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A STATISTICAL ANALYSIS OF THE *EINSTEIN* NORMAL GALAXY SAMPLE. III. RADIO AND X-RAY PROPERTIES OF ELLIPTICAL AND S0 GALAXIES

G. FABBIANO
Harvard-Smithsonian Center for Astrophysics
U. KLEIN
Radioastronomisches Institut der Universität, Bonn
G. TRINCHIERI
Harvard-Smithsonian Center for Astrophysics and Osservatorio Astrofisico di Arcetri, Firenze, Italy
AND
R. WIELEBINSKI
Max-Planck-Institut für Radioastronomie
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ABSTRACT

A sample of 20 elliptical and S0 galaxies has been observed at 4.75 GHz using the Effelsberg 100 m telescope. These galaxies are part of a sample of 29 early-type galaxies observed in the X-rays with the *Einstein Observatory* which was the object of a previous statistical analysis. For 11 of them, integrated flux densities could be derived; for the remaining ones, upper limits are given. Four of the radio-brightest galaxies have in addition been observed at 10.7 GHz, and one has also been observed at 32 GHz. Four of the six galaxies for which flux densities at more than one frequency are available show evidence of flat radio spectra, thus suggesting the presence of compact radio sources.

Using radio flux densities and upper limits from the literature for eight additional galaxies, we performed a statistical analysis of the radio, X-ray, and optical properties of the sample. We find that the radio luminosity of radio-quiet elliptical and S0 galaxies is correlated with their X-ray luminosity, but not with their blue luminosity. Our results agree with the picture of radio nuclear sources in early-type galaxies being accreting compact objects. The fuel could be provided by the radiatively cooling X-ray emitting gas present in these galaxies, thus explaining the correlation of radio and X-ray luminosities. The radio sources of these galaxies may be effectively confined within the galaxy by the X-ray emitting hot interstellar medium. We compare radio and X-ray properties of normal elliptical galaxies with those of double-lobed 3CR galaxies, and we suggest that the former could be scaled-down versions of the latter. Our results suggest a natural explanation for the nonlinear correlation between core and total radio power ($P_c \propto P_t^{0.57}$) of early-type galaxies over a large range of radio power through the interaction with the interstellar medium and the intracluster medium. We also suggest that the strength of the central radio source could help in providing a regulatory mechanism for the nuclear accretion.

Subject headings: galaxies: nuclei — galaxies: X-rays — radiation mechanisms — radio sources: galaxies

I. INTRODUCTION

Spiral, irregular, and dwarf galaxies have been studied in detail in the radio continuum during the past decade. Much knowledge has thereby accumulated concerning star formation processes, the origin and propagation of cosmic rays, and the structure and strength of magnetic fields in galaxies, thus improving the picture of their evolution (e.g., Ekers 1980). Only more recently, with the increased sensitivity available in radio telescopes, has the radio continuum of normal "radio-quiet" elliptical and S0 galaxies become an object of investigation. Active radio-loud elliptical galaxies, whose radio lobes reach far into intergalactic space, are the most studied objects in radio astronomy. However, if we exclude the bright radio galaxies, elliptical and S0 galaxies tend to be fainter radio sources than spiral galaxies in a given absolute magnitude range (Auriemma *et al.* 1977). This and their lower space density (and therefore larger average distances) have made difficult their detection and study in the radio range. Radio continuum surveys of elliptical and S0 galaxies (Ekers and Ekers 1973; Bieging and Biermann 1977; Condon and Dressel 1978; Feretti and Giovannini 1980; Hummel and Kotanyi 1982; Hummel, Kotanyi, and Ekers 1983) have shown that the sources in radio-quiet galaxies tend to be compact and with flat radio spectra. Brighter radio sources in the average are associated with optically brighter galaxies. The morphologies of these radio sources often suggest double-lobed structure, even when the total radio luminosity is comparable with that of a spiral galaxy (Ekers and Kotanyi 1978; Birkinshaw and Davies 1985).

Although these results suggest that the radio emission of elliptical and early-type galaxies is generally of nuclear origin, two outstanding problems still exist. One is the question of the physical processes that lead to this emission, the other is the question of the onset of activity (i.e., why some elliptical galaxies are very bright radio sources) (Hummel, Kotanyi and Ekers 1983; Heckman 1983).

We addressed these questions by studying a sample of 28 E and S0 galaxies which had been previously observed in X-rays with the *Einstein Observatory* (Giacconi *et al.* 1979). We have chosen this sample because X-ray studies have convincingly shown that large quantities ($\sim 10^9$–10^{10} $M_\odot$) of hot X-ray emitting gas are present in luminous E and S0 galaxies (Forman, Jones, and Tucker 1985; Trinchieri and Fabbiano 1985, hereafter Paper II), which until very recently had been thought devoid of an interstellar medium (e.g., Faber and Gallagher 1976). It has also been suggested that this gas might give rise to cooling flows accreting to the cores of the galaxies (Nulsen, Stewart, and Fabian 1984; Trinchieri, Fabbiano, and Canizares 1986). This gas could therefore be effective both in fueling nuclear radio sources (e.g., Hummel, Kotanyi, and Ekers 1983) and in confining them.

We observed 20 of these galaxies with the Effelsberg 100 m telescope, and we collected radio fluxes from the literature for another eight of them. X-ray fluxes for these galaxies have been published by Long and van Speybroeck (1983, hereafter LVS). A statistical analysis of this sample, comparing their X-ray and optical properties, has been presented in Paper II. Here we extend this study to the relationships between their radio, optical, and X-ray luminosities and compare them with those of double-lobed 3CR ellipticals. In Paper I of this series (Fabbiano and Trinchieri 1985), a similar analysis was performed for a sample of spiral and irregular galaxies.

In § II of this paper, we briefly describe the observational procedures and the data reduction and present the results of the observations. In § III we describe the statistical analysis of the data. The results of this analysis are discussed in § IV, and our conclusions are summarized in § V.

II. OBSERVATIONS AND RESULTS

Twenty of the LVS galaxies were observed at 4.75 GHz in 1983 April with the Effelsberg 100 m telescope of the MPIfR at Bonn. The receiver equipment, the observational procedure, and the data analysis were the same as described by Klein, Wielebinski, and Thuan (1984). The three-channel correlation receiver installed in the secondary focus of the telescope was used in the double-beam mode, with the two beams separated on the sky by 8′. Since the sources in normal elliptical galaxies are much smaller than the beam size at this frequency (HPBW = 2′.5), we carried out on-off observations for a total of 60 cycles of 20 s each on a given source, giving an integration time of 20 minutes per galaxy and a sensitivity of $\sim$0.2–0.4 mJy (1 σ) per beam area.

