THE ASTROPHYSICAL JOURNAL, **256**:397–409, 1982 May 15

X-RAY OBSERVATIONS OF PECULIAR GALAXIES WITH THE *EINSTEIN OBSERVATORY*

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Received 1981 May 1; accepted 1981 November 25

ABSTRACT

We report the results of an X-ray survey with the *Einstein* Observatory of 33 galaxies, mostly spiral and irregular. They are chosen to have peculiar morphologies, colors, and in some cases, emission-line spectra. Thirteen galaxies were detected with (0.5–3 keV) X-ray luminosities ranging between 10^{39} and 10^{42} ergs s^{-1}. In some cases, extended or multiple emission regions were detected. The X-ray and optical fluxes and luminosities appear correlated. An even stronger correlation is found between X-ray and radio fluxes and luminosities. The X-ray to optical flux ratios (f_x/f_B) for most of these galaxies are substantially higher than that of M31 but still significantly lower than those of the Seyfert galaxies. There is also a correlation between f_x/f_B and increasingly blue colors, but not morphological type.

We discuss several possible origins of the X-ray emission in the light of our results. We conclude that Seyfert-like nuclear emission is not the dominant mechanism of X-ray production. Comparing our results with those of the X-ray observations of our Galaxy and of the Magellanic Clouds, we find that the X-ray emission can be integrated emission from supernova remnants and Population I binary X-ray sources. This interpretation agrees with the picture emerging from optical and radio studies that late-type blue and disturbed galaxies are experiencing sudden bursts of star formation.

Subject headings: galaxies: nuclei — galaxies: Seyfert — stars: supernovae — X-rays: sources

I. INTRODUCTION

The Hubble sequence and the colors of galaxies have long been studied in order to get some understanding of galaxy evolution. In particular, recent attention has been given to late-type galaxies, especially blue galaxies (Sargent and Searle 1970; Huchra 1977) and galaxies with disturbed morphologies (Arp 1966; Toomre and Toomre 1972). These anomalous galaxies provide valuable tests of theories that link stellar and nuclear evolution to dynamical interactions between neighboring galaxies. Gas transfer and tidal shocks may induce bursts of star formation and/or nuclear activity (Biermann and Fricke 1977; Larson and Tinsley 1978; Stocke 1978; Hummel 1980). A recent optical and radio study of a complete sample of galaxies (Heckman, Balick, and Crane 1980; Heckman 1981*a*, *b*) shows that the nuclei of normal galaxies can be the seat of low-level activity, with emission lines similar to the narrow lines of Seyfert galaxies although generally less luminous. Other recent results (Weedman and Feldman 1980; Kronberg, Biermann, and Schwab 1981; Kronberg and Biermann 1981) suggest that nuclei of galaxies can be the seat of violent bursts of star formation.

The X-ray band provides a new approach to these issues, as both active nuclei and rapid star formation should be associated with enhanced X-ray emission. Until the launch of the *Einstein* satellite (Giacconi *et al.* 1979), X-ray instruments were not sensitive enough to detect any but the brightest Seyfert galaxies with nuclear X-ray luminosities of $\sim 10^{42}-10^{44}$ ergs s^{-1} (Elvis *et al.* 1978; Tananbaum *et al.* 1978) and the very closest normal galaxies (M31, LMC, and SMC). For some other galaxies with emission line nuclei and in interacting systems, the presence of nonthermal nuclear X-ray emission (Griffiths *et al.* 1979) was also suggested. The improved sensitivity of the *Einstein* Observatory allows both the detection of nearby galaxies ($D \sim 10$–20 Mpc) with $L_x \sim 10^{39}-10^{41}$ ergs s^{-1} and the study of the angular distribution of the X-ray emission. In this way, X-ray emission localized in the central nuclear region can be distinguished from more diffuse emission.

In this paper, we report the results of the X-ray observations with the *Einstein* Observatory of 33 galaxies, some of which lie in groups and in interactive pairs. Almost all these galaxies present disturbed morphologies. Many of them are in the Arp catalog (Arp 1966). No uniform, well-defined selection criterion can describe the galaxies in our sample. However, almost all these galaxies have a common characteristic with respect to the optical properties. This can be seen in Figure 1 which shows the optical color/color diagram for the galaxies in our survey for which color information is

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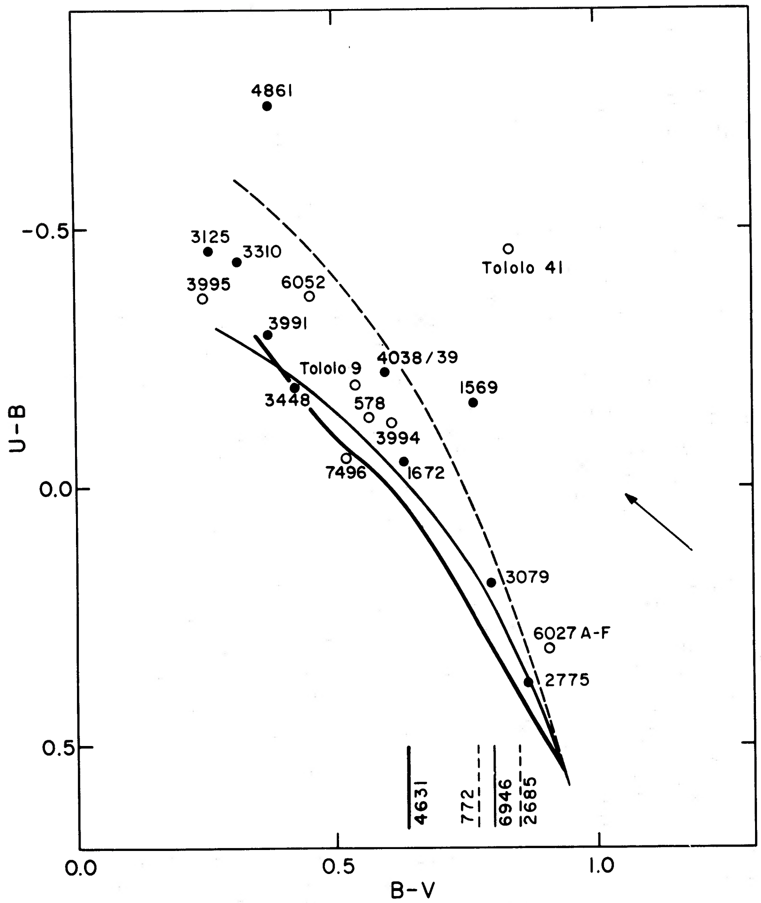

FIG. 1.—The galaxies observed in this survey for which color information is available are plotted in a color-color diagram. We use the uncorrected colors in this figure for uniformity because only for a few of our galaxies corrected colors from the RCBG2 exist. Correcting for reddening will result in a displacement along the line indicated by the arrow, unless partial reddening is present which could result in more complicated reddening lines (Biermann and Fricke 1976). The full circle identifies the galaxies detected in X-rays. For four galaxies, NGC4631, NGC772, NGC6946, and NGC2685, only the $B-V$ color was available in the literature. For these, the full lines identify the galaxies detected in X-rays. The colors we use are from RCBG2 for most of the galaxies; J. P. Huchra 1980, private communication for NGC 3079, NGC 3310, and NGC 4861; Bohuski, Fairall, and Weedman 1978 for NGC 3125, Tololo 9 and Tololo 41; and Osmer, Smith, and Weedman 1978 for NGC 1672. The lines across the diagram are from Larson and Tinsley 1978. For a description, see text.

available. The heavy line crossing diagonally the $U-B/B-V$ plane represents the mean colors of the Hubble Atlas sample of normal galaxies (Larson and Tinsley 1978). The other solid and dashed lines correspond to the theoretical models of Larson and Tinsley (1978) of galaxies with short bursts of star formation ($\tau \sim 10^7$ yr, the dashed line) and with star formation taking place in a longer time ($\tau \sim 5\times10^8$ yr, the solid thin line). Almost all the galaxies in our sample lie in the area between the thin solid and the dashed lines, suggesting that they are experiencing bursts of star formation. This region is compatible with the locus of Markarian galaxies (Huchra 1977). Preliminary results on a few of these galaxies have been reported by Griffiths (1979). The observed sample and the X-ray data are presented in § II. The X-ray data are discussed in § III and compared with the optical and radio properties of the galaxies in § IV. Discussion follows in § V.

