations and to treating the radio upper limit as a detection, but giving the lowest possible ranking to the X-ray upper limit in the correlations between luminosities. The probabilities that we obtain following this procedure are upper limits on the probability of chance correlation. Using this worst case approach, we can confirm that all

TABLE 3

SPEARMAN RANK CORRELATION COEFFICIENTS AND PROBABILITIES (ONE-TAILED)

Correlation	A[a]	B[b]
$\log f_x$ vs. $\log f_B$	0.95 ($<1 \times 10^{-4}$%)	0.91 ($\sim 5 \times 10^{-4}$%)
$\log f_x$ vs. $\log f_R$	0.80 ($\sim 5 \times 10^{-2}$%)	0.80 ($\sim 5 \times 10^{-2}$%)
$\log l_x$ vs. $\log l_B$	0.95 ($<1 \times 10^{-4}$%)	0.52 ($\sim$2.5%)
$\log l_x$ vs. $\log l_R$	0.83 ($\sim 2.5 \times 10^{-2}$%)	0.58 (1%)
$\log l_B$ vs. $\log l_R$	0.71 ($\sim$0.2%)	0.71 ($\sim$0.2%)

[a] Sample consisting of the 13 galaxies detected in X-rays.

[b] Worst possible ranking: the radio upper limit is treated as a detection. The X-ray upper limit is given the worst possible ranking. These give upper limits on the probability of chance correlation.

the correlations are most likely real. This is also confirmed by the parametric analysis discussed later.

Since l_x is not *a priori* dependent on the distance (the sample is not flux limited in the X-rays and we use the upper limit), the correlations between luminosities are not due to a Malmquist bias. This is also proved by the existence of correlations between the fluxes. However, it is still possible that at least one of the correlations between X-ray and optical or radio luminosities could be carried through by a correlation between the optical and the radio luminosities. A correlation between l_B and l_R has been reported for spiral galaxies (Hummel 1981). This correlation is also present within our sample (see Table 3 and Fig. 4).

To establish which correlations are dominant in our sample of galaxies, we analyzed the radio–optical–X-ray data for the sample of 13 detected galaxies simultaneously with the Spearman partial rank correlation test (Kendall and Stuart 1976; Siegel 1956; for previous applications of this method, see Tananbaum *et al.* 1983; Fabbiano *et al.* 1984).

The correlation coefficients and probabilities obtained with the Spearman partial rank correlation test are listed in Table 4. The dominant correlations appear to be those between l_x and l_R and between l_x and l_B. The correlation between l_B and l_R appears to be a by-product of the other two.

Inspection of Figure 3 shows that the relationships between l_x and l_R and between l_x and l_B could both be represented by straight lines in the log-log plots. The slopes of these two lines do however appear different.

To find the functional dependences between l_x, l_R, and l_B, we analyzed our data using the "detections and bounds" method (Avni *et al.* 1980; Avni 1984. For a previous application of this method see Fabbiano, Feigelson, and Zamorani 1982) by assuming straight line dependences between any two quantities and the points distributed with a Gaussian spread σ around this line. In this way we included the upper limit in l_x in our analysis of the correlations between l_x and l_B and between l_x and l_R. We also calculated the slope of the dependence of $\log l_R$ on $\log l_x$ to include the radio upper limit and disregard the X-ray upper limit. The slope we obtain this way is consistent with the slope we had found for the $\log l_x$ versus $\log l_R$ relationship. The slopes of the correlations between the logarithms of the luminosities are given in Table 5 together with their 1 σ errors. Table 5 confirms that all the correlations are real at a high confidence level. Essentially identical results are obtained if we use the upper limit on the X-ray luminosity of NGC 5907 instead of the detection from the 3′ circle.