Four of the galaxies were also observed at 10.7 GHz in 1984 August using the two-channel receiver system equipped with three feeds which is also installed in the secondary focus of the 100 m telescope. The observing procedure was a cross-scanning technique which was chosen in view of the smaller beam size (HPBW = 1′.2). The two other horns, 3′ and 8′ offset, were used as reference feeds. With typically 20 cross scans performed on each of the four galaxies observed at this frequency, the system temperature of $\sim$80 K and the bandwidth of 500 MHz yielded a sensitivity of $\sim$1 mJy (1 σ) per beam area.

We were also able to measure NGC 4649 at 32 GHz using a two-beam, two-channel cooled mixer receiver installed in the primary focus of the 100 m telescope. The two signals were fed into a hybrid, the output of which was correlated to yield their difference. The system temperature was 200 K, the bandwidth 2 GHz, the beam separation was 82″, the HPBW 25″. The galaxy was scanned 30 times in azimuth, yielding a sensitivity of $\sim$5 mJy per beam area.

At 4.75 and 10.7 GHz we used the flux density scale of Baars *et al.* (1977) to calibrate our data relative to the sources NGC 7027, 3C 48, 3C 147, 3C 286, and 3C 295. These were observed by cross scans every 2 hr in order to accomplish the calibration and check the pointing accuracy which did not exceed 6″. At 32 GHz, W30H was used as the calibration source, with an assumed flux density of 3.6 Jy at this frequency.

Table 1 summarizes the 4.75 and 10.7 GHz flux densities with the 1 σ statistical errors and the upper limits for the undetected sources. These upper limits are typically at the 2 σ (statistical) level, except for five of the galaxies that were detected above the 2 σ level with fluxes below 1 mJy. Since the performance of the Effelsberg telescope at such low intensities has not been sufficiently established, we give conservative upper limits of ≤ 1 mJy to these galaxies. Most of the flux densities reported should not be affected by confusion, since the probability of detecting in our beam a background source with flux density $\sim$0.5–1.0 mJy is no more than 10% (estimated from recent work on source counts; Wall *et al.* 1982). In Table 1 we also give the VLA flux at 4.75 GHz (in parentheses; E. Hummel 1985, private communication) for NGC 4636, since our measurement could include contributions from two other fainter sources in the field that cannot be resolved with the Effelsberg beam. The flux density quoted for the bright double-lobed radio source (3C 296) associated with NGC 5532 (Birkinshaw, Laing, and Peacock 1981) has been estimated using published values from Fomalont (1971) and Fomalont, Palimaka, and Bridle (1980). Table 1 also summarizes flux densities published previously at 408 and 1415 MHz.

Table 1 shows that only the strongest sources ($S_{4.75} \approx 10$ mJy) have been detected at lower frequencies. The few 408 MHz detections published by Harnett (1982) may indicate low-frequency steep-spectrum components present in at least some of the galaxies. We find that the spectra of three galaxies observed at 10.7 GHz are flat, contrary to what is found for normal spiral galaxies (Gioia, Gregorini, and Klein 1982; Israel and van der Hulst 1983) and in agreement with the findings of Hummel and Kotanyi (1982) for normal elliptical galaxies. The galaxy NGC 4636 shows evidence of a flat high-frequency component, if the VLA flux densities (which do not include the two serendipitous fainter sources; see above) are used. NGC 524 instead could have a steeper spectrum. These spectral indices are listed in Table 1, and the radio spectra are shown graphically in Figure 1.

Birkinshaw and Davies (1985) have recently published the results of 5 GHz VLA observations of a sample of galaxies, including some of ours. Their results agree with ours except for NGC 3923, which we report as detected, and for which they instead quote an upper limit below 1 mJy. The VLA in the configuration used by Birkinshaw and Davies, however, might underestimate low surface brightness components extended more than 1′ that would be picked up by the Effelsberg telescope. We have used our results in the statistical analysis of the sample reported in § III. A similar analysis using the Birkinshaw and Davies (1985) fluxes gives essentially the same results.

III. STATISTICAL ANALYSIS

a) The Sample

The sample we use for this analysis consists of the 28 E and S0 galaxies in the LVS X-ray sample discussed in Paper II for which radio measurements are available to us. Twenty of these were surveyed with the Bonn 100 m radio telescope, as dis-

TABLE 1

4.75 AND 10.7 GHz FLUX DENSITIES

NGC	α (1950)	δ (1950)	$S_{408\,\mathrm{MHz}}$ (mJy)	References	$S_{1415\,\mathrm{MHz}}$ (mJy)	References	$S_{4750\,\mathrm{MHz}}$ (mJy)	References	$S_{10700\,\mathrm{MHz}}$ (mJy)	α[a]
524......	01^h22^m17	$+09°16'.7$	<30	1	<10	2	4.1 ± 0.8	5	...	−0.93 ± 0.31[b]
720......	01 50.57	−13 59.1	<40	1	<10	3	≤1.0	5	...	...
936......	02 25.08	−01 22.7	<60	1	<10	2	5.5 ± 0.8	5	7 ± 3	−0.13 ± 0.34
1332......	03 24.06	−21 30.5	<60	1	<10	2	≤1.0	5	...	...
2859......	03 21.26	+34 43.7	...	...	<10	2	<1.2	5	...	...
3377......	10 45.05	+14 15.0	<40	1	<10	3	<1.2	5	...	...
3489......	10 57.68	+14 10.2	<30	1	<10	2	1.5 ± 0.5	5	...	...
3585......	11 10.83	−26 28.8	<60	1	<10	3	<1.2	5	...	...
3818......	11 39.41	−05 52.7	...	...	< 8	3	≤1.0	5	...	...
3923......	11 48.50	−28 31.7	...	...	<10	3	4.5 ± 1.0	5	...	...
4251......	12 15.60	+28 27.1	...	...	<10	2	<1.2	5	...	...
4382......	12 22.88	+18 28.0	73 ± 16	1	<10	2	≤1.0	5	...	...
4459......	12 26.48	+14 15.3	...	...	<10	2	2.4 ± 0.8	5	...	...
4636......	12 40.29	+02 57.7	222 ± 20	1	±6	4	45 ± 9(26)	5(4)	24 ± 4	−0.68 ± 0.18[c]
										−0.11 ± 0.24[d]
4638......	12 40.27	+11 42.9	...	...	<10	2	≤1.0	5	...	...
4649......	12 41.15	+11 49.5	41 ± 19	1	26 ± 2	3	24 ± 2	5	26 ± 2[e]	−0.01 ± 0.05
4697......	12 46.01	−05 31.7	...	...	<10	3	1.2 ± 0.5	5	...	...
5532......	14 14.43	+11 02.3	...	...	...	...	~1500[f]	5	...	...
5866......	15 05.12	+55 57.3	...	...	16 ± 2	2	13 ± 1	5	12 ± 2	−0.15 ± 0.03
5898......	15 15.29	−23 55.0	...	...	<23	3	1.1 ± 0.5	5	...	...

