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A STATISTICAL ANALYSIS OF THE *EINSTEIN* NORMAL GALAXY SAMPLE. II. ELLIPTICAL AND S0 GALAXIES

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ABSTRACT

The statistical analysis of a sample of 29 elliptical and S0 field galaxies observed with the *Einstein* observatory is presented. The data show a correlation between the X-ray and the optical blue luminosity of the form $l_x \propto l_B^{1.64\pm0.15}$. This is significantly steeper than the correlation observed in spiral and irregular galaxies: $l_x \propto l_B^{1.08\pm0.07}$.

Several mechanisms for the origin of the X-ray emission in these galaxies have been investigated to explain the observed correlation. Most likely two separate mechanisms are present: thermal radiation from hot gas is required to explain the high-luminosity massive objects ($M \gtrsim 5 \times 10^{11}\ M_\odot$, $L_x \gtrsim 10^{41}$ ergs s^{-1}), while a collection of low-mass binary sources can explain the low-luminosity, low-mass objects.

A comparison between radio-loud and radio-quiet galaxies shows that high optical luminosity, or high mass, is required for the onset of nuclear activity, at both radio and X-ray wavelengths. However, this is not sufficient to ensure the presence of active nuclear sources, and a second parameter (at least) is needed.

A comparison between radio-loud elliptical galaxies and QSOs shows that the same X-ray emission mechanism that is operating in QSOs could explain the high X-ray luminosity end of the radio-loud galaxy distribution.

Subject headings: galaxies: nuclei — galaxies: stellar content — galaxies: X-rays

I. INTRODUCTION

In the companion paper (Fabbiano and Trinchieri 1985, hereafter FT) we discuss the X-ray properties of spiral and irregular galaxies and find that their X-ray emission is dominated by the integrated output of binary X-ray sources, mostly belonging to the Population I component.

A different picture of the nature of the X-ray emission of elliptical and S0 galaxies is given by the results of the X-ray observations published so far. Extended thermal emission has been associated with elliptical galaxies in the Virgo Cluster (e.g., M87, Fabricant and Gorenstein 1983; M84 and M86, Forman, Jones, and Tucker 1984), in poor groups (e.g., NGC 5848, Biermann and Kronberg 1983) and in more isolated galaxies (Nulsen, Stewart, and Fabian 1984). However, high-resolution observations of the bulge of M31 (Van Speybroeck *et al.* 1979) reveal that the X-ray emission of this spheroidal system is composed of many bright pointlike sources. The results of FT also suggest that all early-type spiral galaxies have similar bulge components in their X-ray emission. Bulges are believed to be spheroidal systems very similar to elliptical galaxies (e.g., Faber 1981).

Establishing the presence of hot X-ray emitting gas or X-ray emitting stellar remnants or both in elliptical galaxies will be crucial for a more complete understanding of these stellar systems. The content of elliptical and S0 galaxies, both in the form of visible matter (stars) and of gas, has been a subject of debate and study for many years. Elliptical galaxies are generally believed to contain predominantly an old, metal-rich stellar population dominated by K and M giants (see Frogel *et al.* 1975*a*, *b*; Gunn, Stryker, and Tinsley 1981). Models for continuous star formation predict colors in general agreement with the observed integrated colors, but they also predict a color gradient from red to blue toward the nucleus, contrary to what is generally observed (Larson and Tinsley 1974; Faber 1973). This suggests that either the star formation occurs with a very steep or truncated initial mass function (IMF), or the star formation occurs in bursts (see Faber and Gallagher 1976; Sanders 1981).

Interstellar gas, either ionized or neutral, has been searched for in elliptical galaxies. About 10^9–$10^{10}\ M_\odot$ of interstellar gas should reside in these galaxies as a result of stellar evolution (see Faber and Gallagher 1976, and references therein). Since observations in H I and at optical wavelengths have mostly failed to detect cold or ionized gas in elliptical and S0 galaxies, Faber and Gallagher (1976) suggested hot galactic winds as a gas removal mechanism, although they acknowledged that star formation resulting only in low-mass stars could be a suitable alternative. Hot gas in isolated elliptical galaxies might be directly detectable in X-rays, as it has been detected in M87 and other Virgo Cluster galaxies (see above).

The X-ray observations might also provide a new insight into the problem of nuclear activity in early-type galaxies. The limited observational evidence to date points toward mass and ellipticity (Heckman 1983; Heeschen 1970; Hummel, Kotanyi, and Ekers 1983) as crucial parameters for the onset of nuclear activity. These parameters might regulate the flow of gas accreting to the cores and feeding a central black hole. X-ray observations of a sample of normal elliptical galaxies of different optical luminosity (and mass) could help in pinpointing the critical mass for gas retention and onset of activity.

In this paper we study the statistical properties of the X-ray emission from a sample of 29 relatively isolated, normal elliptical and S0 galaxies. The results will be compared with those obtained for a sample of normal spiral and irregular galaxies (Fabbiano, Trinchieri, and Macdonald 1984; FT) to investigate the origin of the X-ray emission in early-type galaxies and the possible emission mechanisms. The influence of a powerful radio source and the onset of nuclear activity will also be investigated by comparing our normal sample with the 3CR galaxies sample (Fabbiano *et al.* 1984).

II. THE SAMPLE

Most of the galaxies used in the following analysis are part of a sample of normal galaxies compiled by Long and Van Speybroeck (1983, hereafter LVS) from the data of several observers. Four additional galaxies discussed by Nulsen, Stewart, and Fabian (1984), NGC 1172, NGC 1395, NGC 2974, and NGC 6876, have been included. The resulting sample consists of 29 early-type galaxies (with morphological parameter $T < 0$ as defined by de Vaucouleurs, de Vaucouleurs, and Corwin 1976) that were observed in X-rays with the *Einstein* observatory. The X-ray luminosities in the 0.5–3.0 keV band and the distances of all the galaxies are taken from LVS and Nulsen, Stewart, and Fabian (1984). The X-ray luminosity of NGC 4636 given in LVS might be underestimated by a factor of ~ 1.5 (see Stanger and Schwarz 1984). Since the data in LVS were analyzed in a uniform way, and we do not have a second estimate of the X-ray luminosity of most of the galaxies, we have chosen to use the LVS X-ray luminosities for all galaxies. Using the more recent estimate of the luminosity of NGC 4636 would not change our conclusions.

Blue magnitudes and color indices $U-B$ and $B-V$ are from de Vaucouleurs, de Vaucouleurs, and Corwin (1976). We have used the corrected face-on total magnitude and colors when available. Corrected infrared H (1.6 μm) magnitudes are available for 17 galaxies (Persson, Frogel, and Aaronson 1979; Aarsonson 1977), and the radio continuum fluxes, or upper limits, at 1400 MHz, for 18 galaxies (Hummel 1980). The fluxes at 408 MHz (Harnett 1982) and 2380 MHz (Dressel and Condon 1978) are available for four additional galaxies. For consistency with FT, we have used monochromatic values for the fluxes (mJy) and luminosities (ergs s^{-1} Hz^{-1}). The 2 keV X-ray monochromatic luminosities are derived from the 0.5–3.0 keV band luminosities. In Table 1 we list the galaxies in this sample, together with their infrared (H), optical (B), and X-ray (2 keV) monochromatic luminosities.