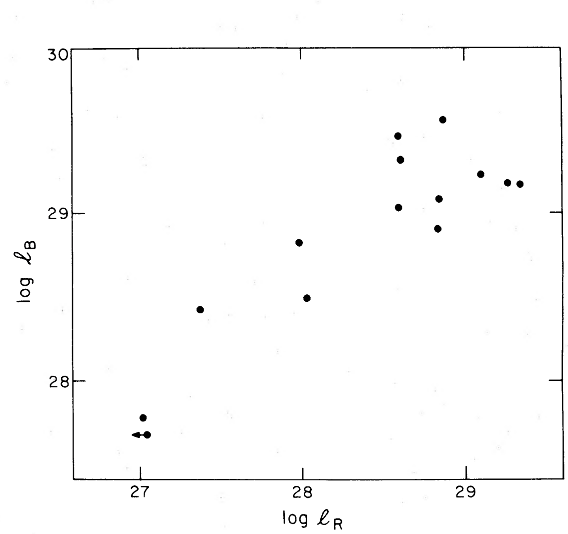

FIG. 4.—Correlation between the radio and the blue monochromatic luminosities for the galaxies in our sample.

TABLE 4

SPEARMAN PARTIAL RANK CORRELATION COEFFICIENTS AND PROBABILITIES (ONE-TAILED)

$\rho_{XB.R}$	$(P_{XB.R})$	$\rho_{XR.B}$	$(P_{XR.B})$	$\rho_{BR.X}$	$(P_{BR.X})$
0.91	$(\sim 2 \times 10^{-3}\%)$	0.72	$(\sim 0.2\%)$	-0.45[a]	$\sim 7\%$

[a] Anticorrelation.

The X-ray luminosity l_x of late spiral galaxies appears to be linearly correlated with the optical luminosity in the blue l_B. The relationship between l_x and l_R is, however, different, being a power law with exponent $\alpha \approx 0.6$. The two slopes ($X-R$ and $X-B$) are inconsistent with each other at the 2.9 σ confidence level ($P \approx 3 \times 10^{-3}$ of the two correlations having consistent slopes).

b) l_x versus l_H

We also explored a possible correlation between l_x and the monochromatic H band (1.65 μm) luminosity l_H. We found in the literature (Aaronson, Mould, and Huchra 1980; Aaronson 1977; Aaronson *et al.* 1982) H magnitudes for 11 of our 14 galaxies, and we corrected them using the growth curves of Aaronson, Huchra, and Mould (1979). We did not find any signficant correlation between the corrected H luminosities and the X-ray luminosities, although a possible trend could be hidden by the large scatter (Fig. 5). Also, no clear correlation between l_x and the $B-H$ color (which should be a mass indicator; Tully, Mould, and Aaronson 1982) was found.

c) f_x/f_B versus Morphological Type and Colors

As shown by the histogram of Figure 2*c* the X-ray to optical flux ratios of normal spiral galaxies cover a very narrow range of values. It is therefore not surprising that no trends of f_x/f_B as a function of either the morphological types or the colors of the galaxies are found in our data. Figure 6 shows the plot of f_x/f_B versus $(U-B)_T{}^0$ (from RCBG2). Plotted in the same figure are the peculiar blue galaxies of Fabbiano, Feigelson, and Zamorani (1982) for which, in contrast to normal galaxies, a trend with $(U-B)_T{}^0$ was found. The more normal spiral galaxies appear to be at the bottom of this distribution. Similarly, no trend was found between f_x/f_R and either morphological type or color.

V. THE RADIO OPTICAL CORRELATION IN A COMPLETE SAMPLE OF SPIRAL GALAXIES

As discussed in the previous section, the X-ray luminosity in the spiral galaxies of our sample is not linearly correlated with

TABLE 5

LINEAR FIT COEFFICIENTS AND DISPERSION

y[a]	x	A	B	σ
$\log l_x$	$\log l_B$	0.95 ± 0.07	-5.5	0.15
$\log l_x$	$\log l_R$	0.60 ± 0.10	4.9	0.25
$\log l_R$	$\log l_B$	1.30 ± 0.17	-9.1	0.35
$\log l_R$	$\log l_x$	1.40 ± 0.20	-2.3	0.35

[a] $y = \mathrm{A}x + \mathrm{B}$ with a dispersion σ around the straight line.