[a] $S_\nu \approx \nu^\alpha$.
[b] Using the 2.38 GHz flux density published by Dressel and Condon 1978.
[c] α is between 1.4 and 5.0 GHz.
[d] α is between 5.0 and 10.7 GHz.
[e] $S_{33000\,\mathrm{MHz}} = 32 \pm 3$ mJy (see § II).
[f] Double-lobed radio galaxy.

REFERENCES.—(1) Harnett 1982. (2) Hummel and Kotanyi 1982. (3) Hummel, Kotanyi, and Ekers 1983. (4) Hummel 1986, in preparation (from VLA observations). (5) This work.

cussed in the previous section. For the other eight we used data from the literature. Table 2 lists the galaxies in the sample, together with their 5 GHz, blue, and 2 keV monochromatic fluxes and luminosities, for the same distances used in Paper II. Two of the galaxies, NGC 1316 (Fornax A) and NGC 5532 (3C 296), are bright radio sources and show double-lobe structure. The other galaxies have radio luminosities consistent with those of radio-faint field elliptical galaxies (e.g., Hummel, Kotanyi, and Ekers 1983). Since the presence of these two radio galaxies might introduce a bias in our correlation analysis, we have analyzed both the entire 28 galaxies sample and the sample of 26 galaxies obtained by discarding them.

Although the sample used in this analysis is not statistically complete, it is, however, representative of normal E and S0 galaxies, covering absolute blue magnitudes $M_B = -18$ to -24, as shown in Paper II. Our analysis also does not suffer from assuming a flux limit in either the X-ray or the radio band, since all galaxies were observed in these two bands and are included in the analysis independently from their being detected or not.

b) Correlation Analysis

Figures 2*a* and 2*b* show the 5 GHz monochromatic radio luminosity l_R plotted versus the X-ray 2 keV monochromatic luminosity l_x and the blue luminosity l_B for the sample of 26 radio-quiet galaxies. The X-ray luminosity l_x is plotted versus l_B in Figure 2*c*. Figure 3 shows plots of l_R versus l_x and of l_R versus l_B for the 28 galaxies sample, including the two radio-loud ones. Although a large number of limits is present in both l_x and l_R, Figure 2 suggests a correlation of l_x with l_B (the presence of this correlation in early-type galaxies was extensively discussed in Paper II) and also of l_x with l_R, although with more scatter in the latter case. The l_R, l_B plot instead does not show any correlation between these two quantities. To quantify these results we have performed a two-dimensional maximum likelihood analysis, following the methods outlined by Schmitt (1985) which allow us to make full use of all the available information, including all the limits in either or both variables.

The results for the correlations between luminosities are summarized in Table 3, which gives the results of a Monte Carlo (bootstrap) calculation on the maximum likelihood estimates for the correlation coefficient and the linear regression coefficients. As discussed in Schmitt (1985), the bootstrap is a nonparametric way of calculating errors of quantities derived from a maximum likelihood distribution function. The error of each quantity is estimated by calculating the maximum likelihood distribution function *f* and then studying the distribution of the maximum likelihood estimate of the quantity in question by using random samples distributed like *f*. The bootstrap (1 σ) errors given in Table 3 were all calculated for 99 bootstrap replications. The correlation coefficients for the l_x, l_R and the l_R, l_x regressions are slightly different. This is due to a different redefinition of the lowest upper limits as detections in the two cases, needed in order to obtain normalized distribution functions (Schmitt 1985).

Table 3 shows that the strongest correlation is the one between X-ray and optical luminosities. X-ray and radio luminosities are also correlated in both the "radio-quiet" sample of 26 galaxies and the sample including the double-lobed radio galaxies, Fornax A and 3C 296. The radio and blue luminosities are not correlated if one excludes the two double-lobed radio galaxies from the correlation analysis. They are correlated if one includes them. But even in this case the corre-