II. X-RAY OBSERVATIONS

Thirty-three galaxies, some of them in groups, were observed in 22 $\sim 1°\times 1°$ fields with the Imaging Proportional Counter (IPC) on board the *Einstein* Observatory (Giacconi *et al.* 1979). The results of the Einstein observations are summarized in Table 1. The galaxies are listed in column (1). The most accurate published position of the nucleus with its reference and the centroid of the X-ray counts distribution are listed in column (2). The *Einstein* sequence numbers, which identify the IPC field, are listed in column (3). Columns (4) and (5) list the date of the observation and the effective exposure

TABLE 1

X-RAY DATA

Name NGC (1)	RA, δ(1950)[a] (2)			*Einstein* Sequence Number (3)	Date of Observation (Year, Day) (4)	Time (s) (5)	Counts[b] (6)	N_H (cm^{-2}) (7)	f_x(0.5–3 keV) (ergs cm^{-2} s^{-1}) (8)	*D* (Mpc) (9)	L_x(0.5–3 keV) (ergs s^{-1}) (10)	Extent (′) (11)	Hardness Ratio (12)
523	1 22 1.0	33 45 55	1	4199	1979, 210	3352	<14.7	3.0×10^{20}	$<1.2\times10^{-13}$	99	$<1.3\times10^{41}$	...	...
	...					...					...	...	
578	1 28 5.6	−22 55 27	2	424	1979, 201	2573	<21.8	3.0×10^{20}	$<2.4\times10^{-13}$	34	$<3.2\times10^{40}$	...	...
	...						...					...	...
772	1 56 35.3	18 45 50	1	464	1979, 201	702	<8.6	3.0×10^{20}	$<3.2\times10^{-13}$	51	$<9.5\times10^{40}$	...	...
	...						...					...	...
1569	4 26 5.8	64 44 18	1	414	1979, 58	2893	87.5	2.4×10^{21}	9.8×10^{-13}	3	1.0×10^{39}	0.5	1.4
	4 26 7.0	64 44 43					10.6					>0.2	0.4
1672	4 44.92	−59 20.2	3	427	1980, 104	4881	129.4	3.0×10^{20}[c]	6.0×10^{-13}	22	3.3×10^{40}	0.7	1.6
	4 44 58.5	−59 19 52					16.0					>0.4	0.4
2685	8 51 40.4	58 55 30	4	415	1979, 283	936	<15.3	5.0×10^{20}	$<4.0\times10^{-13}$	19	$<1.8\times10^{40}$	...	...
	...											...	...
2773	9 07 4.8	7 22 40	1	457	1979, 142	2933	<25.8	5.0×10^{20}	$<2.5\times10^{-13}$	19	$<9.8\times10^{39}$	...	...
	...						...					...	...
2775	9 07 41.0	7 14 35	1	457	1979, 142	2933	29.7	5.0×10^{20}	2.6×10^{-13}	19	1.1×10^{40}	0.5	1.4
	9 07 41.8	7 15 23					6.7					[d]	0.6
2777	9 08 2.5	7 24 41	1	457	1979, 142	2933	<20.6	5.0×10^{20}	$<1.9\times10^{-13}$	19	$<7.0\times10^{39}$	...	...
	...						...					...	...
3073	9 57 29.2	55 51 30	1	423	1979, 119	1058	<17.2	3.0×10^{20}	$<4.6\times10^{-13}$	24	$<2.6\times10^{40}$	...	...
	...						...					...	...
3079	9 58 35.4	55 55 11	1	423	1979, 119	1058	16.8	3.0×10^{20}	3.7×10^{-13}	24	2.4×10^{40}	[e]	0.9
	9 58 37.4	55 55 44					5.2					[e]	0.6
3125	10 4.30	−29 41.5	3	430	1979, 168	1771	25.0	7.0×10^{20}	3.3×10^{-13}	22	1.8×10^{40}	[e]	...
	10 4 19.1	−29 40 43					7.3					[e]	...
Tololo 9	10 32	−28.3	5	429	1979, 168	1759	<10.2	6.0×10^{20}	$<1.2\times10^{-13}$	73	$<7.7\times10^{40}$	...	...
	...						...					...	...
3310	10 35 40.3	53 45 45	1	467	1979, 118	1278	46.5	3.0×10^{20}	8.2×10^{-13}	21	4.1×10^{40}	0.1	3.7
	10 35 42.4	53 46 6					7.5					[d]	1.7

TABLE 1—*Continued*

Name NGC (1)	RA, δ(1950)[a] (2)	*Einstein* Sequence Number (3)	Date of Observation (Year, Day) (4)	Time (s) (5)	Counts[b] (6)	N_H (cm^{-2}) (7)	f_x(0.5–3 keV) (ergs cm^{-2} s^{-1}) (8)	D (Mpc) (9)	L_x(0.5–3 keV) (ergs s^{-1}) (10)	Extent (′) (11)	Hardness Ratio (12)
3448	10 51 38.4 54 34 23 1	416	1979, 118	1801	21.3	3.0×10^{20}	2.6×10^{-13}	29	2.7×10^{40}	0.5	5.9
	10 51 46.3 54 35 11				5.9					d	5.7
3991	11 54 56.2 32 36 58 1	443	1979, 141	1337	34.7	3.0×10^{20}	5.1×10^{-13}	66	2.5×10^{41}	e	...
	11 54 58.9 32 37 10				11.1					e	...
3994	11 55 1.5 32 33 26 1	443	1979, 141	1337	<14.8	3.0×10^{20}	$<2.7\times10^{-13}$	66	$<1.4\times10^{41}$	...	...
	...				...					...	...
3995	11 55 9.9 32 34 20 1	443	1979, 161	1337	<14.8	3.0×10^{20}	$<2.7\times10^{-13}$	66	$<1.4\times10^{41}$	...	...
	...				...					...	...
4038	11 59 19.0 −18 35 5 4	469	1979, 172	1350	63.1	3.0×10^{20}	1.1×10^{-12}	29	1.2×10^{41}	0.5	0.5
4039	11 59 20.2 −18 36 21 4				9.5					>0.0	0.2
	11 59 20.0 −18 35 23										
4631	12 39 41.5 32 48 54 1	471	1978, 354	2298	78.5	3.0×10^{20}	6.8×10^{-13}	13	1.3×10^{40}	0.7	0.7
	12 39 29.0 32 48 21				11.7					>0.3	0.2
4861	12 56 38.5 35 7 56 1	445	1978, 352	1737	20.8	3.0×10^{20}	3.1×10^{-13}	17	1.0×10^{40}	e	1.6
	12 56 39.2 35 7 50.5				5.7					e	0.9
Tololo 41	14 00 −29.9 5	433	1979, 206	1323	<8.4	5.0×10^{20}	$<1.6\times10^{-13}$	139	$<3.7\times10^{41}$	...	...
	...				...					...	...
6027 A-F	15 57.01 20 54.2 3	462	1979, 36	1622	<13.4	3.0×10^{20}	$<2.4\times10^{-13}$	84	$<1.9\times10^{41}$	...	...
	...				...					...	...
6052	16 3 1.8 20 40 40 1	411	1979, 242	688	<17.8	3.0×10^{20}	$<6.8\times10^{-13}$	96	$<7.1\times10^{41}$	...	...
	...				...					...	...
6454	17 44 0.4 55 43 24.8 6	421	1979, 205	1295	31.2	3.0×10^{20}	5.8×10^{-13}	187	2.3×10^{42}	0.5	0.7
	17 44 5.0 55 44 16				6.5					d	0.3
6946	20 33 48.8 59 58 50 1	422	1979, 145	1134	53.3	2.8×10^{21}	1.7×10^{-12}	7	9.7×10^{39}	0.7	1.1
	20 33 56.7 60 00 17				9.6					>0.2	0.4
7496	23 6.98 −43 42.0 3	435	1979, 141	391	<8.6	3.0×10^{20}	$<5.9\times10^{-13}$	29	$<5.6\times10^{40}$	...	...
	...				...					...	...