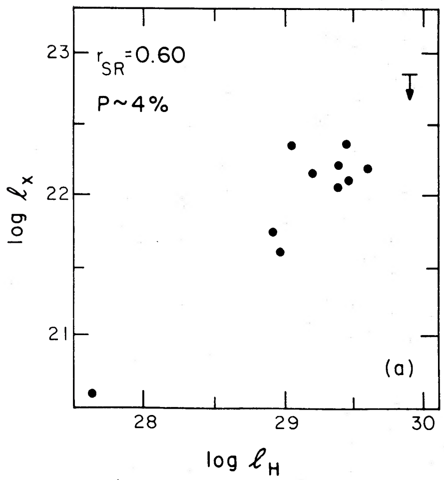

FIG. 5.—Log l_x versus log l_H, the integrated luminosity in the H band (Aaronson, Huchra, and Mould 1979).

the total radio power at 1.4 GHz, but follows the relationship $l_x \propto l_R^{0.6}$. Supporting evidence for this result can be obtained from a reanalysis of a complete radio and optical sample of galaxies: If $l_x \propto l_R^{0.6}$ and $l_x \propto l_B^{\sim 1.0}$, then we would expect that $l_R \propto l_B^{\sim 1.6}$. A correlation in this sense is seen in our sample. However, this is in contrast with the findings of Hummel (1980) who reported a linear correlation between l_R and l_B, in spiral galaxies.

In an attempt to settle the question of the slope of the log l_R, log l_B correlation, we reanalyzed the complete radio and optical sample of galaxies of Gioia and Gregorini (1980). This sample comprises 91 spiral galaxies with $m_{ph} \leq 12$ and $+20° < \delta < +60°$. All these galaxies were observed at 408 MHz with the Bologna radio telescope. Given the fairly universal slope of the nonthermal radio continuum spectrum of normal galaxies (see Gioia, Gregorini, and Klein 1982), a sample measured at 408 MHz can be directly compared with a sample at any other radio continuum frequency below ~2000 MHz, where the thermal radio emission might flatten the spectrum. Since the radio data include a significant number of upper limits, we analyzed the relationship between radio and blue luminosities using the "detection and bounds" method, as explained in § IV. Using the entire sample, we find $l_R \propto l_B^{1.12 \pm 0.17}$ with a dispersion $\sigma \approx 0.8$ in the log l_R, where the error on the slope is a 68% error. This result, although it might suggest a slope steeper than unity, is essentially consistent with the linear relationship found by Hummel (1980). However, as remarked previously in this paper, our sample of galaxies observed in X-rays is composed mainly of late-type spirals.

If we now divide the Gioia and Gregorini sample into two subsamples, one consiststing of galaxies later than Sbc ($T > 4$; Fig. 7*b*), and the other one consisting of the complementary sample (Fig, 7*a*), we find something different. While the early sample appears to be very weakly correlated or noncorrelated ($l_R \propto l_B^{0.6 \pm 0.2}$), the late galaxy sample is fitted by $l_R \propto l_B^{1.6 \pm 0.25}$. This is in the direction suggested by our data. In both cases the dispersion is $\sigma = 0.60$ in the log l_R. The two exponents are not consistent with each other at the 3.1 σ level. Different relationships between the radio and optical luminosities of early- and late-type spiral galaxies had also been suggested by Gavazzi and Trinchieri (1981). These authors, however, did not find any explicit functional dependences.