Due to the selection criteria, the resulting sample is not statistically complete. However, we believe it is a representative sample of normal nearby early-type galaxies. Figure 1 shows the distribution of blue apparent magnitude m_B and absolute magnitude M_B for the 29 galaxies used in this work. They cover a wide absolute magnitude range between $M_B \approx -18$ and $M_B \approx -23$ with colors in the range of normal elliptical and S0 colors (Larson and Tinsley 1978; see Fig. 9*a* in LVS). With the exception of NGC 1316 (Fornax A) and NGC 5532 (3C 296), they have weak or undetected radio continuum emission and do not show strong nuclear activity. They can also be regarded as a sample of relatively isolated galaxies. They are not at the center of rich clusters, although some are in poor groups (e.g., NGC 6876 in Pavo) or at the outskirts of the Virgo Cluster (e.g., NGC 4636 or NGC 4649).

III. RESULTS

Our analysis of the sample of elliptical and S0 galaxies is similar to our analysis of the sample of spiral and irregular galaxies (for details on the analysis, see FT).

a) *The Distribution of X-Ray Luminosities and X-Ray-to-Optical Flux Ratios*

Figure 2*a* shows the distribution of 0.5–3.0 keV X-ray luminosities for the 19 galaxies in the sample. Nineteen galaxies

TABLE 1

MONOCHROMATIC LUMINOSITIES
(ergs s^{-1} Hz^{-1})

NGC	D (Mpc)	log l_H	log l_B	log l_x
524......	51.90	...	29.66	23.18
720......	38.58	...	29.54	23.27
936......	26.64	29.79	29.27	<22.91
1172......	30.00	...	28.63	<22.12
1316......	32.64	30.54	30.00	23.59
1332......	30.40	29.91	29.36	22.89
1380......	29.28	29.91	29.36	22.75
1395......	34.00	29.94	29.31	23.01
1533......	11.20	...	28.20	21.46
1574......	19.98	29.38	28.93	<22.51
2859......	29.26	...	29.11	<22.41
2974......	40.00	29.86	29.34	22.85
3377......	15.98	28.20	28.80	<21.89
3489......	15.98	...	28.81	<22.01
3585......	24.74	29.73	29.26	22.05
3818......	31.66	...	28.75	<22.69
3923......	32.70	29.94	29.46	22.98
4251......	18.44	...	28.76	<21.76
4382......	20.26	29.90	29.41	22.77
4459......	20.78	29.50	28.94	<22.36
4636......	25.44	29.85	29.42	23.19
4638......	20.26	...	28.64	21.50
4649......	21.86	30.04	29.56	23.50
4697......	26.14	30.03	29.57	22.76
5102......	7.90	28.60	28.54	<21.76
5532......	142.12	...	29.98	23.85
5866......	19.40	29.56	29.15	22.25
5898......	42.56	...	29.15	22.62
6876......	80.00	...	29.46	23.76

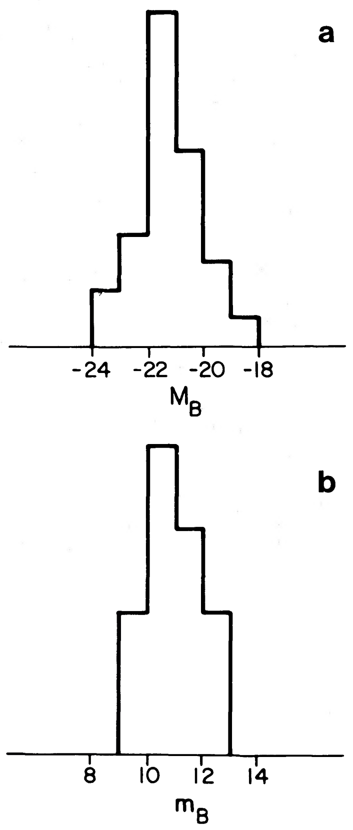

FIG. 1.—Distribution of (*a*) blue absolute magnitudes and (*b*) apparent magnitudes.

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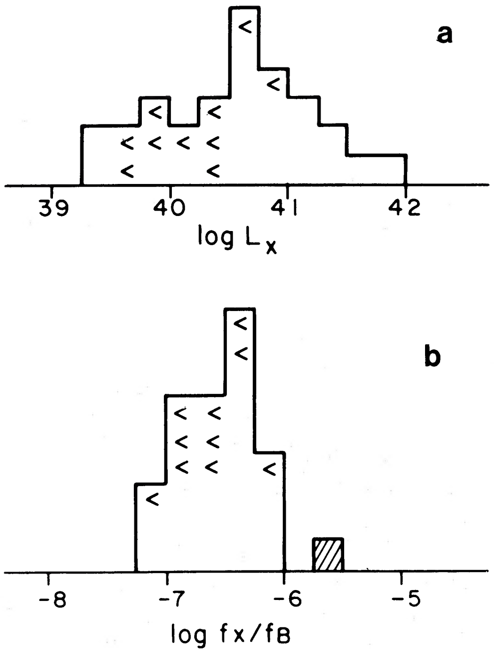

FIG. 2.—(*a*) Distribution of the X-ray luminosities L_x for the galaxies in the sample. (*b*) Distribution of the X-ray–to–optical flux ratios of f_x/f_B. The hatched box represents NGC 6876, for which only a Harvard magnitude is listed in de Vaucouleurs, de Vaucouleurs, and Corwin (1976).

($\sim$65%) were detected with X-ray luminosities in the range 2×10^{39} to 6×10^{41} ergs s^{-1}. The mean X-ray luminosity of the galaxies in the sample is $\langle L_x \rangle = 9 \times 10^{40}$ ergs s^{-1}, calculated using the "detection and bounds" (DB) method (Avni *et al.* 1980; Avni 1984; FT). As already noted by LVS, elliptical and S0 galaxies have on average a higher X-ray luminosity than spiral and irregular galaxies, although the two distributions overlap for more than a decade (see FT). The X-ray–to–optical monochromatic flux ratios f_x/f_B of early-type galaxies have a narrow distribution that ranges from 6×10^{-8} to 9×10^{-7} and is similar to the f_x/f_B distribution for late-type galaxies (FT), although less peaked (Fig. 2*b*).

b) Correlation Between X-Ray and Other Integrated Quantities

In Figure 3*a* the monochromatic X-ray luminosity l_x is plotted versus the optical blue luminosity l_B. The corresponding fluxes are plotted in Figure 3*b*. A correlation is evident in both cases. In order to give a quantitative estimate of the confidence level of each correlation, we applied the Spearman rank correlation test to our data, as in FT. The correlation coefficients r_{SR} and corresponding probabilities P_{SR} of a chance correlation are shown in Table 2. We calculated the correlation coefficients using the detections only (column A) and using both detections and bounds after assigning a worst case rank to the upper limits (column B). Since the latter coefficient represents a lower limit to the significance level of the correlation, we are confident that both the correlations found between the fluxes and the luminosities are real. The sample is not X-ray flux-limited, both detections and upper limits were included in the analysis, and there is a correlation also between the fluxes, so we can exclude the possibility that the correlation between the luminosities is due to a distance bias.