[a] The upper entry is optical/radio; the lower entry is X-ray. The reference sources are as follows: (1) Dressel and Condon 1976. (2) Gallouët, Heidman, and Dampierre 1975. (3) De Vaucouleurs, de Vaucouleurs, and Corwin 1976. (4) Gallouët, Heidman, and Dampierre 1973. (5) Penston *et al.* 1977. (6) Kühr *et al.* 1979.

[b] The upper entry is net counts; the lower entry is the statistical error.

[c] The position of NGC 1672 is not covered by the Heiles (1975) survey. Since it is at high galactic latitude (−39°), we assume $N_H=3.0\times10^{20}$ cm^{-2}.

[d] The 3 σ lower limit to the extent does not exclude a point source.

[e] No counts detected in the outer annulus (see text).

NOTES ON INDIVIDUAL ENTRIES

N523 = Arp 158 = IV Zw 45—Bright knot and streamer (Arp 1966); merger of two galaxies (Chincarini and Heckathorn 1973).

N578—Normal galaxy with weak Balmer lines (Martin 1976).

N772 = Arp 78—Large spiral galaxy perturbed by nearby elliptical about the size of M32 (Arp 1964). Several smaller galaxies with much higher redshift appear connected to NGC 772 by luminous filaments (Arp 1970).

N1569 = Arp 210 = VII Zw 16—Similar to M82. Bright Hα envelope extending twice the radius of the galaxy and two starlike nuclei (Hodge 1974; de Vaucouleurs, de Vaucouleurs, and Pence 1974). Thermal radio emission from the overall galaxy and stronger nonthermal source coincident with the bluest region of the galaxy (Seaquist and Bignell 1976).

N1672—Sersic-Pastoriza (1965) spiral with resolved emission line nucleus (Osmer, Smith, and Weedman 1974). Possible broad forbidden lines—Seyfert 2? (Veron, Veron, and Zuiderwijck 1980).

N2685 = Arp 336—Elliptical body with circumgalactic ring composed of H II regions and dust (Burbidge and Burbidge 1959).

N2773, N2775, N2777—Galaxies in group.

N3073 = Mkn 131 = Ho 156b—Pair with 3079 (RCBG2).

N3079 = Ho 156a = 4C 55.19—Anomalous radio synchrotron emission and structure (De Bruyn 1977). Emission line nucleus (Heckman 1980*b*). In group with NGC 3073 and third anonymous galaxy (RCBG2).

N3125 = Tololo 3—Very blue. Emission line nucleus. He II 4686 in emission (Penston *et al.* 1977).

Tololo 9—Emission line nucleus. He II 4686 in emission. Detected at 6 cm. (Penston *et al.* 1977).

N3310 = Arp 217—Bright compact galaxy with Hα arc and jet pointing to it (Arp 1966). Bright radio continuum emission (Van der Kruit 1971, 1976). Optical emission lines (H II regions) (Heckman, Balick, and Crane 1980).

N3448 = Arp 205—It could also be classified as Sd or Sm with a very peculiar nucleus, either exhibiting a strong absorption in the central region or a double interacting galaxy (Bottinelli, Duflot, and Gouguenheim 1978). Dwarf companion at 3′.8 (RCBG2).

N3991, N3994, N3995 = Arp 313 = Ho 309c,b,a = Haro 5 = VV523, VV249—N3991 has a blue nucleus (Haro 1956) and radio emission comparable to that of Seyfert galaxies (Seaquist and Bell 1968). In multiple interacting system (de Vaucouleurs, de Vaucouleurs, and Corwin 1976).

N4038, N4039 = Arp 244 = VV245—The "Antennae." Merging galaxies with long streamers (Arp 1966; Toomre and Toomre 1972) and bright emission knots in nuclei (Rubin, Ford, and D'Odorico 1970). Radio emission associated with the central region of the system (Purton and Wright 1972; van der Hulst 1978).

N4631 = Arp 281 = Ho 442a = K 350a—Edge-on galaxy with knots of emission (Arp 1966). In group with NGC 4656 and NGC 4627 (RCBG2). Radio halo and bridges (Ekers and Sancisi 1977). Bright radio nucleus (de Bruyn 1977).

N4861 = Arp 266 = Mkn 59 = I Zw 49 = K 362 = VV797—Resolved into knots (Arp 1966). Probably normal rotating late type galaxy (de Vaucouleurs and de Vaucouleurs 1964; Carozzi, Chamaraux, and Duflot-Augarde 1974). Very blue galaxy (Huchra 1977). Emission lines spectrum similar to H II regions (Alloin, Bergeron, and Pelat 1978).

Tololo 41—Emission-line nucleus. Strong Hα. Very blue (Penston *et al.* 1977).

N6027 A-F = VII Zw 631 = VV115—Seyfert's sextet. Chain of galaxies (Arp 1966). Extended radio source (Burke and Miley 1973).

N6052 = Arp 209 = Mkn 297 = VV86—Chaotic with loops (Arp 1966). H II regions emission lines (Weedman 1972; Sandage 1978). Very blue (du Puy and de Veny 1969). Recent merger of two galaxies (Duflot 1976). In the same group as Seyfert's sextet (Casini, Heidmann, and Tarenghi 1979). Steep UV spectrum (Benvenuti, Casini, and Heidmann 1979).

N6454 = 4C.55.33.1—D galaxy in a cluster (Tritton 1972).

N6946 = Arp 29 = 4C 59.31.1—Face-on spiral with bright Hα arm (Arp 1966) and radio disk (Van der Kruit, Allen, and Rots 1977). Five supernovae detected since 1917.