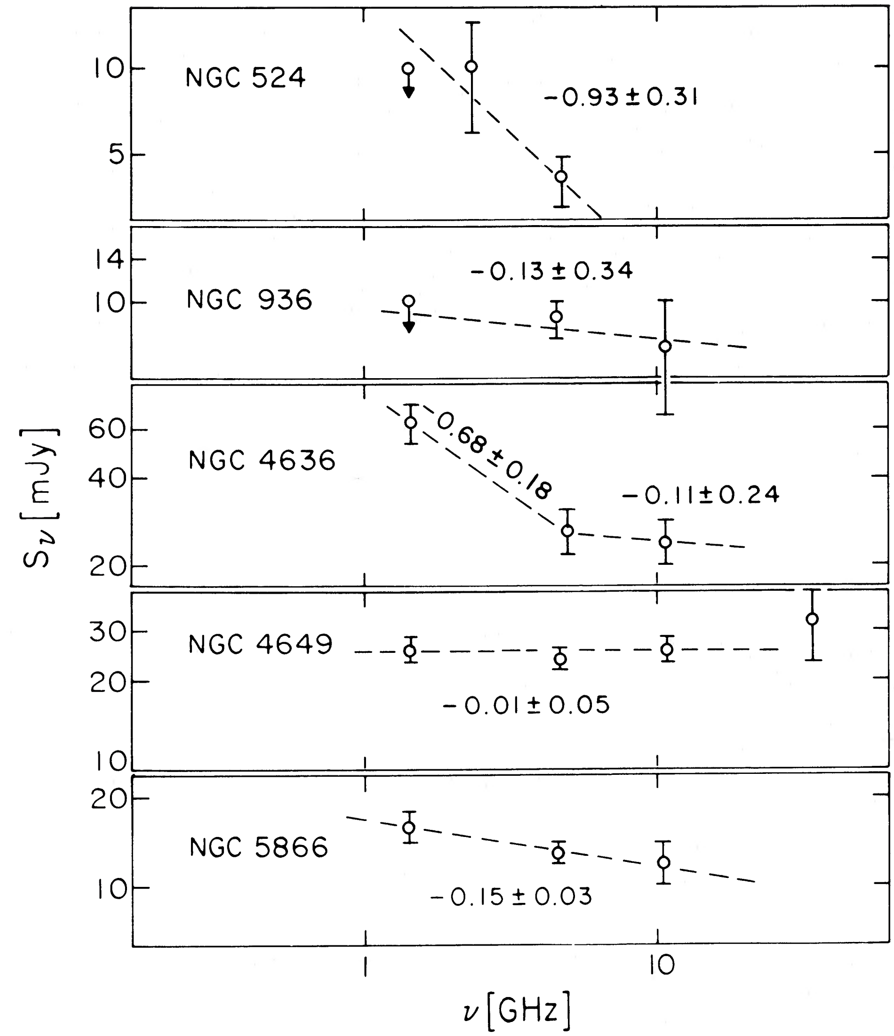

FIG. 1.—Integrated radio continuum spectra of the elliptical galaxies in this paper for which flux densities at several frequencies are available. Dashed lines represent the least-squares straight-line fits to the data.

lation is weaker than those between l_x and l_B and between l_x and l_R for the same sample. The linear regression slopes of the various correlations are different. In particular, the slope of the log l_x versus log l_B correlations is $\sim$1.6–1.7 (as already noticed in Paper II). The slope of the log l_R versus log l_x correlation is shallower and could be consistent with linearity in the radio-quiet sample. We performed the same correlation analysis on the logarithms of the monochromatic fluxes (f_x, f_R, and f_B), and we found results in agreement with those reported above. In particular, the fluxes f_x and f_B are correlated, and f_x and f_R could be weakly correlated. Instead, f_R and f_B are definitely not correlated.

The question might arise if the correlations between luminosities that we have discussed above could be due to a distance bias (Malmquist effect). We are confident that this is not the case for the following reasons. First, as discussed in § III*a*, the sample is not flux limited in either the X-ray or radio frequencies, since all galaxies were observed and *both* detections and upper limits are used in the statistical analysis. Second, similar, although weaker, correlations are also present between the fluxes. Third, if the observed correlations were due to a distance effect, we would also expect to see the same trend between radio and optical luminosities, which are instead only weakly correlated, or not correlated at all, if one excludes the two radio-bright galaxies. We conclude then that the X-ray luminosity of radio-quiet elliptical and S0 galaxies is correlated with both their optical luminosity and their 5 GHz radio power. The much weaker (if any) correlation between radio and optical luminosities is likely to be the by-product of the other two stronger ones.

We point out that these results were obtained by conservatively assigning upper limits to the five galaxies detected below 1 mJy (§ II). If these galaxies were considered as detected, our results would be even stronger. Also, as discussed in § II, our results do not change appreciably if we use the VLA fluxes (and upper limits) of Birkinshaw and Davies (1985) for some of the galaxies instead of the Effelsberg fluxes.

c) Comparison with Spiral Galaxies

The X-ray luminosity of luminous elliptical and S0 galaxies is dominated by a diffuse gaseous component (Paper II; Forman, Jones, and Tucker 1985), while that of spiral and irregular systems is likely to be the product of a population of individual X-ray sources (Paper I). A direct comparison of