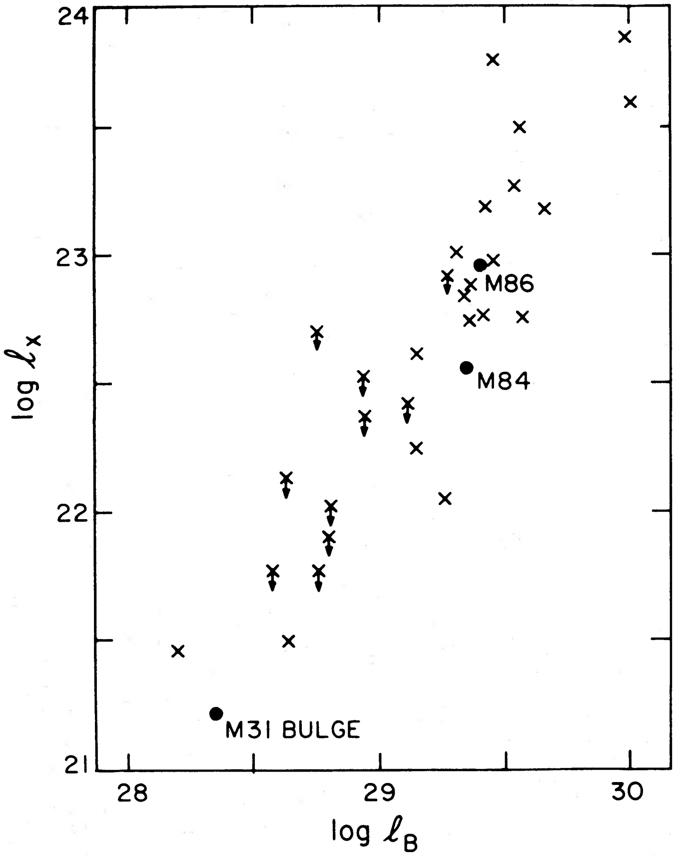

FIG. 3*a*

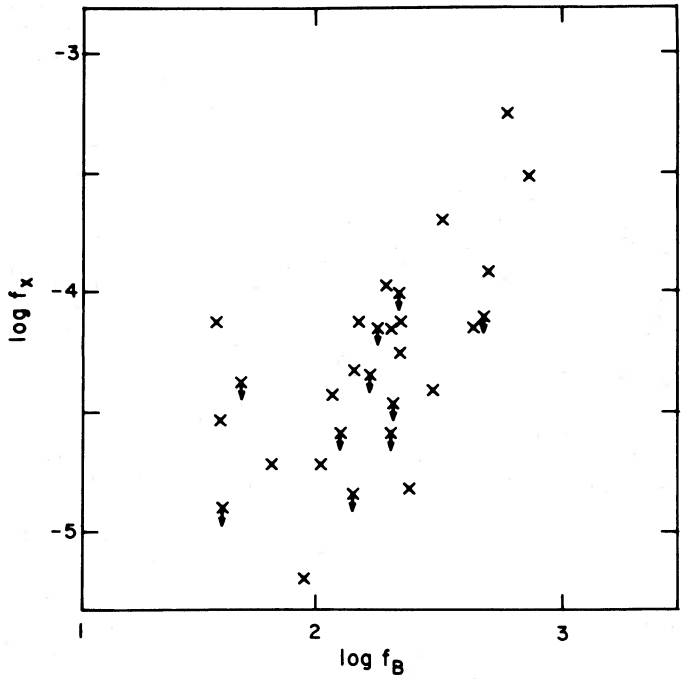

FIG. 3*b*

FIG. 3.—(*a*) Plot of the X-ray monochromatic 2 keV luminosity against the blue luminosity in units of ergs s^{-1} Hz^{-1}. M84, M86 and the bulge of M31 are also shown. (*b*) The X-ray monochromatic flux against blue flux in units of mJy.

TABLE 2

SPEARMAN RANK CORRELATION COEFFICIENTS AND PROBABILITIES (one-tailed)

	A			B		
CORRELATIONS	N	r_{SR}	P_{SR}	N	r_{SR}	P_{SR}
l_x vs. l_B	19	0.82	$\sim 1 \times 10^{-5}$	29	0.79	$<1 \times 10^{-6}$
f_x vs. f_B	19	0.66	$\sim 1 \times 10^{-3}$	29	0.32	$\sim 5\%$

NOTE.—A, detections only; B, "worst case" ranking for upper limits.

The blue magnitude is the only quantity for which information is available for all the galaxies. Twenty-six of the 29 galaxies have published $B-V$ colors from which we can derive the V magnitudes. Infrared H (1.6 μm) magnitudes have been published for about half the galaxies in the sample. To find the functional dependence of l_x on l_B, l_v, and l_H, we analyzed the data using the DB method (see FT). The method allows us to use the information given by both detections and upper limits in the X-ray data to derive the parameters that best describe the correlation. The assumptions to be made are that the dependence can be represented by a straight line, that the points are normally distributed around the best fit line with a spread σ, and that both detections and bounds are from the same parent population. The results are summarized in Table 3. In all instances the relation between X-ray and optical-infrared luminosities can be fitted with a power law with exponent $\alpha \approx 1.6$.

We also find that bluer early-type galaxies tend to have lower X-ray luminosities. However, we would expect this correlation as a consequence of the correlation between X-ray and optical luminosity and of the already established correlations between the optical magnitude and galaxy colors (see van den Bergh 1975, and references therein). Only about five galaxies of the present sample have radio continuum fluxes available in the literature. Therefore no useful information can be obtained on a possible correlation between X-ray and radio emission in early-type galaxies with the data available at present. This point will be addressed more fully in a future paper, using recently obtained radio flux measurements (Klein *et al.*, in preparation).

c) Comparison with Normal Spiral and Irregular Galaxies

Fabbiano, Trinchieri, and Macdonald (1984) and FT studied the statistical X-ray properties of spiral and irregular galaxies. They found that the X-ray luminosity of those galaxies is correlated with the optical luminosity with a functional dependence $l_x \propto l_B{}^{1.08 \pm 0.07}$.

TABLE 3

LINEAR FIT COEFFICIENTS AND DISPERSION

Y[a]	X[a]	A	99% Confidence Range	B	σ
$\log l_x$	$\log l_B$	1.64 ± 0.15	1.26–2.05	−25.4	0.30
$\log l_x$	$\log l_V$	1.52 ± 0.14	1.2 –1.86	−22.3	0.25
$\log l_x$	$\log l_H$	$1.65^{+0.25}_{-0.35}$	1.00–2.40	−26.5	0.25
$\log f_x$	$\log f_B$	$0.8\ ^{+0.30}_{-0.20}$	0.20–1.50	−6.2	0.40
$\log f_x$	$\log f_V$	$1.1\ ^{+0.25}_{-0.15}$	0.55–1.7	−7.2	0.35
$\log f_x$	$\log f_H$	1.55 ± 0.35	0.65–2.45	−8.7	0.30

[a] $Y = AX + B$ with a dispersion σ around the straight line.

The elliptical and S0 galaxies show a correlation between l_x and l_B, with a much steeper functional dependence: $l_x \propto l_B{}^{1.64 \pm 0.15}$. The lower boundary of the 99% confidence region on the exponent, ~ 1.26, is higher than the upper boundary of the 99% confidence region found for spiral galaxies, which is $\lesssim 1.23$. The probability that the slope obtained for the spiral and irregular galaxy sample could fit the early-type sample is $P \approx 10^{-4}$.