N7496—Emission line nucleus (Martin 1976) with strong UV continuum (Shobbrook 1966). Broad lines, like a Seyfert 2 galaxy (Veron *et al.* 1981).

time on the galaxy for each field. Column (6) gives the net counts (source minus background) typically detected in a circle of 2′.0 radius around the X-ray centroid at energies between 0.5 and 3.5 keV and the statistical uncertainty on the counts (1 σ). In all cases we derived the background locally from a annulus of 6′.7 radius surrounding the 2′ radius circle. For four of the galaxies (NGC 1672, NGC 4038/39, NGC 4631, and NGC 6946) which showed extent on a visual inspection of the data, we calculated the source counts from a circle of 3′.3 radius. For all the galaxies not detected, the 3 σ upper limits on the intensity are listed. Column (7) lists the equivalent hydrogen absorption column N_H due to our galaxy (Heiles 1975). Column (8) gives the fluxes corrected for the absorption in our galaxy in the (0.5–3 keV) energy range. These fluxes were calculated for a thermal bremsstrahlung spectrum with $kT = 10$ keV and the absorption column listed in column (7). The use of different thermal spectra with kT's from 2 keV to 10 keV or power law spectra with energy spectral index α ranging from 0.5 to 2.0 changes the fluxes by a factor of $\sim\pm20\%$ at the most. For a more detailed description of the methods used in the evaluation of the flux, see Tananbaum *et al.* (1979). Column (9) gives the distances in megaparsecs, calculated from the radial velocities of the *Second Reference Catalog of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976, hereafter RCBG2), assuming $H_0 = 50$ km s^{-1} Mpc^{-1}, and column (10) gives the (0.5–3 keV) luminosities corrected for the absorption in our Galaxy. The use of the de Vaucouleurs (1979) lower recent estimates of distances for some of the galaxies typically results in decreasing the luminosities by less than a factor of 4, except for the two extreme cases of NGC 772 and NGC 4631 for which the difference is a factor 7 and 14, respectively. Column (11) lists our estimate for the extent of the sources in the assumption of a Gaussian X-ray surface brightness and underneath it the 3 σ lower limits to the extent. To derive these quantities we used the method described by Henry *et al.* (1979), except that counts from Pulse Height Analizer (PHA) channels ≥ 4 were used. Applying this method on an IPC observation of 3C 273 (a strong point source), a $\sigma = 0\rlap{.}'77 \pm 0.01$ was obtained, compatible with preflight calibration. We used this Gaussian to deconvolve the Gaussians obtained from the galaxy data. Column (12) lists the hardness ratios (the ratio of the number of counts above to those below 1.2 keV) and their statistical errors.

III. RESULTS

Of the 22 individual and groups of galaxies under study, 13 are detected at least at the 3 σ level with soft X-ray fluxes between 2 and 17×10^{-13} ergs cm^{-2} s^{-1}. The corresponding luminosities range from 1×10^{39} to 2.3×10^{42} ergs s^{-1}. Since most sources have fewer than ~ 80 photons, little information is obtained regarding the X-ray spectra. All but one source (NGC 4038/39 which appears rather soft) are consistent with hardness ratios of ~ 1, implying that the intrinsic spectra are neither extremely soft ($kT > 1$ keV) nor extremely cutoff ($N_{\rm H} < 1 \times 10^{22}$ cm^{-2}). Since these galaxies were observed at the beginning of the *Einstein* mission, when the IPC experienced wide variations in the instrument gain, it is not possible to simply add all the observed spectra and study the characteristics of the "average" spectrum.

In most cases the angular separation between the centroids of the X-ray emission and the optical positions (nuclei) is less than or about 1′, consistent with the uncertainty in the IPC positional determination. The angular separations for NGC 3448, NGC 4631, and NGC 6946, however, lie well outside of the 1′ circle. NGC 4631 and NGC 6946 are both more than 10′ in diameter and present a complex distribution of X-ray surface brightness. NGC 4631 shows two distinct emission regions. The fainter one is in the proximity of the radio nuclear source and the stronger one could be associated with the fainter radio emission at the west of the nucleus. NGC 6946 could be consistent with at least three discrete sources or diffuse X-ray emission regions clustering in the central region of the galaxy. Further mapping of the X-rays and an accurate comparison with the radio data will be needed to give more quantitative results. They will be discussed in detail in a separate paper. The X-ray source near NGC 3448 is $1\rlap{.}'4$ from the main body of the galaxy. At present we can only consider the identification of this X-ray source as tentative.

The X-ray surface brightness distributions of the five galaxies with the highest net counts in our sample (NGC 1569, NGC 1672, NGC 4038/39, NGC 4631, and NGC 6946) are not compatible with a single point source at the 3 σ level. The lack of evidence of extent (at the 3 σ level) for the remaining galaxies may well be due to poor statistics (15 to 45 net counts). We also note that our method to detect source extension is best suited to the case of a relatively simple surface brightness distribution. It only gives an indication of the source not being compatible with a single point source in the more complex cases.

IV. COMPARISON WITH RADIO AND OPTICAL PROPERTIES

The radio (1400 MHz) and optical monochromatic fluxes of the galaxies in our sample are summarized in Table 2. Column (2) lists the blue magnitude corrected for inclination and reddening (B_T^o) from the RCBG2. When this is not available, the apparent blue magnitude (B) from the RCBG2 is listed or, the visual or blue magnitude from other sources. Column (3) lists the morphological parameter T from the RCBG2. Column (4) lists the radio flux density (in mJy) at 1400 MHz. When this quantity was not available from the literature, we extrapolated or interpolated adjacent measurements assuming a radio spectrum of form $\nu^{-\alpha}$ with $\alpha = 0.7$. The sources of the radio data we used to derive this quantity are listed in column (5). Column (6) and (7) list the monochromatic B and 2 keV fluxes (in mJy), respectively. Column (8) gives the ratio of these two quantities. Throughout Table 2 all the magnitudes other than B_T^o, and all the fluxes and the flux ratios derived from these are enclosed in parentheses. In Figure 2, we plot the composite spectra radio to X-rays for the galaxies in our sample detected in X-rays for which radio measurement at different frequencies are available. A surprising result is apparent from this figure: The X-ray point tends to fall close to the extrapolation of the radio spectrum. An exception is NGC 6454, where the radio spectrum is flatter than $\alpha \approx 0.7$, suggesting the possibility of a nuclear radio source.

a) *Correlations between X-Ray and Optical and X-Ray and Radio Fluxes and Luminosities*

We have looked for correlations between the X-ray emission and either the optical or the radio emission. Figure 3*a* and Figure 3*c* show $\log f_x$ plotted versus $\log f_B$ and $\log f_R$, respectively. Although there is a certain spread in the points (especially in the $\log f_x$ versus $\log f_B$ plot), the presence of a correlation is suggested in both cases by the relative distributions of the detections and the upper limits. For flux limited samples, a search for correlations between fluxes has the advantage of avoiding the problem of introducing spurious correlations between luminosities when distance corrections are applied. At the same time, it is also possible for uncorrelated luminosity distributions to show flux correlations under special circumstances. To check for this possibility, we have also plotted the intrinsic monochromatic luminosities against each other in Figures 3*b* and 3*d*. From both these two latter plots, correlations are also evident. Since the upper limits are essential to establish the correlations between fluxes, nonparametric methods