VI. DISCUSSION

a) The Integrated X-ray Properties of Normal Late-Type Spiral Galaxies

Our sample is a small sample of spiral galaxies (at least if we exclude NGC 5253 which could be classified as a non-Magellanic irregular). Eleven out of the 14 galaxies have morphological type $T \geq 4$, i.e., they are Sbc or later type galaxies. Nine of these are Sc or later types ($T > 4$). These galaxies have regular morphologies and colors and as such can be considered representative of normal late-type spiral galaxies. Even if there are no obvious biases in the selection, the sample is certainly small. Therefore our results should be considered as indicative and must await future confirmation when a significantly larger sample of normal spiral galaxies will be available in X-rays. As pointed out in § II, the X-ray fluxes presented in this paper refer to the X-ray emission integrated over the entire galaxies. Since most of the galaxies are large in angular extent, their X-ray emission can be at least partially resolved with the instruments on the *Einstein* satellite. This X-ray emission appears definitely extended and complex (Paper II).

The (0.5–3.0 keV) X-ray luminosities of our spiral galaxies range from $\sim 10^{38}$ to $\sim 10^{40}$ ergs s^{-1}. These luminosities are sufficiently low as not to pose major difficulties in explaining them with a collection of X-ray sources like those resolved in the Milky Way and in Local Group galaxies, such as M31 and the Magellanic Clouds. If most of the X-ray emission is due to bright accretion binary X-ray sources, will $L_x \approx 10^{37}$ ergs s^{-1}, 10–1000 of these sources are required.

A fraction of the X-ray emission can also be associated with the nuclear region. In M81, a Seyfert-like nuclear source is present (Elvis and Van Speybroeck 1982), which accounts for about two-thirds of the total X-ray emission. None of our other galaxies is likely to have such a bright pointlike nuclear source, although a few have been reported to have starburst nuclei. Such are NGC 253 (Wynn-Williams *et al.* 1979), IC 342 (Becklin *et al.* 1980), NGC 2903 (Alloin 1973), and M83 (Bohlin

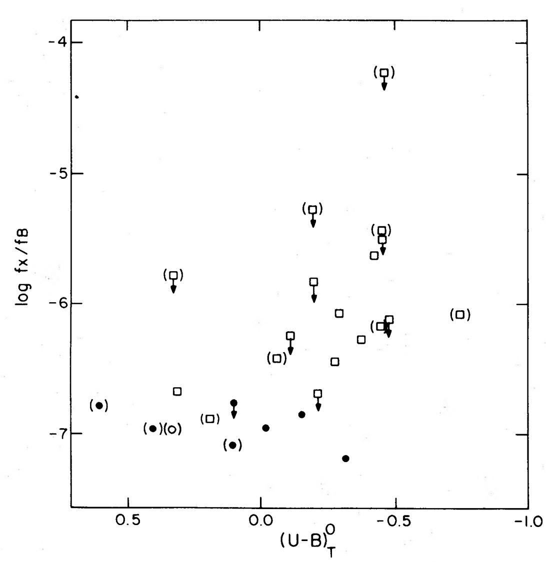

FIG. 6.—The log of X-ray to blue flux ratios (f_x/f_B) are plotted versus the $(U-B)_T{}^0$ color. The squares identify the peculiar galaxies of Fabbiano, Feigelson, and Zamorani (1982). The dots and squares enclosed in parentheses are those for which the corrected colors $(U-B)_T{}^0$ were not available. In these cases we used $U-B$ from RCBG2. The empty dot identifies NGC 5907.