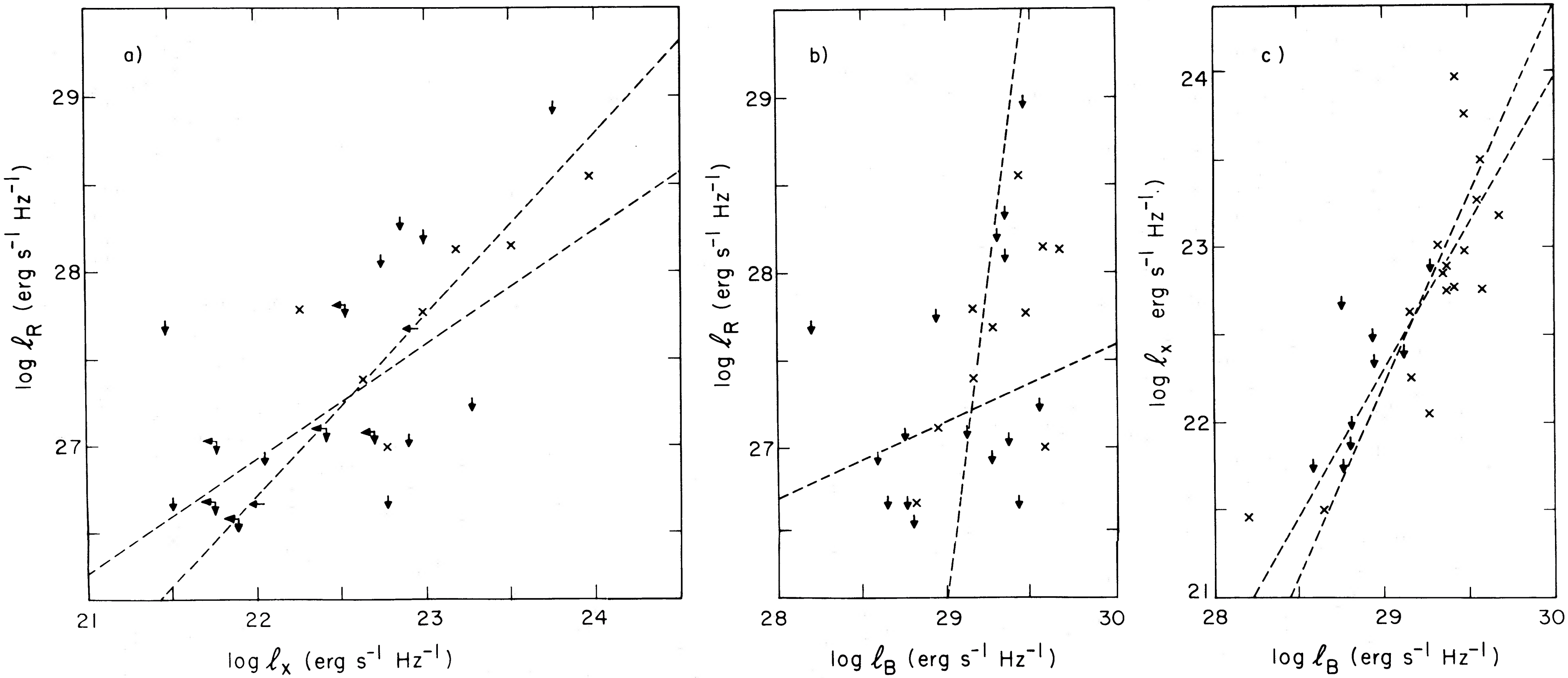

FIG. 2.—Sample of 26 radio-quiet galaxies. (*a*) Plot of the log of the 5 GHz radio (l_R) vs. the log of the 2 keV X-ray (l_x) monochromatic luminosities. (*b*) Plot of log l_R vs. the log of the monochromatic *B* luminosity (l_B). (*c*) Plot of log l_x vs. log l_B. Dashed lines represent "best fit" regression lines from Table 3.

TABLE 2

RADIO, OPTICAL, AND X-RAY FLUXES AND LUMINOSITIES

NGC	log f_R[a] (5 GHz)	log f_B[a]	log f_x[a] (2 keV)	log l_R[b] (5 GHz)	log l_B[b]	log l_x[b] (2 keV)
524...	0.61	2.15	−4.33	28.12	29.66	23.18
720...	<0.00	2.29	−3.98	<27.25	29.54	23.27
936...	0.74	2.34	<−4.02	27.67	29.27	<22.91
1316...	4.82[c]	2.89	−3.52	31.93	30.00	23.59
1332...	<0.00	2.31	−4.16	<27.05	29.36	22.89
1380...	<1.08[d]	2.35	−4.26	<28.09	29.36	22.75
1395...	<1.08[d]	2.17	−4.13	<28.22	29.31	23.01
1533...	<1.52[e]	2.02	−4.72	<27.70	28.20	21.46
1574...	<1.08[d]	2.25	<−4.17	<27.76	28.93	<22.51
2859...	<0.08	2.10	<−4.60	<27.09	29.11	<22.41
2974...	<1.08[d]	2.06	−4.43	<28.36	29.34	22.85
3377...	<0.08	2.31	<−4.60	<26.57	28.80	<21.89
3489...	0.18	2.32	<−4.48	26.67	28.81	<22.01
3585...	<0.08	2.39	−4.82	<26.95	29.26	22.05
3818...	<0.00	1.67	<−4.39	<27.08	28.75	<22.69
3923...	0.65	2.35	−4.13	27.76	29.46	22.98
4251...	<0.08	2.15	<−4.85	<26.69	28.76	<21.76
4382...	<0.00	2.72	−3.92	<26.69	29.41	22.77
4459...	0.38	2.22	<−4.36	27.10	28.94	<22.36
4636...	1.65	2.53	−2.90[f]	28.54	29.42	23.99
4638...	<0.00	1.95	−5.19	<26.69	28.64	21.50
4649...	1.38	2.80	−3.26	28.14	29.56	23.50
4697...	0.08	2.66	−4.15	26.99	29.57	22.76
5102...	<1.08[d]	2.70	<−4.12	<26.96	28.58	<21.76
5532...	3.18	1.59	−4.54	31.57	29.98	23.85
5866...	1.11	2.49	−4.41	27.77	29.15	22.25
5898...	0.04	1.81	−4.72	27.38	29.15	22.62
6876...	<1.08[d]	1.57	−4.13	<28.97	29.46	23.76

[a] Monochromatic fluxes are in units of mJy.
[b] Monochromatic luminosities are in units of ergs s^{-1} Hz^{-1}. They were derived from the monchromatic fluxes for the same distances as in Trinchieri and Fabbiano 1985.
[c] Fornax A; flux from Sadler 1984.
[d] Disney and Wall 1972.
[e] 2.7 GHz upper limit; Sadler 1984.
[f] This is a revised X-ray flux; see Forman, Jones, and Tucker 1985 and Stanger and Schwarz 1986.

radio and X-ray properties of elliptical and S0 galaxies with spirals and irregulars is therefore not meaningful. If one wanted to explore a possible relationship of the radio emission of elliptical and S0 galaxies to the X-ray emitting stellar population (which is strongly linked with the radio emission in spiral galaxies; Paper I), one should first subtract the contribution of their gaseous component from their total X-ray emission. This is a fairly uncertain operation that could be done extrapolating from low-luminosity systems under certain simplifying assumptions (Paper II).

We therefore resolved to compare only the radio and optical luminosities of the galaxies which are the object of this paper with those of the galaxies discussed in Paper I in order to verify that our results are consistent with previous observations.

In Figure 4 we plot the log of the optical luminosity l_B versus the log of the 5 GHz radio luminosity l_R for the elliptical and S0 galaxies and for the spiral galaxies discussed in Paper I. The 5 GHz radio power for the spiral galaxies was calculated from the 1.4 GHz values used in Paper I, on the assumption of a power-law spectrum ($l_R \propto \nu^{+\alpha}$) with an index $\alpha = -0.73$ (Gioia, Gregorini, and Klein 1982). In Figure 4 the line log $l_B = 9.2 + 0.7 \log l_R$ which describes the distribution of points for the late-type spiral and irregular galaxy sample (Sc–Im) of Paper I is also shown. It is clear from the figure that, for the same optical luminosity, elliptical galaxies can be a factor of 10 less luminous in radio than late-type spiral galaxies. This is consistent with a comparison of the radio luminosity functions of elliptical and S0 galaxies and spiral and irregular galaxies (Auriemma *et al.* 1977; Hummel 1980). Early-type spirals (Sa–Sbc) appear to be intermediate between ellipticals and late-type spirals in their optical-radio luminosities.