TABLE 2

OPTICAL, RADIO, AND X-RAY PROPERTIES

Name (NGC) (1)	B_T^0 (2)	T (3)	f_R (1400 MHz) (mJy) (4)	Radio Reference (5)	f_B[a] (mJy) (6)	f_x (2 keV) (mJy) (7)	f_x/f_B (8)
523	(13.5) 1	...	15	2	(15.3)	$<1.5\times10^{-5}$	$<(1.0\times10^{-6})$
578	11.13	5	50	3,4	156.8	$<3.0\times10^{-5}$	$<1.9\times10^{-7}$
772	10.65	3	155	2,3,4,5,6	244.0	$<4.3\times10^{-5}$	$<1.8\times10^{-7}$
1569	10.58	10	420	4,7,8,9	260.2	1.4×10^{-4}	5.3×10^{-7}
1672	10.63	3	333	5,10	248.5	8.6×10^{-5}	3.5×10^{-7}
2685	11.51	−2	<19	4,11,12	110.5	$<5.8\times10^{-5}$	$<5.2\times10^{-7}$
2773	(14.5) 1	...	...	...	(6.1)	$<3.9\times10^{-5}$	$<(6.4\times10^{-6})$
2775	10.85	2	<50	2,3,4,6	202.9	4.1×10^{-5}	2.0×10^{-7}
2777	(14.0) 1	2	28	2	(8.2)	$<3.0\times10^{-5}$	$<(3.7\times10^{-6})$
3073	(14.0) 1	−3	...	...	(8.2)	$<6.5\times10^{-5}$	$<(7.9\times10^{-6})$
3079	10.43	5	850	3,4,8,9, 11,13,14,15	298.8	5.0×10^{-5}	1.7×10^{-7}
3125	(13.55) 16	−5	<400	17	(13.3)	4.5×10^{-5}	(3.4×10^{-6})
Tololo 9	(14.74) 16	...	37	18	(3.4)	$<1.7\times10^{-5}$	$<(5.0\times10^{-6})$
3310	10.90	3	30	4,8,9,11, 14,19	193.8	1.2×10^{-4}	6.5×10^{-7}
3448	11.59	0	80	3,4,9,20	102.6	3.6×10^{-5}	3.5×10^{-7}
3991	12.86	5	175	20	31.9	6.9×10^{-5}	2.2×10^{-6}
3994	12.97	9	60	21	28.8	$<3.9\times10^{-5}$	$<1.4\times10^{-6}$
3995	12.26	9	45	2,3,9	55.4	$<3.9\times10^{-5}$	$<7.0\times10^{-7}$
4038/39	10.88	9	250	3,5,22,23	197.4	1.5×10^{-4}	7.6×10^{-7}
4631	9.03	7	1300	2,4,9,14,24	1084.9	1.1×10^{-4}	1.0×10^{-7}
4861	12.24	9	20	2,3,4	56.4	4.4×10^{-5}	7.8×10^{-7}
Tololo 41	(16.85) 16	...	<500	17	(0.4)	$<2.2\times10^{-5}$	$<(5.6\times10^{-5})$
6027 A-F	(13.35)	...	27	2,22	(20.4)	$<3.2\times10^{-5}$	$<(1.6\times10^{-6})$
6052	13.03	5	85	2,9,25	27.2	$<9.1\times10^{-5}$	$<3.3\times10^{-6}$
6454	(14.5) 1	...	760	26,27	(6.0)	7.6×10^{-5}	(1.3×10^{-5})
6946	8.49	6	1400	4,9,11,14 28	1783.9	2.2×10^{-4}	1.2×10^{-7}
7496	11.25	3	...	...	140.4	$<7.4\times10^{-5}$	$<5.3\times10^{-7}$

[a] To derive these fluxes from the magnitudes, Johnson's table (1966) was used.

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cannot be used to evaluate their significance. We therefore applied a parametric method that uses the information given by both detections and upper limits (Y. Avni 1982). The only assumption needed is that $\log f_x$ and $\log L_x$ have a Gaussian distribution with dispersion σ around a straight line relation of the type: $a \log F + b$, where F will be either f_B, L_B, f_R, or L_R. By minimizing the function $S = -2 \ln L$, where L is the likelihood function, the parameters a, b, and σ can be derived. The error on the parameter a (which gives the significance of the correlation) can be calculated with a variational method (Avni *et al.* 1980).

For the X-ray optical relationships, using 13 detections and 14 upper limits, we obtain:

$$\log f_x = (0.37 \pm 0.10) \log f_B - 5.10,$$

$$\sigma(\log f_x) = 0.32,$$

and

$$\log L_x = 0.66^{+0.24}_{-0.28} \log L_B + 3.38,$$

$$\sigma(\log L_x) = 0.54.$$

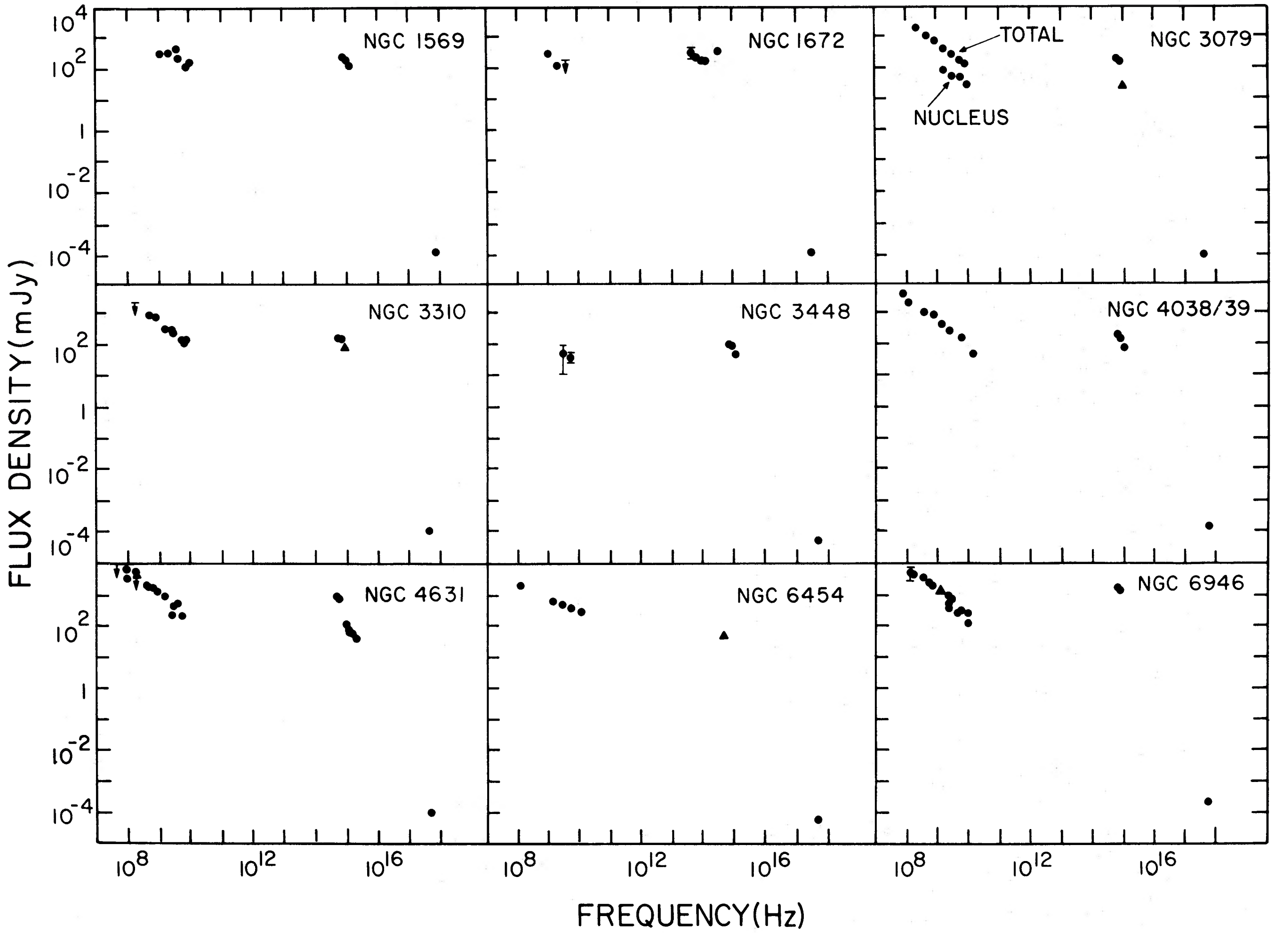

FIG. 2.—Composite radio to X-ray spectra. The X-ray values are from this survey, the optical points are from RCBG2, and Sulentic and Tifft 1973. IR photometry for NGC 1672 is from Glass 1973. UV photometry for NGC 4631 is from Coleman, Wu, and Weedman 1980. For the references for the radio flux densities, see Table 2.