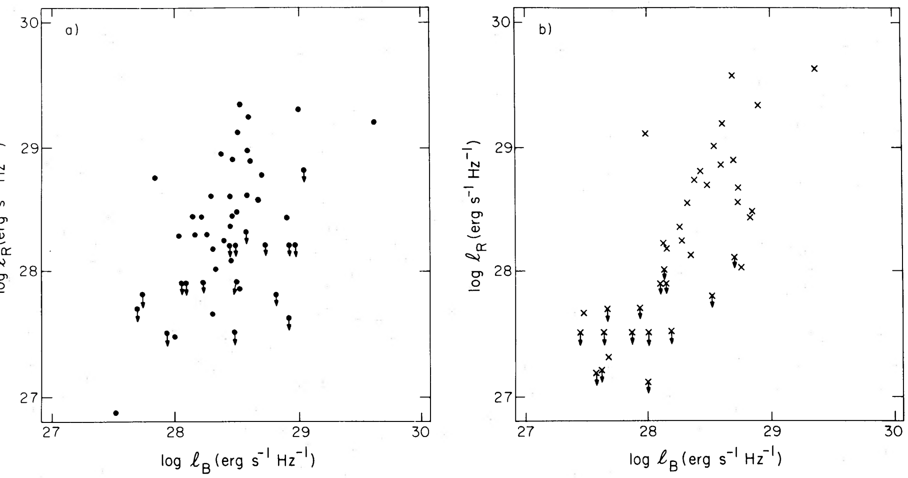

FIG. 7.—(*a*) Log l_R at 408 MHz versus log l_B for the early spirals of Gioia and Gregorini (1980). (*b*) The same plot but for the late spirals (later than Sbc).

et al. 1984). The central nuclear X-ray sources, at least in the case of NGC 253 and M83, for which HRI high resolution data exist (Fabbiano and Trinchieri 1984; Trinchieri, Fabbiano, and Palumbo 1984) and possibly also IC 342 (Paper II), appear extended. The X-ray luminosities of these sources are typically smaller than the total luminosity of the whole galaxy. It is therefore not surprising that normal spiral galaxies with a starburst nuclear region do not differentiate themselves from the general trends in the correlations between l_x, l_B, and l_R. Only galaxies for which the starburst activity is far more widespread, as for the peculiar galaxies in the sample of Fabbiano, Feigelson, and Zamorani (1982), present a noticeable increase in the X-ray emission.

b) The X-Ray/Optical Correlation

The monochromatic X-ray luminosity l_x is linearly correlated with the optical luminosity in the blue l_B. No strong correlation was found between l_x and the luminosity in the *H* band l_H. The blue luminosity l_B measures the Population I stellar component and is not proportional to the mass of spiral galaxies, which might be represented better by l_H (Aaronson, Huchra, and Mould 1979). The linear correlation found between l_x and l_B therefore suggests that the number of X-ray sources in spiral galaxies, or equivalently the X-ray source production rate (given the fairly short lifetimes; see van den Heuvel 1980), is not proportional to the mass of the galaxies, but is strictly connected with the Population I component.

Two classes of X-ray sources have been found in the Milky Way, responsible in similar amounts for the bulk of the X-ray emission (e.g., van den Heuvel 1980 and references therein; Fabian 1980 and references therein). "Type I" sources are typically bright X-ray pulsars in binary systems with bright early-type massive companions. These sources tend to be associated with the spiral arms and are generally believed to belong to the Population I stellar component. "Type II" sources are generally believed to be binary systems composed of a neutron star and of a low mass companion (see, e.g., Rappaport, Joss, and Webbink 1982). They tend to concentrate in the bulge and around the galactic center. A first suggestion (van den Heuvel 1980), that they could be capture binaries, was shown to be unlikely by a subsequent statistical study (Lightman and Grindlay 1982), given the typical stellar densities of galactic bulges. These authors advanced the hypothesis of remnants of disrupted globular clusters (see also Long and Van Speybroeck 1983).