A clearer representation of this result is shown in Figure 4. Here we plot the distribution of the residuals obtained from the sample of early-type galaxies after removing the best fit obtained above (Fig. 4*a*). The residuals are normally distributed around a mean of zero. On the contrary, the residuals obtained for early-type galaxies about the best fit regression line of the spiral and irregular galaxy sample (FT) are systematically displaced towards negative values (Fig. 4*b*), contrary to what would be expected if the present samples could be fitted with the same parameters as the FT sample. We can quantify this difference by applying the Kolmogorov-Smirnov (KS) test to the distributions of residuals we obtained. Given the presence of bounds in the data, we could not apply the KS test directly. However, since we are testing whether the two distributions differ, we can estimate how the bounds should be distributed to make the two distributions more similar. This corresponds to having all the bounds in Figure 4*b* in the highest bin ($\geq +0.4$) and those in Figure 4*a* at their value. The KS test applied to the distributions thus obtained gives a probability of $\sim 5\%$ that the two distributions are alike. This should be regarded as a maximum value, since we have assumed the most unfavorable distribution of the bounds. Schmitt (1985) has adapted to the field of astronomy some statistical methods for the comparison of two samples in the presence of bounds in the data. We have applied the three tests in Schmitt, namely the logrank, Gehan, and Wilcoxon tests, to the two distributions of residuals in Figure 4. The results are consistent with the "adapted" KS test discussed above: we find a probability $P \approx 5\%$ for the logrank test and $P \lesssim 2\%$ for

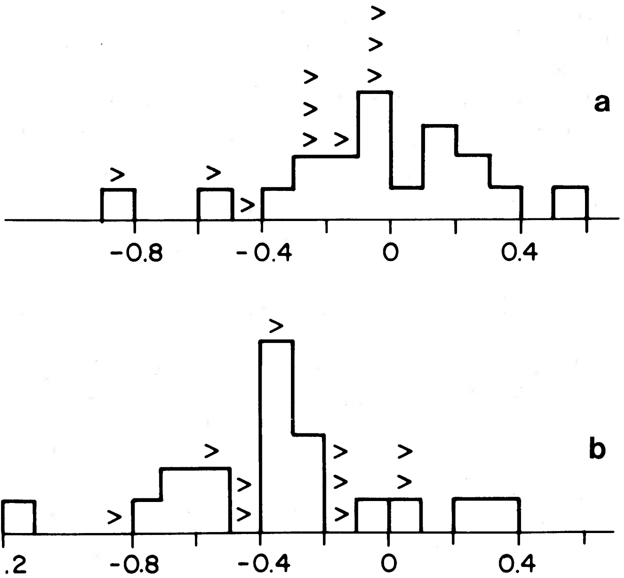

FIG. 4.—(*a*) Distribution of the residuals obtained for the elliptical and S0 galaxy sample after subtracting the best fit $\log l_x = 1.64 \log l_B - 25.4$. (*b*) Same, using $\log l_x = 1.08 l_B - 9.2$.

the Gehan and Wilcoxon tests that the two distributions are alike.

IV. DISCUSSION

In § III, we have shown that the X-ray luminosity of elliptical and S0 galaxies is correlated with their blue luminosity with a functional dependence of the form $l_x \propto l_B^{1.64 \pm 0.15}$. The same functional dependence is found between the X-ray luminosity and the infrared luminosity: $l_x \propto l_H^{1.65 \pm 0.30}$. This similarity is not surprising, since in these galaxies the infrared to optical color has a narrow distribution (Persson, Frogel, and Aaronson 1979). Since the correlation of l_x and l_H is derived using only about half the galaxies in the sample and does not introduce new information, we will not discuss it further. These correlations indicate that the origin of the X-ray emission in early-type galaxies is closely connected to the luminous mass of the galaxy. In particular, the X-ray luminosity is a steep function of the mass, i.e., the more massive galaxies have a higher X-ray luminosity per unit mass. This is different from the result found for spiral and irregular galaxies where, as shown in FT, the X-ray luminosity is a linear function of the blue luminosity ($l_x \propto l_B$), but not of the infrared luminosity ($l_x \propto l_H^{\sim 0.74}$), and there is evidence that star formation, rather than mass, is a fundamental parameter for the X-ray emission.

The steep dependence of the X-ray emission on the optical emission in elliptical and S0 galaxies suggests either a different origin for the X-ray emission than in spiral and irregular galaxies, or at least the presence of an additional X-ray emitting component. The X-ray observations of a few nearby galaxies, both isolated and in sparse regions of clusters, have shown that the X-ray emission has a scale comparable to or larger than the optical extent (Nulsen, Stewart, and Fabian 1984; Stanger and Schwarz 1984; Forman, Jones, and Tucker 1985). However, due to the combination of the limited sensitivity and angular resolution of the *Einstein* observatory with the distance and the relatively small angular size of elliptical galaxies, individual sources could not be resolved in those galaxies. M32, the dwarf elliptical companion of M31, is close enough for the IPC to detect individual binary sources. The observations suggest the presence of two sources coincident with the galaxy (see Van Speybroeck and Bechtold 1981).

In the discussion below we consider two plausible explanations for the X-ray emission from normal elliptical and S0 galaxies: the thermal radiation from a hot interstellar medium, and the integrated emission of individual sources. We also discuss the possibility of a contribution from a nuclear source and the onset of nuclear activity in early-type galaxies. In what follows, we have assumed a constant mass-to-light ratio M/L of 10. With this choice, we will be consistent with the work of White and Chevalier (1984; see below).

a) *Gas*

Bechtold *et al.* (1983) and Forman, Jones, and Tucker (1984) find extended X-ray emission associated with elliptical galaxies in clusters, which they interpret as thermal radiation from hot gaseous coronae. They suggest that this gas is expelled through the galactic winds and is confined near the galaxies by the pressure of the intergalactic medium. The galaxies M84 and M86 are plotted in Figure 3*a* as examples of hot gaseous coronae.

However, such phenomena are only expected in galaxies in clusters, where the external medium is dense enough to stop the wind and trap the hot gas around the galaxies. For isolated galaxies, the estimated X-ray luminosities of the galactic winds would be too low to be detected (Mathews and Baker 1971). Two alternative mechanisms for the thermal emission of hot gas have been investigated. Forman, Jones, and Tucker (1985) suggest that hot coronae around galaxies could be a property of both cluster and isolated early-type galaxies. The gas would be bound to the galaxies by massive dark halos that extend beyond the optical image. Alternatively Nulsen, Stewart, and Fabian (1984); White and Chevalier (1984); and Stanger and Schwarz (1984) suggest a mechanism of infalling accreting gas similar to that observed in the centers of rich clusters of galaxies.

It is not the purpose of this paper to investigate in detail the mechanisms responsible for the thermal emission from hot gas, i.e., hot coronae or inflows. We can, however, compare the predictions of the models with the observations. The results can be seen in Figure 5. Neither model can explain the whole range of the observations and the relationship $l_x \propto l_B^{1.64}$. The hot coronae model predicts a functional dependence of the X-ray on the optical luminosity of the form $l_x \propto l_B^{2.0}$ (Forman, Jones, and Tucker 1985). Although in general agreement with the data, this is steeper than the best fit slope of 1.64 derived above. Moreover, this model would predict that even at low X-ray luminosities the X-ray emission is dominated by hot gas emission. This is in disagreement with the high-resolution X-ray observations of the bulge of M31, where pointlike sources clearly dominate the emission (Van Speybroeck *et al.* 1979).