We therefore have a 3.7 σ correlation between $\log f_x$ and $\log f_B$ and a 3.3 σ correlation between $\log L_x$ and $\log L_B$. Similarly in the relationships with the radio emission, using 11 detections (number of points for which both radio and X-ray fluxes and luminosities are known) and 10 upper limits, we obtain:

$$\log f_x = (0.57 \pm 0.11) \log f_R - 5.59,$$

$$\sigma(\log f_x) = 0.26,$$

and

$$\log L_x = (0.76 \pm 0.10) \log L_R + 0.40,$$

$$\sigma(\log L_x) = 0.34.$$

We therefore have a 5.6 σ correlation between the fluxes and a 7.6 σ correlation between the luminosities.

We conclude that the X-ray emission is correlated with both the optical and the total radio emission at 1400 MHz. The correlation is much tighter in the radio than in the optical case. Nothing can be said about any correlations of the X-ray flux or luminosity with the nuclear radio flux or luminosity. In fact, for only three of the galaxies in our sample (NGC 3079, NGC 3448, and NGC 3994) has the detection of a nuclear radio component been reported (Van der Kruit 1971; Huchtmeier 1975; Heckman, Balick, and Crane 1980; Hummel 1980; E. Hummel 1981, private communication).

b) *Distribution of* f_x/f_B

An application of the maximum likelihood method to the observed distribution of f_x/f_B (Fig. 4*b*), using both detections and upper limits (Avni *et al.* 1980), gives a median value of f_x/f_B for this sample a factor of 15

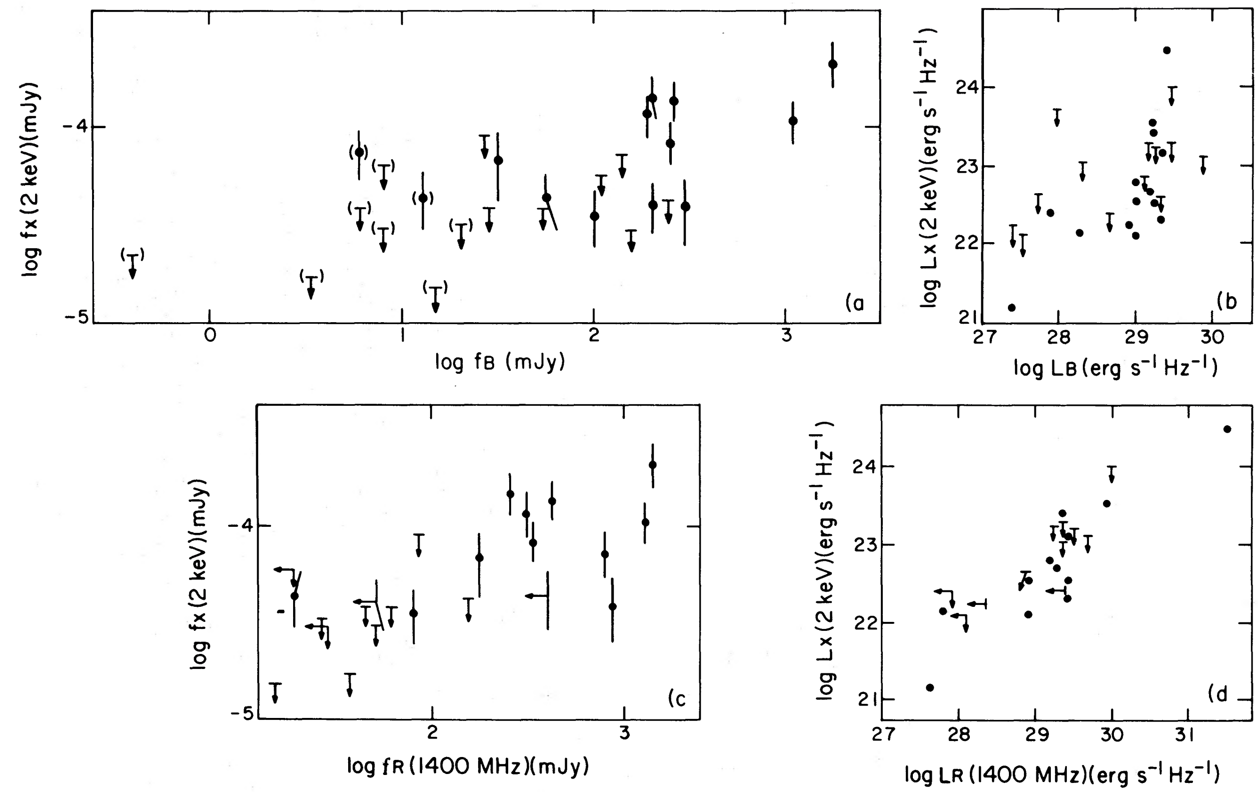

FIG. 3.—(a) Logf_x vs. logf_B. The dots and the arrows that represent the upper limits on f_x are enclosed in parentheses for all the galaxies for which B_T^0 (from RCBG2) is not available. The error bars on the X-ray fluxes include both the statistical and the 20% error due to the uncertainty in the spectrum. (b) Log L_x vs. log L_B. Here L_x and L_B are the monochromatic X-ray and optical blue luminosities in ergs s^{-1} Hz^{-1}. (c) Logf_x vs. logf_R. (d) Log L_x vs. log L_R. L_R is the monochromatic radio luminosity at 1400 MHz in ergs s^{-1} Hz^{-1}.

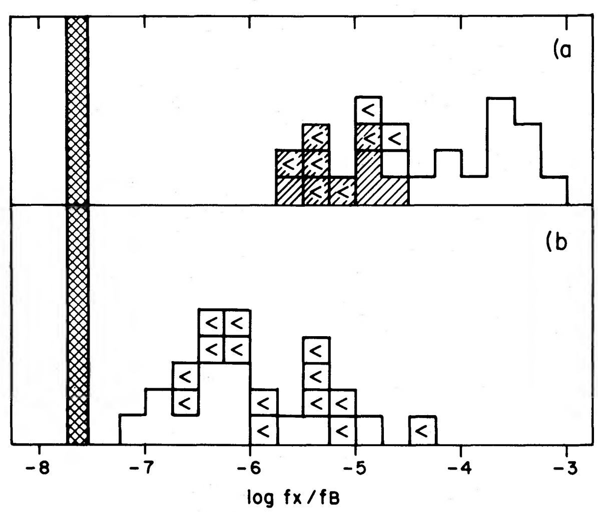

FIG. 4.—Histogram of the logf_x/f_B for the Seyfert galaxies (a) and the galaxies in this survey (b). The shaded area in (a) represents the Seyfert 2 galaxies and the clear area the Seyfert 1's. The vertical cross hatched area represents the locus of galaxies having the same f_x/f_B as M31. The upper limits are indicated by a "$<$" in the corresponding square.

higher than that of M31. However, eight of the galaxies detected in our survey have f_x/f_B a factor of 25 or more higher than that of M31. A comparison with the Seyfert galaxies (Kriss, Canizares, and Ricker 1980) (Fig. 4a) shows that the distribution of f_x/f_B of our galaxies is clearly separated from that of the Seyfert 1 galaxies, the Seyfert 1 galaxies having $f_x/f_B \sim 400$ times larger in the average than the galaxies here surveyed. On the contrary, Seyfert 2 galaxies, for most of which only upper limits in X-ray are available, have f_x/f_B consistent with those of the galaxies here surveyed.

c) f_x/f_B versus Morphological Type and Colors

There is no evidence of correlation between f_x/f_B and the morphological parameter T of the RCBG2 (Fig. 5). The Spearman Rank correlation coefficient is $r_s = -0.08$. We obtain a similar result when we compare f_x/f_R with the morphological type.