We can expect that the integrated luminosity of the "type I" X-ray sources should be strictly linked with the luminosity in the blue band. We would expect that the integrated luminosity of "type II" sources should be correlated with the mass of the galaxy (or the *H* band luminosity), if they are Population II objects. Since our sample contains mainly spiral galaxies of morphological parameter $T > 4$ (Sc and later types), Population I X-ray sources could contribute most of the X-ray emission. This could explain the good linear correlation of l_x with l_B. On the other hand, 30% of the sample (four galaxies) are Sbc or earlier types. These galaxies follow closely the general correlations. The Milky Way itself is most likely an Sc galaxy (Hodge 1984). We could assume, then, that the sample is representative of the X-ray properties of all spiral galaxies and contains both kinds of X-ray sources. In this case the majority of "type II" sources could be related to the younger stellar component. Models for "type II" sources have been proposed, in which a wide binary system, composed of a neutron star and a low-mass main-sequence star, evolves into a close X-ray emitting binary system. The time scale for the main sequence secondary to spiral close to the neutron star is a few 10^9 yr (Rappaport, Joss, and Webbink 1982; Patterson 1984). If such a system is a native binary system, composed of a massive fast evolving star and of a less massive companion, and it survives the supernova explosion of the primary, it could belong to the same generation of stars that now contribute most of the blue light.

c) The X-Ray/Radio Correlation

Our results of §§ IV and V indicate that the radio luminosity of late-type spiral galaxies increases more rapidly than the X-ray luminosity with the increasing X-ray (and optical) luminosity of the galaxies.

By analogy with the Milky Way and Local Group galaxies (Bradt and McClintock 1983; Long, Helfand, and Grabelsky 1981; Van Speybroeck *et al.* 1979), we can expect that most of the X-ray emission originates from binary X-ray sources. According to the current theoretical scenarios of X-ray source formation (van den Heuvel 1980), the number of young Population I ("type I") binary X-ray sources should be proportional to the supernova rate. As discussed earlier in this paper, the number of the "type II" binaries could also be proportional to the supernova rate. If the radio emission is due only to the young Population I component (as suggested first by Lequeux 1971; see also Biermann 1976, Klein 1982, and Kennicutt 1983), we would than expect a linear relationship between l_x and l_R. A Population II component of the X-ray emission composed of capture binaries or stripped globular clusters (van den Heuvel 1980; Lightman and Grindlay 1982) could at the most only add scatter to the correlation.

A component decoupled from recent star formation could be present in the radio emission of spiral galaxies, as suggested by van der Kruit, Allen, and Rots (1977) and Hummel (1981). The $l_x \propto l_R^{0.6}$ relationship implies that this component, if present, should be more pronounced in optically brighter galaxies. In this hypothesis, however, it would be hard to understand our results on the Gioia and Gregorini sample, which suggest an excess of radio emission *only* in bright late-type spirals and not in the early-type spirals with prominent Population II bulges, and relatively less affected by recent star formation.

Alternatively, the $l_x \propto l_R^{0.6}$ relationship could indicate a functional relationship between the magnetic field and the luminosity (and therefore the mass) of spiral galaxies. This possibility is also supported by the analysis of the radio data of a small sample of spiral galaxies, that suggests the presence of stronger magnetic fields in more luminous galaxies (Beck 1983).

d) *Comparison with Peculiar Galaxies*

Fabbiano, Feigelson, and Zamorani (1982) studied the X-ray properties of a sample of peculiar galaxies, composed mainly of spiral and irregular galaxies. These galaxies are characterized by disturbed morphologies. They also tend to have U color excesses and frequently radio emission excesses (Biermann 1976) when compared to normal spirals such as those discussed in the present paper (see Fig. 1). This has led various authors (Huchra 1977; Larson and Tinsley 1978; Biermann and Fricke 1977) to suggest that they are the sites of recent, violent, bursts of star formation.

The X-ray survey of peculiar galaxies found correlations between the X-ray luminosity and both the blue and radio luminosities. These correlations persist in the normal late-type spiral galaxies. In the peculiar sample, however, the correlation between the X-ray and the blue luminosity presented a larger scatter than the one reported in this paper. This is mainly due to the spread in the distribution of L_x for peculiar galaxies (Fig. 2). The peculiar galaxy data show increased X-ray emission up to a factor of 10–100 higher than for the normal spirals.