Nulsen, Stewart, and Fabian (1984) suggested that, on the assumption of a steady cooling flow and no supernova energy input, $L_x \approx L_v^{1.5}$. This relationship would be in agreement with the correlation that we find. However, this phenomenon must fail at the low luminosities, because no gaseous component was found in the bulge of M31 (Van Speybroeck *et al.* 1979). The cooling flow calculations of White and Chevalier (1984), which include supernova energy input, instead show that the X-ray luminosity should be a roughly linear function of the mass, hence of the optical luminosity. This is in disagreement with the data, if the entire range of luminosities is considered. If the cooling flow model is applied to high-luminosity objects (see Nulsen, Stewart, and Fabian 1984; Stanger and Schwarz 1984), the results are in agreement with the observations. At lower luminosities, the White and Chevalier model predicts too much X-ray emission. To be consistent with the data, it would need to be truncated below an optical luminosity of few times 10^{29} ergs s^{-1} Hz^{-1}.

b) *Individual Sources*

The observations of spiral galaxies have shown that binary sources make the major contribution to the X-ray emission in those galaxies. Although we do not have the same detailed information on elliptical and S0 galaxies, it is reasonable to assume that if discrete X-ray sources are responsible for the observed X-ray emission, these are probably associated with low-mass stars and low-mass binary systems, either in the main body of the galaxy or in globular clusters.

i) *Low-Mass Stars*

The stellar component contribution is probably only a fraction of the observed X-ray luminosity in elliptical and S0 galaxies. Feigelson *et al.* (1981) have estimated that the diffuse X-ray emission observed in Cen A can be accounted for by dM dwarfs only if their median X-ray luminosity is higher than

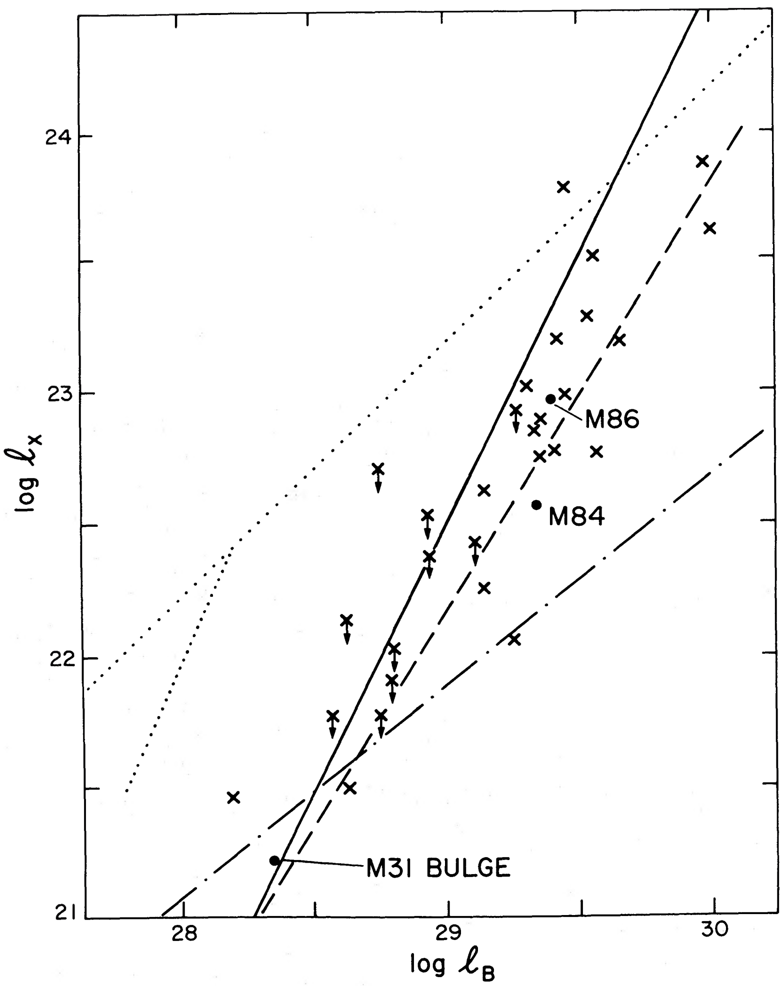

FIG. 5.—Same as Fig. 3*a*. The lines represent the different models considered: *dashed line*, best fit $l_x \propto l_B^{1.64}$; *solid line*, predicted dependence and normalization from the model of Forman, Jones, and Tucker (1985); *dot-dashed line*, individual sources; *dotted lines*, White and Chevalier (1984) model for $T \geq 1 \times 10^6$ K and $T \geq 2 \times 10^6$ K, in the assumption of supernova energy input.

that observed in M stars in the Milky Way. With similar arguments, we can estimate that the stellar component could contribute ~1% to 10% of the observed X-ray luminosity.

ii) *Globular Cluster Sources*

Both in our galaxy and in M31, ~10% of the known globular clusters have been detected in X-rays with $L_x > 10^{36}$ ergs s^{-1} (Hertz and Grindlay 1983; LVS). However, the average X-ray luminosity of globulars is higher in M31 (Van Speybroeck and Bechtold 1981). The galaxies in our sample should have on the average between ~500 and ~10,000 globular clusters if the number of globular clusters is a linear function of the optical luminosity (hence of the luminous mass, Harris and Racine 1979). If we assume that the distribution in X-ray luminosity for globular cluster X-ray sources in these galaxies is the same as in M31, we expect that these sources will contribute between ~2×10^{39} and ~4×10^{40} ergs s^{-1} to the total X-ray luminosity of early-type galaxies. This would represent a significant fraction of the X-ray luminosity for the lower mass objects ($M_T \lesssim 10^{11}\ M_\odot$) but only a few percent of the L_x for higher mass galaxies.

iii) *Low-Mass Binary Sources*

The detailed observations of the bulge of M31 in X-rays have shown that the emission is dominated by pointlike sources with $L_x \gtrsim 10^{37}$ ergs s^{-1} (Van Speybroeck *et al.* 1979). As often discussed in the literature (e.g., Faber 1981, and references therein), bulges are indistinguishable from elliptical galaxies in their surface brightness profiles, broad-band colors, and velocity dispersions. This would suggest that the same pointlike sources that are observed to dominate the X-ray emission of the bulge of M31 are very likely to be present in elliptical and S0 galaxies as well. Figure 3*a* shows that the bulge of M31 lies on the correlation between l_x and l_B of elliptical and S0 galaxies, among the low-luminosity objects. The similarity between bulges and low-luminosity elliptical galaxies is thus likely to extend to their X-ray emission.

The high X-ray luminosity of the X-ray sources and the stellar population present in bulges indicate that most likely these sources are low-mass binary systems (see also Vader *et al.* 1982, and references therein). However, the X-ray observations of the bulge of M31 (see Van Speybroeck *et al.* 1979) suggest the presence of two different populations, the higher X-ray luminosity "inner bulge" sources clustering in the inner 400 pc and the lower L_x "outer bulge" sources.

Several mechanisms for the formalism of these sources have been suggested. A low-mass star may capture an evolved object. To provide the high X-ray luminosity of these sources, the captured object should be either a neutron star or a black hole. Given the stellar density distribution, the capture mechanism could explain the inner bulge sources observed in M31 (see Van den Heuvel 1980), but fails to explain the formation of ("outer bulge") sources in less dense regions. Vader *et al.* (1982) argue against the formation of X-ray binaries by capture even in the innermost region of the bulge. They observe that since the binary X-ray sources and novae are similar systems, the capture mechanism should affect both similarly and result in a comparable distribution of X-ray sources and novae. The observed distribution of novae shows a "hole" in the center (Rosino 1973) not observed in the X-ray source distribution, which closely follows the light distribution. However, recent observations of novae in the M31 bulge seem to disprove the evidence of such a "hole" and suggest that the novae too follow the light distribution down to the nucleus (Ciardullo *et al.* 1984).