The ratio f_x/f_B does appear to be correlated with the galaxy colors. Fig. 6 shows logf_x/f_B plotted versus $(U-B)_T^0$. The galaxies that have a larger X-ray to optical flux ratio tend also to have the bluest colors.

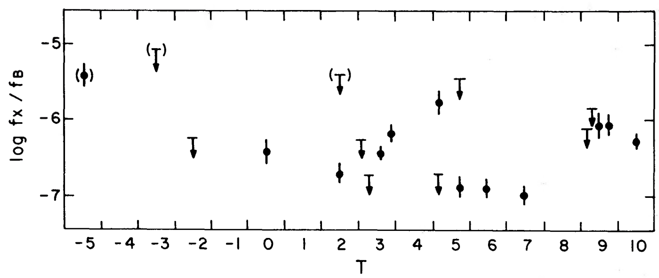

FIG. 5.—Log of f_x/f_B vs. the morphological parameter T (RCBG2)

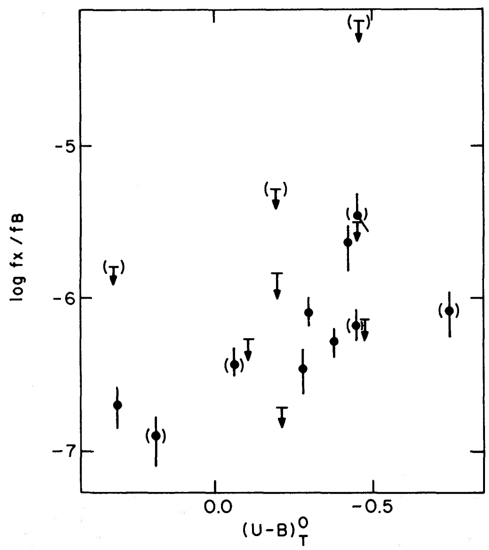

FIG. 6.—Log of f_x/f_B versus $(U-B)^0_T$ (RCBG2). The points representing those galaxies for which the corrected color index is not available are enclosed in parentheses. After correction, these points will move somewhat towards smaller values of $U-B$. For references on the $U-B$ values used in this graph, see caption of Fig. 1.

Applying the Spearman rank correlation test, we obtain a probability of a chance occurrence $<1\%$. The upper limits all appear to be consistent with the trend suggested by the detections. Using the parametric method discussed in § IV*a* with 10 detections and eight upper limits, we obtain a 3 σ correlation. A similar correlation is suggested between f_x/f_B and $(B-V)^0_T$, where we obtain a 6% probability of chance occurrence.

We also investigated the behavior of f_x/f_B in function of the "color excess", i.e. the difference between the observed colors of the galaxies and those for normal field galaxies of the same morphological type. This is not an easy task because of the uncertainties associated with the morphological type of distorted galaxies, the spread in colors of field galaxies, and the intrinsic reddening. If, however, we use the morphological types as reported on Table 2 and the average colors for each morphological type (Huchra 1977), we find that for the detected galaxies whose total deviation (toward the blue) from the average colors is $\Delta > 0.5$ mag the ratio f_x/f_B is about 3 times that of the detected galaxies with $\Delta < 0.5$ mag ($f_x/f_B \sim 1.5 \times 10^{-6}$ compared to 3.7×10^{-7}).

V. DISCUSSION

a) *Nuclear Activity*

Most of the galaxies discussed in this paper have associated neighboring galaxies (Table 1). Statistical studies of radio emission in galaxies suggest (Stocke 1978; Hummel 1980) that the presence of a companion could induce nuclear activity. Moreover, for one of the galaxies detected in our survey, NGC 1672, the presence of a Seyfert 2 nucleus has been suggested (Veron, Veron and Zuiderwijck 1980). Although our data cannot exclude the presence of a nuclear component of the X-ray emission, they show that in quite a few cases nuclear emission alone cannot explain the whole of the detected flux, as evidenced by our results on the angular extent of the X-ray sources (§ III). The correlations between X-ray and total optical emission and between X-ray and radio emission (which is primarily disk emission in these galaxies) (§ IV*a*) further suggest a disk rather than nuclear origin of the X-rays.

b) *Integrated Emission of Discrete Galactic X-Ray Sources*

The X-ray emission of our galaxy and of nearby galaxies like M31 (Van Speybroeck *et al.* 1979), the Large Magellanic Cloud (Long and Helfand 1979; Long, Helfand, and Grabelsky 1981), and the Small Magellanic Cloud (Seward and Mitchell 1981), is dominated by a small number of discrete bright sources, like globular clusters, binary systems and relatively young supernova remnants (SNR). Globular clusters, being Population II objects, would not give rise to the observed relationship between f_x/f_B and blue colors in our sample. A number of SNRs in our Galaxy have been observed in X-rays with $L_x \sim 10^{33}-10^{36}$ ergs s^{-1}. In the LMC, which might better resemble the late-type peculiar galaxies because of its morphological type and low metallicity, SNRs are responsible for $\sim 10\%$ of the total

X-ray emission and are more luminous than those of the Milky Way. For an average $L_x \approx 10^{37}$ ergs s^{-1} and a lifetime $\tau \approx 5000$ yr for young SNRs, as suggested by the LMC observations of Long and Helfand (1979), 20–200 supernova explosions per century would be needed in order to produce an integrated X-ray luminosity of $\approx 10^{40-41}$ ergs s^{-1} for a given galaxy. The integrated contribution of older SNRs will not be as important as the contribution of the younger ones due to the rapid decay of their X-ray luminosity with time (Gorenstein, Harnden, and Tucker 1974; see also Long and Helfand 1979). In one of the galaxies of our survey, NGC 6946, five supernovae have been observed in the last 100 years (RCBG2; Wild 1980). This galaxy, however, has redder colors than most galaxies in our survey and a fairly regular morphology. Other galaxies far more blue and with perturbed morphological appearance might experience a comparable or higher supernova rate. Therefore, a supernova rate of 10–20 per century in late-type galaxies, although higher than in normal galaxies, would not be unreasonable (see also Tammann 1978). It is then likely that SNRs might account for a substantial fraction of the X-ray emission, although probably not for the whole of it.