The radio emission also increases by similar factors, as shown by the histograms of Figure 2. In particular the f_x/f_R ratios are the same in normal and peculiar galaxies (Figs. 2*g* and 2*h*), while f_x/f_B (and f_R/f_B) tend to increase (Figs. 2*c*–2*f*). Higher f_x/f_B ratios are observed in galaxies with bluer colors (Fig. 5 and Fabbiano, Feigelson, and Zamorani 1982). A similar behavior has been noticed for the f_R/f_B ratio (Biermann 1976). The above supports the suggestion that the X-ray properties of the peculiar galaxies are related to their excess of Population I sources (Fabbiano, Feigelson, and Zamorani 1982; Fabbiano and Panagia 1983). A burst of star formation will modify the colors of a galaxy (Larson and Tinsley 1978), but it may not affect dramatically its optical luminosity that could still be dominated by the older stellar population. A large increase in short-lived bright X-ray sources and supernova remnants as a result of the evolution of massive newly formed stars will, however, change the X-ray and radio luminosities.

The ratios f_x/f_R are similarly distributed, although with a substantial scatter, in the normal and in the peculiar galaxies (Fig. 2). This might suggest a similar nature of the X-ray and radio emission in both kinds of galaxies and indicate a preponderance of the Population I component in the X-ray and radio emission of normal late-type spiral galaxies.

VII. CONCLUSIONS

The results of this paper can be summarized as follows:

1. The X-ray survey of a sample of 14 spiral and irregular normal galaxies, 11 of which are of late morphological type, led to the detection of 13 of them with total (0.5–3.0 keV) X-ray luminosities between 2.4×10^{38} and 1.6×10^{40} ergs s^{-1}.

2. The X-ray luminosity is correlated with both the optical and the radio continuum luminosities. However, the two correlations follow different functional dependences: $l_x \propto l_B^{0.95 \pm 0.07}$ and $l_x \propto l_R^{0.60 \pm 0.10}$. A less steep slope in the X-ray/radio correlation is indirectly confirmed by the reanalysis of the complete radio sample of spiral galaxies of Gioia and Gregorini (1980). A simultaneous analysis of the correlations between l_x, l_B, and l_R with the Spearman partial rank correlation test, suggests that the $R-B$ correlation could be a consequence of the $X-B$ and $X-R$ correlations. No correlations were found between l_x and both the H band luminosity and the $B-H$ color.

3. No correlations were found between f_x/f_B and both the morphological parameter T and the color index $(U-B)_T{}^0$. A similar null result was found for the ratio f_x/f_R.

4. A comparison with the sample of peculiar galaxies studied by Fabbiano, Feigelson, and Zamorani (1982) shows that normal galaxies tend to have smaller f_x/f_B and f_R/f_B ratios, while the f_x/f_R ratios are the same.

The above results show a close connection between the X-ray source production rate and the total optical luminosity of normal spiral galaxies. The X-ray luminosity, however, does not seem to be directly correlated with the mass of the galaxies (as represented by the H band luminosity or the $B-H$ color), but with the blue luminosity. This suggests that even the "type II" component of the X-ray luminosity might not be constituted by very old systems. If the "type II" X-ray sources are native binary systems (not capture binaries), their estimated age is $\sim$a few 10^9 yr, consistent with the age of the bulk of the blue-emitting main-sequence stars.

Our results also open new and interesting questions on the nature of the radio emission in spiral galaxies and its relationship to the supernova rate and the galactic magnetic fields. Clearly, more extensive X-ray and radio studies are needed to compare spiral galaxies of different morphological type and to compare spiral and elliptical galaxies. These issues will be addressed in a forthcoming paper (Trinchieri and Fabbiano 1984). Also detailed high-resolution studies of a large number of individual galaxies are needed to compare the X-ray source distribution with multicolor optical photometry.

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