The "outer bulge" sources could be the remnants of disrupted globular clusters (LVS; see also Grindlay and Hertz 1983). However, Vader *et al.* (1982) have shown that the expected number of such sources is well below the observed value. Most likely these sources result from the evolution of native binary systems (Vader *et al.* 1982). The formation and evolutionary models for such sources are still quite uncertain. The time scale for the formation of low-mass binary X-ray sources could range from a few times 10^9 yr to $\sim 10^{10}$ yr (Rappaport, Joss, and Webbink 1982; Webbink, Rappaport, and Savonije 1983; Taam 1983; Patterson 1984). Therefore they could be related to either the old stellar population or to relatively recent star formation activity. Supporting evidence for the presence of a relatively young population in early-type galaxies comes from the observations of Frogel, Persson, and Cohen (1980). These authors find that the infrared colors of E galaxies could not be explained with the same stellar evolution models that adequately fit the globular cluster data. They tentatively interpret this discrepancy as implying the presence of an intermediate-age population, most likely red supergiants (1–2 $M_\odot$) of a few times 10^9 yr. Such a star formation event could be related to a population of X-ray–emitting binaries only if the initial mass function (IMF) were such as to provide a significant number of native binary systems containing a relatively fast evolving member. Alternatively, X-ray–emitting binaries could evolve from low-mass binary systems that have undergone a Type I supernova event (Gursky 1976; Webbink, Rappaport, and Savonije 1983; Canal, Isern, and Labay 1984). For the latter case, there would be no strong constraint on the age of the original binary system or on the IMF.

Using these models for the formation of low-mass X-ray sources, we can estimate the expected contribution of these sources to the total X-ray luminosity. We expect the integrated X-ray luminosity of the native binary system component to be linearly proportional to the luminous mass of the galaxy, if the gas available for star formation is the result of the mass loss from stars. If all the sources in the outer bulge of M31 are the result of the evolution of such systems into X-ray sources, we can simply scale their number with the total mass. Although this number is an upper limit to the expected number of "native" binary X-ray sources, it is a good estimate of the expected number of sources that were formed through processes that would give a linear relation between integrated X-ray luminosity (or number of sources) and mass (e.g., disrupted globular cluster X-ray sources).

TABLE 4

NUMBER OF CAPTURE X-RAY BINARY SOURCES ($L_x = 10^{37}$ ergs s^{-1})

M_T[a] ($M_\odot$)	r_e[a] (pc)	$r_{\rm capture}$ (pc)	$N_{\rm capture}$
3×10^9	150	64	120
3×10^{10}	700	300	80
3×10^{11}	2000	850	184
3×10^{12}	7000	3000	254

[a] From Young 1976.

To estimate the number of X-ray sources formed by capture ($N_{\rm capture}$) we have used the formula in Lightman and Grindlay (1982) for sources with $L_x = 10^{37}$ ergs s^{-1}:

$$N_{\rm capture} \approx 60\left(\frac{n}{0.01\ {\rm pc}}\right)\left(\frac{N}{10^{11}}\right)f\left(\frac{\sigma}{250\ {\rm km\ s^{-1}}}\right)^{-1}, \quad (1)$$

where n is the star density, N the number of stars, σ their velocity dispersion, and f the fraction of neutron stars present, which depends on the IMF. Table 4 gives the number of captured X-ray sources $N_{\rm capture}$ estimated as a function of total masses M_T. In order to obtain $N_{\rm capture}$, we have made the following assumptions:

1. We have taken into account the radial dependence of the quantities in equation (1). To do so, we have used the tables given by Young (1976) for a spherical system that obeys the de Vaucouleurs' $r^{1/4}$ law. For such systems the total mass M_T is related to the effective radius r_e (defined as the radius that contains one-half the total light) by $M_T \propto r_e^2$ (de Vaucouleurs 1958).
2. As shown by equation (1), capture will be most efficient in regions of higher stellar densities and lower stellar velocities (i.e., the innermost regions). We have therefore estimated $N_{\rm capture}$ inside a region of radius $r_{\rm capture}$, chosen to be a fixed fraction of r_e. In particular, $r_{\rm capture} \approx 0.44 r_e$. This was obtained assuming $r_{\rm capture} \approx 400$ pc for a spheroid with $M_T \approx 5 \times 10^{11}\ M_\odot$ (assumed for the bulge of M31, with $B \approx 5.14$ [de Vaucouleurs 1958] and $M/L = 8.5$ [Faber and Gallagher 1979]), in order to be able to compare our estimates with the bulge of M31. A constant fraction of the total mass is consequently contained within $r_{\rm capture}$.
3. The free parameter f was chosen to be $f \approx 1 \times 10^{-3}$, in order to reproduce the X-ray observations of the bulge of M31. An average stellar mass $M \approx 0.4\ M_\odot$ was assumed for stars.

As can be seen from Table 4, $N_{\rm capture}$ is a very weak function of the total mass M_T. We can explain this by deriving an approximate functional dependence between $N_{\rm capture}$ and M_T. From equation (1) with the above assumptions, we can express $N_{\rm capture}$ as

$$N_{\rm capture} \approx M_T^2/\sigma r_e^3\ . \quad (2)$$

The optical luminosity (hence M_T for constant M/L) is related to σ according to $L_{\rm opt} \propto \sigma^4$ (Faber and Jackson 1976). Substituting for r_e and σ in equation (2) gives

$$N_{\rm capture} \approx M_T^{1/4}\ . \quad (3)$$

Therefore the contribution of captured binary systems to the X-ray luminosity of elliptical galaxies becomes relatively less important in more luminous (massive) galaxies.

iv) *Summary*

Figure 5 shows the contribution of discrete sources to the X-ray emission of elliptical and S0 galaxies as a function of optical luminosity (or mass). The contributions of the stellar component, the globular cluster sources, and the native binaries scale linearly with mass. They are normalized at the observations of M31. We have shown above that the number of X-ray binaries formed by "capture" is a function of the mass with a slope $\sim\frac{1}{4}$, and that they contribute very little to the X-ray emission of high-luminosity galaxies. Therefore the integrated X-ray luminosity of various types of individual sources increases almost linearly with the optical luminosity of the galaxies. This means that we can entirely explain the X-ray emission of low-luminosity elliptical galaxies (up to a few times 10^{40} ergs s^{-1}) with the integrated emission of low-mass binaries and globular cluster X-ray sources. However, this component could account for only a few percent of the X-ray luminosity of the more luminous objects. Moreover, the integrated emission of discrete sources fails to explain the steep slope observed between l_x and l_B.

c) *Spectra*

As discussed above, the two most likely mechanisms for the X-ray emission from normal early-type galaxies are the thermal emission from hot gas and the integrated emission from low-mass binaries, distributed in the galaxy and in globular clusters. A very powerful tool for separating these two components is the spectral signature of the emission. X-ray binary sources show a thermal bremsstrahlung spectrum with characteristic temperatures $\gtrsim 5$ keV (e.g., van den Heuvel 1980). The same spectrum is observed in globular cluster sources (Hertz and Grindlay 1983). The X-ray emission from hot gas should instead be characterized by a much softer spectrum, with $kT \lesssim 1$ keV, as estimated by White and Chevalier (1984). The X-ray observations of the high-mass galaxy M87 show that the gas is at a temperature of a few keV in the outer regions but decreases to ~ 1 keV in the region within a 3′ radius from the nucleus (Fabricant and Gorenstein 1983).