We can quantify the above statement by means of a Kolmogoroff-Smirnoff (K-S) test. Using the line plotted in Figure 4 to describe the l_B, l_R correlation of late-type spiral and irregular galaxies as a baseline, we can calculate the difference between the logarithms of the observed and the expected l_B for each radio luminosity l_R. The histograms of these differences are plotted in Figure 5. We apply a K-S test to compare these histograms. To be conservative, we place the upper limits so as to minimize the difference between any two distributions. As a result of this procedure, we obtain a probability $p < 0.1\%$ that the two distributions of Figures 5*a* (E and S0) and 5*c* (late-type spirals) could be drawn from the same parent population. If we apply the same conservative test to the histograms of Figure 5*a* (E and S0) and 5*b* (early-type spirals), we find a less definite difference ($p \approx 10\%$). The histograms of early- and late-type spirals are statistically consistent. These results agree with the trend of decreasing l_R (for the same l_B) with morphological type (from late-type galaxies to E and S0) suggested by Figure 4.

IV. DISCUSSION

a) Cooling Flows and the Feeding of the Nuclear Engine

There is widespread evidence pointing to intrinsic differences between the radio emission of spiral galaxies and of elliptical and S0 galaxies and suggesting a nuclear origin for the radio sources in the latter (e.g., Ekers 1980; Hummel, van der Hulst, and Dickey 1984). Our results of §§ II and III*c* are in agreement with this picture and with previous work on the subject.

The principal result of our statistical analysis (§ III*b*) is that in radio-quiet ($l_R < 10^{29}$ ergs s^{-1} Hz^{-1}) elliptical and S0 galaxies a stronger link exists between radio (l_R) and X-ray (l_x) luminosities than between radio (l_R) and optical (l_B) luminosities. Within the statistical uncertainties, the correlation

TABLE 3

CORRELATION BETWEEN LUMINOSITIES[a]

y, x	r_c	A	B
l_x, l_R	0.69 ± 0.05	$0.40^{+0.10}_{-0.08}$	$11.6^{+2.2}_{-2.7}$
	$0.79^{+0.09}_{-0.15}$	$0.88^{+0.23}_{-0.22}$	$-1.5^{+6.0}_{-6.1}$
l_R, l_x	$0.68^{+0.06}_{-0.08}$	$1.06^{+0.35}_{-0.20}$	$3.7^{+4.2}_{-7.6}$
	$0.78^{+0.09}_{-0.20}$[b]	$0.63^{+0.13}_{-0.15}$	$12.9^{+3.5}_{-2.5}$
l_x, l_B	$0.90^{+0.04}_{-0.05}$	$1.61^{+0.15}_{-0.13}$	$-24.5^{+3.7}_{-4.3}$
	$0.88^{+0.04}_{-0.05}$	$1.68^{+0.21}_{-0.22}$	$-26.5^{+6.5}_{-6.1}$
l_B, l_x	$0.90^{+0.04}_{-0.05}$	$0.50^{+0.07}_{-0.06}$	$17.9^{+1.4}_{-1.7}$
	$0.88^{+0.04}_{-0.05}$	$0.46^{+0.08}_{-0.07}$	$18.8^{+1.6}_{-1.9}$
l_R, l_B	$0.60^{+0.12}_{-0.17}$[b]	$1.87^{+0.85}_{-0.93}$	$-27.5^{+24.7}_{-29.5}$
	0.28 ± 0.21[c]	$0.46^{+0.39}_{-0.35}$	$13.6^{+10.1}_{-11.4}$
l_B, l_R	$0.60^{+0.12}_{-0.17}$[b]	$0.18^{+0.04}_{-0.03}$	$24.2^{+0.9}_{-1.1}$
	0.28 ± 0.21[c]	$0.17^{+0.13}_{-0.12}$	$24.4^{+3.1}_{-3.5}$

NOTE.—Upper row of each y, x pair corresponds to 28 galaxies sample; lower row corresponds to "radio-quiet" sample of 26 galaxies.
[a] $\log y = A \log x + B$.
[b] About 2% probability of spurious correlation.
[c] Uncorrelated.

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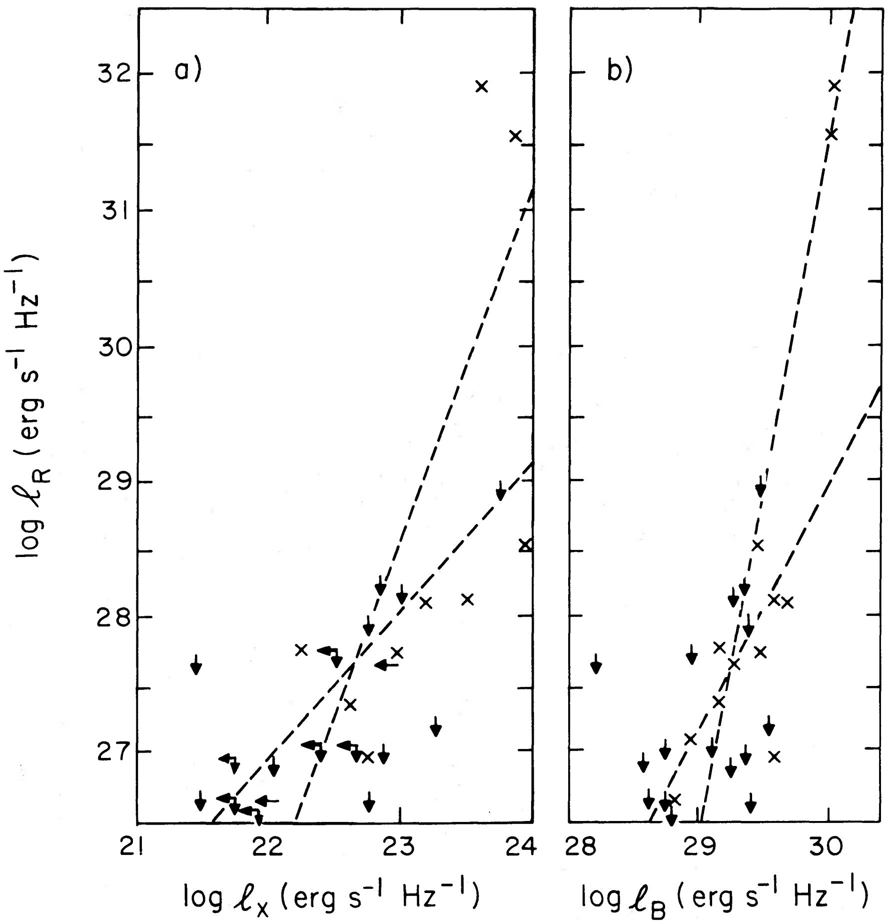

FIG. 3.—(*a*) Plots of log l_R vs. log l_x and (*b*) of log l_R vs. log l_B for the entire sample of 28 galaxies, including the radio-loud NGC 1316 (Fornax A) and NGC 5532 (3C 296). Dashed lines represent the maximum likelihood regression lines from Table 3.