Binary systems are likely to be the main component of the X-ray emission of the late-type peculiar galaxies. Population I binary systems, in which the primary is an OB supergiant and the secondary a neutron star (or a black hole), have been identified as strong X-ray sources both in our Galaxy (with $L_x \sim 10^{37}$ ergs s^{-1}) and in the Magellanic Clouds (where they can have L_x's as high as $\sim 10^{38}-10^{39}$ ergs s^{-1} [Clark *et al.* 1978]). Although X-ray binaries typically have flat spectra at high energies, they can have soft X-ray excesses. SMC X-1 is reported to emit $\sim 3\times10^{39}$ ergs s^{-1} between 0.15 and 0.8 keV with a spectrum of $kT = 0.3$ keV or $\alpha = 3.5$ (Bunner and Sanders 1979). Hercules X-1 has a similar, though weaker, soft X-ray spectrum (Shulman *et al.* 1975). The $\sim 10^4$ OB stars in our own Galaxy produce ~ 20 early-type binary X-ray sources (van den Heuvel 1980). Ultraviolet *IUE* observations of NGC 6052 (Mkn 297), one of the galaxies in our survey, suggest that this galaxy has $\sim 10^5$ OB stars (Benvenuti, Casini, and Heidmann 1979). A similar number of OB stars can be inferred from infrared observations of NGC 6946 (Telesco and Harper 1980). Assuming a typical X-ray luminosity of $\sim 10^{38-39}$ ergs s^{-1} for each binary X-ray source (by analogy with the LMC sources), we can therefore estimate a number of binaries of ~ 200 and an integrated X-ray luminosity $L_x \sim 2\times10^{40-41}$ ergs s^{-1} comparable to the detected X-ray luminosities.

We can exclude a significant contribution from the integrated X-ray output of the normal Population I stellar content of the galaxies. In fact, even if we obtain $f_x/f_B \sim 10^{-7}-10^{-6}$ for O stars from the results of Vaiana *et al.* (1981), 10^7-10^8 O stars would be needed to attain an integrated $L_x \approx 10^{40}-10^{41}$ ergs s^{-1}. This is probably two orders of magnitude (or more) higher than the actual number of early stars in these galaxies.

The integrated spectra of the peculiar galaxies (Fig. 2) and the correlation between f_x and f_R (Fig. 6) tend to support the hypothesis that SNRs and binary sources are responsible for most of the X-ray emission. Also, the rate of Type II supernova events (which originate from massive Population I progenitors) appears to be correlated with galaxy colors (Tamman 1978) in the same sense as the f_x/f_B. Assuming 10^{-1} Jy yr at 5 GHz as the total time integral of nonthermal radio continuum radiation coming from a supernova remnant at 20 Mpc (Biermann and Fricke 1977), and calculating a similar quantity in the X-ray band (for a SNR with $L_x \sim 10^{37}$ ergs s^{-1}, $\tau \sim 5\times10^3$ yr), we obtain a ratio of the X-ray to the radio flux $f_x/f_R \approx 2\times10^{-6}$. We can perform a similar calculation in the case of the X-ray binaries, assuming an $L_x \approx 10^{38}$ ergs s^{-1} and a lifetime $\tau \approx 4\times10^4$ yr (van den Heuvel 1977). In this case, however, the calculation is even more uncertain because we have to scale for the X-ray binary formation rate versus the supernova rate, since we assume that the radio output is always due to SNRs. Assuming proportionality between X-ray binaries and supernovae and using our own galaxy as normalization, the expected number of 200 X-ray binaries implies a supernova rate of 10–30 per century. Then, with the typical parameters for SNRs and binaries as given above, we can calculate a ratio $f_x/f_R \approx 5\times10^{-6}$. Both these values of f_x/f_R are higher (by factors of 4 to 10) than the average ratio observed for the galaxies in our sample. However, given the large uncertainties in the assumed parameters both in radio and in X-ray, the difference between the expected and the observed f_x/f_R may not be significant. On the other hand, if we take these higher values of f_x/f_R at their face value, they suggest that, if supernovae and binaries contribute most of the X-ray emission, then the nonthermal radio emission from SNRs cannot be responsible for the total radio flux, and a different emission mechanism is required. A similar conclusion was reached by Biermann and Fricke (1977) in a study about the origin of the radio and optical radiation from Markarian galaxies.

c) Other X-Ray Production Mechanisms

The inverse Compton scattering of the radio electrons off the radio photons would give in all cases fluxes several orders of magnitude smaller than the observed ones. Inverse Compton, off the background 3 K blackbody radiation or the optical photon field of the galaxies, could contribute significantly only if the magnetic field is $B \approx 10^{-7}$ gauss. For a more likely value of the magnetic field, like $B \approx 3\times10^{-6}$ gauss, the contribution of the inverse Compton radiation could be only a few percent of the total. We can set lower limits of

$\sim 3 \times 10^{-7}$ gauss on the average magnetic field of NGC 772 and NGC 6052 from the Compton scattering off the optical photons.

The possibility of synchrotron radiation extending from radio to X-rays could be suggested by the fact that the X-ray fluxes tend to fall on the extension of the radio spectrum (Fig. 2). However, the electron synchrotron lifetime at X-ray frequencies ($\sim 10^{17}$ Hz) is $\sim 10^4$ yr if $B \approx 3 \times 10^{-6}$ gauss, about two orders of magnitude less than the cosmic ray lifetime in the disk of the Galaxy (Wentzel 1974). This implies that if the electron injection spectrum between 10^{10} and 10^{14} eV is a single power law, the synchrotron losses would steepen it considerably at the higher energies, giving a synchrotron contribution at the X-ray considerably below the observed value. The X-ray synchrotron would be comparable to the observed fluxes only if reacceleration of the higher energy cosmic ray electrons takes place on time scales $\leq 10^4$ yr.

Spheroidal hot gaseous haloes have been predicted to exist around spiral galaxies (Norman and Silk 1979), in most cases with predicted X-ray luminosities below our detection level. In NGC 4631 and 6946 in particular, the X-rays originate from the central region of the galaxy and appear sufficiently clumpy to cast doubts on a possible halo origin.

VI. CONCLUSION

The principal results of our X-ray survey of peculiar galaxies are the following:

1. The X-ray luminosities of these galaxies are in the 10^{39}–10^{42} ergs s^{-1} range. The galaxies with the higher photon count show evidence of extended or multiple emission regions.

2. f_x is correlated with both f_B and f_R, and so is L_x with L_B and L_R.

3. f_x/f_B's are significantly larger than that of M31, although smaller than those of the Seyfert galaxies.

4. Within our sample, we do not find any significant trend of f_x/f_B or f_x/f_R with morphological type.

5. There is a correlation between f_x/f_B and colors and also possibly color excesses.

These results led us to conclude that nuclear activity is not the predominant source of X-rays in late-type peculiar galaxies and that the X-ray emission is likely to originate from the Population I galactic component. In particular, we can explain the detected fluxes as the integrated emission from binary X-ray sources with a possible contribution from young SNRs. This interpretation requires an O star content higher than the one of our Galaxy (but compatible with what is suggested by UV and IR observations of some of these galaxies) and X-ray luminosities of individual sources on the order of those in the Magellanic sources. We find that the galaxies with colors that most deviate from normal colors, implying recent bursts of star formation, tend to have higher f_x/f_B. Supporting evidence for this interpretation could emerge from improved estimates of the O star content based on ultraviolet measurements. It will be also important to compare our results with the studies of the X-ray emission of more normal galaxies.

We acknowledge useful discussions with Y. Avni, P. Biermann, M. Elvis, J. Huchra, and N. Panagia. We particularly thank Leon Van Speybroeck for his interest in this paper and his assistance in some aspects of the data analysis. This work was supported under NASA contract NAS8-30751. One of us, G. Z., acknowledges support by a European Space Agency fellowship.

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