The X-ray spectra available for some of the elliptical and S0 galaxies show temperatures of the order of 1 keV (Stanger and Schwarz 1984; Forman, Jones, and Tucker 1985; Nulsen, Stewart, and Fabian 1984). This would favor the hot gas emission over the binary and globular cluster source emission in early-type galaxies. However, the spectra were only derived for the high-luminosity objects ($l_x \gtrsim 10^{23}$ ergs s^{-1} Hz^{-1}). In these galaxies the hot gas is indeed likely to dominate the X-ray emission.

d) *The Onset of Nuclear Activity in Elliptical Galaxies*

The detailed observations of a few normal elliptical and S0 galaxies (Nulsen, Stewart, and Fabian 1984; Stanger and Schwarz 1984; Forman, Jones, and Tucker 1985) show that the X-ray emission of the more luminous objects is extended on a scale comparable to or larger than the optical extent. This evidence excludes the possibility that the bulk of the X-ray emission in normal early-type galaxies is due a nuclear source. With the present data we cannot directly isolate and study weak nuclear X-ray emission in these galaxies. To study the onset and the effect of X-ray nuclear activity in elliptical galaxies, we can compare the present sample with the sample of bright elliptical galaxies associated with strong 3CR radio sources studied by Fabbiano *et al.* (1984). 3CR galaxies are X-ray sources with L_x in the range 10^{42}–10^{45} ergs s^{-1}, and their X-ray luminosity is well correlated with their nuclear radio power, and often with emission line features, thus suggesting a nuclear origin for the X-ray emission.

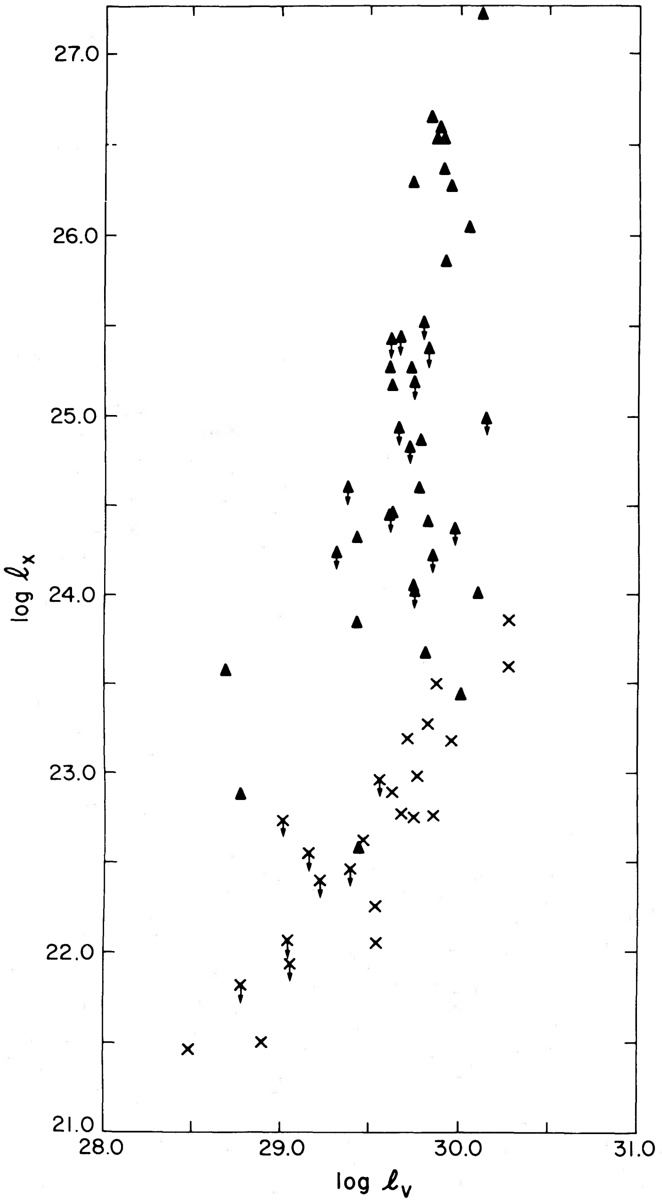

FIG. 6.—The monochromatic X-ray luminosity is plotted against the optical luminosity for normal elliptical and S0 galaxies (this sample, *crosses*) and the 3CR galaxies (Fabbiano *et al.* 1984, *triangles*). The *V*-band magnitudes have been used for consistency with the data for 3CR galaxies.

The monochromatic X-ray and optical luminosities of the 3CR galaxies from Fabbiano *et al.* (1984) and of the normal galaxies from this sample are shown in Figure 6. The 3CR galaxies follow the general trend between X-ray and optical luminosity found for normal galaxies, but are systematically displaced toward higher X-ray luminosities, although with some overlap at $l_x \approx 10^{23}$–10^{24} ergs s^{-1} Hz^{-1}. In particular, the higher X-ray luminosity objects show a very steep relation of X-ray to optical luminosity. With a linear regression analysis (see § III) applied to the high–X-ray–luminosity ($l_x \geq 10^{25}$ ergs s^{-1} Hz^{-1}) 3CR galaxies, we find: $\log l_x = (4.0 \pm 0.1) \log l_V - 93.74$, with a 99% confidence region for the slope between 1.85 and 6.0. This is significantly steeper than that found for normal early-type galaxies (see Table 3).

The high–X-ray–luminosity galaxies are also optically bright ($l_V > 2 \times 10^{29}$ ergs s^{-1} Hz^{-1}). This would suggest that high luminosity is necessary for the onset of a powerful nuclear source. However, it is evident from Figure 6 that this is not sufficient to ensure nuclear activity, since normal and active (3CR) galaxies are in the same range of optical luminosity. Two parameters, mass and ellipticity, have been suggested to govern the onset of radio activity in elliptical galaxies (Heckman 1983; Heeschen 1970; Hummel, Kotanyi, and Ekers 1983). A critical mass might be needed to retain enough gas to fuel the nuclear engine (see Norman and Silk 1979). Even optically bright but radio-quiet galaxies may have this critical mass, since a substantial amount of their interstellar gas is visible at X-ray temperatures at the present time (see above). Ellipticity might be the critical parameter that regulates the accretion onto the nuclear source (Hummel, Kotanyi, and Ekers 1983) and the onset of nuclear activity in radio-loud galaxies. These are two independent quantities, since massive galaxies do not tend to be rounder than less massive ones (see Davies *et al.* 1983; Tonry and Davis 1981).

It would then follow that the X-ray–luminous 3CR galaxies are round and massive systems, where the gas is continuously accreting onto the nucleus and is powering a central (radio and X-ray) source. This central source sustains a powerful extended radio source (most often a classical double) and dominates the emission in X-rays. Similar conclusions are reached by Dressel and Wilson (1985) from the study of the X-ray emission from a small sample of early-type galaxies with compact nuclear radio sources. The 3CR galaxies with $l_x < 10^{25}$ ergs s^{-1} Hz^{-1} could be massive but flatter systems (or round but less massive ones). Their nuclear sources do not dominate their X-ray emission, which thus becomes similar to that of normal radio-quiet early-type galaxies of similar high optical luminosity. The latter might be flatter and less massive systems, where the importance of the central sources has become negligible.