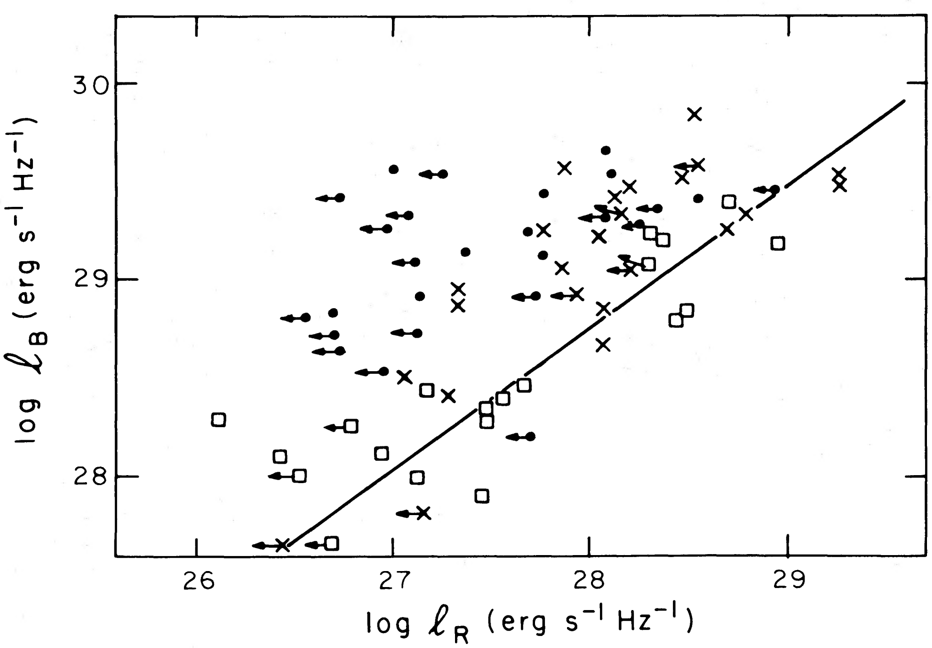

FIG. 4.—Plot of log l_B vs. log l_R for the radio-quiet elliptical and S0 galaxies (*dots*), early-type spiral galaxies (*crosses*), and late-type spiral galaxies (*squares*). The line represents the correlation observed between l_B and l_R in late-type spiral and irregular galaxies.

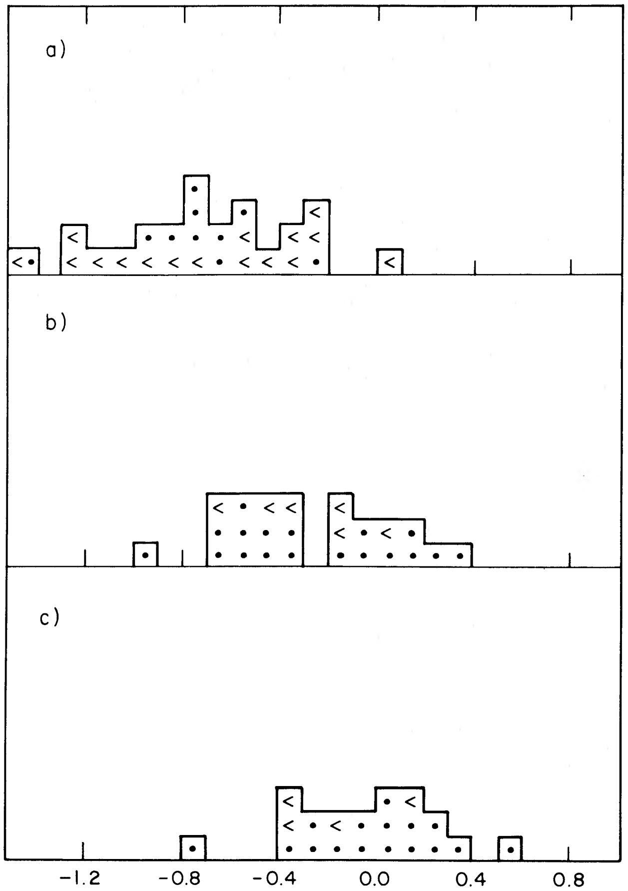

FIG. 5.—Histograms of the differences between the logarithm of the "expected" optical luminosity according to the l_B, l_R relationship of late-type spiral and irregular galaxies (see text) and the logarithm of the observed l_B. Ellipticals and S0 galaxies are plotted in Fig. 6*a*, early-type spirals (Sa–Sbc) in Fig. 6*b*, and late-type spirals and irregulars (Sc–Im) in Fig. 6*c*.

between radio and X-ray luminosities for the radio-quiet sample is consistent with being linear (see Table 3). The relationship of the radio emission with the optical and the X-ray luminosities have been previously explored, respectively, by Hummel, Kotanyi, and Ekers (1983) and Dressel and Wilson (1985).

Hummel, Kotanyi, and Ekers (1983) find that E and S0 galaxies with $M_B < -20$ are stronger radio emitters than galaxies with $-20 < M_B < -17$ and suggest that the radio emission is correlated with the optical luminosity. Although we do not find a correlation between l_x and l_B, our results are not in contradiction with theirs. This can be seen by inspection of Figure 2*b*, which shows that galaxies with $l_B < 5 \times 10^{28}$ ergs s^{-1} Hz^{-1} (corresponding to $M_B > -20$, the low-luminosity bin of Hummel, Kotanyi and Ekers) have a smaller probability of being detected in the radio continuum. The scatter, however, is very large, excluding any significant functional relationships between l_R and l_B in our range of radio and optical luminosities. Introducing a new variable, the X-ray luminosity l_x, in the analysis, we find that l_R is instead correlated with l_x. In our sample of radio-quiet galaxies, the much weaker l_R, l_B effect is likely to be a secondary effect resulting from the stronger l_x, l_B and l_R, l_x correlations (see § III*b*). Our sample, however, does not include a significant number of galaxies with l_R in the range of 10^{29}–10^{31} ergs s^{-1} Hz^{-1}, as does the sample of Hummel, Kotanyi, and Ekers. The presence of galaxies in this luminosity range might give a stronger dependence of the radio luminosity on the optical magnitude.