The above scenario, however, cannot account for the very steep dependence of the X-ray luminosity on the optical luminosity for X-ray luminous 3CR galaxies. If we regard these latter as having X-ray–optical properties intermediate between galaxies and quasars, we might be able to understand this steep relation. Tananbaum *et al.* (1983) have studied a sample of 3CR quasars observed in X-rays and found that for these objects, $l_x \propto l_0^{\sim 0.5}$. An exponent of ~0.7 is obtained by Zamorani (1982) for a more heterogeneous sample of radio-loud quasars. The optical and X-ray luminosities for the 3CR galaxies and 3CR quasars are shown in Figure 7. A power-law exponent of 0.5–0.8 for the quasar sample can be explained in terms of accretion models at a rate near the Eddington limit (see Tucker 1983). In these models, the optical luminosity refers to the luminosity of the region where the X-rays originate. In 3CR galaxies, however, the optical emission is probably dominated by the parent galaxy, while the nuclear region is most likely what we observe in quasars. The extrapolation of the X-ray–optical correlation for quasars to lower luminosities (see Fig. 7) shows that while the X-ray emission from the nucleus would still be dominant, its expected optical lumin-

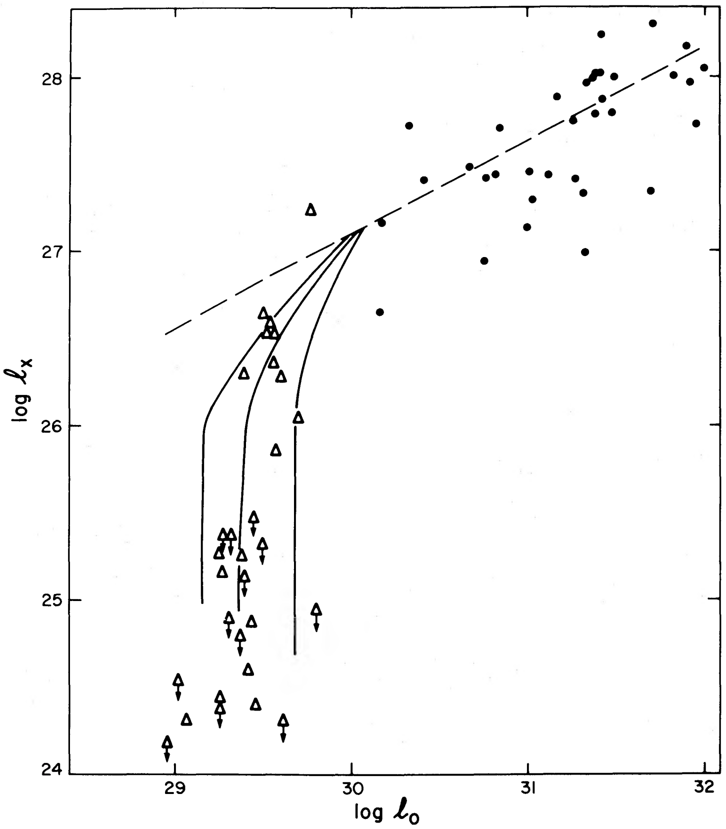

FIG. 7.—The monochromatic X-ray luminosity of 3CR quasars (Tananbaum *et al.* 1983, *circles*) and 3CR galaxies (Fabbiano *et al.* 1984, *triangles*) plotted as a function of optical luminosity (as defined in Zamorani *et al.* 1981). The dashed line represents the best fit to the 3CR quasar data. The solid lines represent how this best fit is modified when the effect of the whole galaxy is considered for three different optical luminosities.

osity would give a marginal contribution to the total optical emission for $l_x \lesssim 10^{26}$ ergs s^{-1} Hz^{-1}. Adding the parent galaxy contribution to the nuclear emission changes the optical luminosity substantially, but not the X-ray luminosity. In Figure 7, we show this effect. The curves plotted are obtained by adding the total optical luminosity of the galaxy (for three choices of l_0) to the optical luminosity of the nucleus as predicted from the correlation observed in radio-loud quasars. Since the total galaxy dominates in the optical when the X-ray luminosity is $l_x \lesssim 10^{26}$ ergs s^{-1} Hz^{-1}, the resulting curves are almost independent of the observed total optical luminosity. As shown in Figure 7, this could give a reasonable explanation of the steep X-ray–optical correlation in X-ray luminous 3CR galaxies.

V. SUMMARY AND CONCLUSIONS

We have shown that in early-type galaxies the X-ray luminosity l_x is correlated with the optical (blue) luminosity l_B. This correlation is significantly steeper than that observed for late-type galaxies: $l_x \propto l_B^{1.64 \pm 0.15}$ for the elliptical and S0 galaxy sample, while $l_x \propto l_B^{1.08 \pm 0.07}$ for spirals and irregulars (FT). The difference between these two relations is significant at the 99.99% confidence level. This result suggests a different origin of the X-ray emission in early-type galaxies.

There seem to be two separate mechanisms for the X-ray emission in high-luminosity and low-luminosity objects: thermal emission from hot gas is most likely responsible for the emission in galaxies with $L_x \gtrsim 10^{41}$ ergs s^{-1}, while low-mass binary sources dominate in galaxies with $L_x \lesssim 10^{40}$ ergs s^{-1}. There is some evidence to support the hot gas origin. The X-ray spectra of a few high-luminosity objects are too soft for low-mass binary sources but are consistent with a thermal emission of gas at $\sim 10^7$ K. The detailed observations of a few objects, namely, M84 and M86, are consistent with hot gas emission. However, this hot gas component cannot dominate in low-luminosity objects, as shown by the observations of the bulge of M31 and possibly of M32, where compact sources dominate. In low-luminosity objects the X-ray emission can be accounted for by a collection of globular cluster and low-mass binary sources. Similar tentative conclusions have been reached by Stanger and Schwarz (1984) based on a smaller sample of early-type galaxies. This indicates that a critical galaxy mass might be needed to retain a large amount of hot gas (see Norman and Silk 1979).

The power-law exponent of the $l_x - l_B$ relation was derived assuming that a single law could represent the data. However, it is most likely that two separate relations of l_x to l_B are needed. We expect a linear relationship between l_x and l_B at low optical and X-ray luminosities; at high luminosities, both a steep dependence of l_x on l_B, such as that expected from the hot coronae model (Forman, Jones, and Tucker 1985), or from gravitational cooling flows (Nulsen, Stewart, and Fabian 1984). They could also be consistent with a linear dependence truncated below $l_B \approx 2 \times 10^{29}$ ergs s^{-1} Hz^{-1}, if cooling flows with a significant supernova energy input occur (White and Chevalier 1984). For a mass-to-light ratio $M/L = 10$, this corresponds to a galaxy mass $M \approx 5 \times 10^{11}\ M_\odot$.

The extended X-ray emission of radio-quiet galaxies (Stanger and Schwarz 1984; Forman, Jones, and Tucker 1985; Nulsen, Stewart, and Fabian 1984) is qualitatively different from the emission observed in radio-loud galaxies of the same optical luminosity (3CR galaxies), where the X-ray emission is much stronger and is most likely of nuclear origin (Fabbiano *et al.* 1984). In particular, the 3CR galaxies can be regarded, in their X-ray properties, as an extension at lower luminosities of quasars of similar radio properties (3CR sample, Tananbaum *et al.* 1983). The high optical luminosity, or possibly the high mass (Heckman 1983), is most likely a necessary, but not sufficient, condition for the onset of a powerful nuclear X-ray source in early-type galaxies. In analogy to what has been suggested for the radio nuclear activity (Hummel, Kotanyi, and Ekers 1983), the galaxy ellipticity might influence the nuclear activity in X-rays.

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