The results of Dressel and Wilson (1985) are in close agreement with ours. Dressel and Wilson (1985), analyzing a sample of 13 early-type galaxies observed in the X-ray range with *Einstein* and comparing them with some of the galaxies discussed here, find that galaxies with larger X-ray to optical luminosity ratios tend to be more powerful radio sources. Given the steep $l_x \propto l_B^{1.6-1.7}$ relationship present in elliptical and S0 galaxies (Paper II; Table 3), the galaxies with larger l_x/l_B ratios are also those with larger l_x. Therefore, the trend of larger X-ray to optical luminosity ratios being associated with more powerful radio emission, found by Dressel and Wilson, conceals the presence of a correlation between l_x and l_R.

Hummel, Kotanyi, and Ekers (1983) (see also Dressel and Wilson 1985) linked their result to the possibility that more luminous/massive galaxies could be more effective in supplying the central nuclear source with gaseous fuel. Our present results of a strong link between X-ray and radio emission agree with this hypothesis and give an easy explanation for the gas supply. By looking at the l_R, l_x diagram (Fig. 2*a*), it is evident that galaxies with $l_x \gtrsim 2 \times 10^{22}$ ergs s^{-1} Hz^{-1} (0.5–3.5 keV $L_x \gtrsim 10^{40}$ ergs s^{-1}) tend to have significantly more radio emission than X-ray fainter galaxies. The former are likely to retain a gaseous component, which also dominates the X-ray emission (Paper II; also Forman, Jones, and Tucker 1985). As noticed by Nulsen, Stewart, and Fabian (1984), this hot gaseous component can be dense enough to have cooling times much shorter than the Hubble time. This is particularly true in the centermost regions, as evidenced by the X-ray surface brightness profiles of some bright elliptical galaxies (Trinchieri, Fabbiano, and Canizares 1986) which imply central cooling times as short as $\sim 10^7$ yr. In the absence of heating, short cooling times would cause a cooling flow of gas toward the galaxy's central regions (Nulsen, Stewart, and Fabian 1984; White and Chevalier 1984). A fraction of this infalling material could be accreted by a central compact object (black hole) and power the radio source (e.g., Rees 1980). A correlation between radio power and X-ray luminosity has also been reported in cD galaxies in clusters and has been interpreted as evidence of gravitationally accreting cooling flows (Valentijn and Bijleveld 1983; also Jones and Forman 1984).

b) *Confinement of the Radio Sources by the X-Ray Emitting Gas*

The radio emission of radio-quiet elliptical and S0 galaxies is typically confined within the optical body of the galaxy (this paper; Ekers and Kotany 1978; Stanger, Warwick, and Schwarz 1984). The absence of very extended radio emission could be a result of the interaction of radio jet/lobes with the surrounding environment. X-ray observations of these galaxies suggest the presence of $\sim 10^{10}$ $M_\odot$ of X-ray emitting gas with average densities of $\sim 10^{-27}$ g cm^{-3} (Paper II; Forman, Jones, and Tucker 1985; Trinchieri, Fabbiano, and Canizares 1986). In the minimum energy condition (e.g., Miley 1980), we find that such gas could be extremely effective in thermally confining within the galaxies a radio source of power comparable to the ones detected, if the typical dimensions of these sources are of a few kiloparsecs, and their geometries range from spherical to ellipsoidal with a ratio of ~ 10 between major and minor axes.

TABLE 4

THERMAL CONFINEMENT OF THE RADIO SOURCES[a]

Galaxy (NGC) (1)	Component (2)	α (3)	F_0(5 GHz) (Jy) (4)	θ_x (5)	θ_y (6)	S (kpc) (7)	B_{me} (G) (8)	ρ_{ext} (g cm^{-3}) (9)	ρ_{ext}[b] (X-rays) (g cm^{-3}) (10)
4472[c]	Core	−0.6	57×10^{-3}	3″	3″	0.6	1.5×10^{-5}	5.8×10^{-27}	9.0×10^{-26}
	Total	−0.7	95×10^{-3}	150	150	14.0	1.5×10^{-6}	5.2×10^{-29}	2.0×10^{-27}
4636[d]	Total	−0.6	40×10^{-3}	36	2	1.0	1.2×10^{-5}	3.6×10^{-27}	4.0×10^{-26}
4649[d]	Core	0.0	25×10^{-3}	12	12	1.0	1.2×10^{-5}	3.6×10^{-27}	1.0×10^{-26}
	Total	0.0	25×10^{-3}	36	12	1.0	9.1×10^{-6}	2.1×10^{-27}	4.0×10^{-26}

[a] Using the expression in Miley 1980, where α is the spectral index ($F_\nu \propto \nu^\alpha$), θ_x and θ_y are the typical angular sizes of the radio source, and S is the typical linear size. The quantity B_{me} is the derived minimum energy magnetic field, and ρ_{ext} is the external pressure required to confine thermally the radio source for a gas with temperature $T \approx 10^7$ K. Lower and upper cutoff frequencies used for these calculations are 0.01 and 50 GHz.

[b] The quantity ρ_{ext} (X-ray) is the density of the X-ray emitting gas, derived from the observed radial X-ray surface brightness profiles (Trinchieri, Fabbiano, and Canizares 1986).

[c] Observed radio quantities are from Ekers and Kotanyi 1978.

[d] Radio parameters are from this paper and from Stanger, Warwick, and Schwarz 1984. NGC 4649 is a core-dominated source.

The results of a more detailed calculation for three galaxies, for which radio and X-ray maps are available, are summarized in Table 4. The galaxies are NGC 4636 and NGC 4649, which are included in the LVS sample studied in this paper, and NGC 4472, which also follows the general correlation trends (Forman, Jones, and Tucker 1985). Radio maps and fluxes can be found in Stanger, Warwick, and Schwarz (1984) for the first two, and Ekers and Kotanyi (1977) for NGC 4472. The X-ray surface brightness and gas density profiles are given in Trinchieri, Fabbiano, and Canizares (1986). Applying the minimum energy thermal confinement calculation to these three galaxies, we find that the X-ray emitting hot gas could easily be dense enough to confine thermally the radio sources, both cores and extended features.

If the condition of thermal confinement of the radio source applies, we can rewrite the minimum energy equation as a function of the X-ray and radio luminosity. Under the simplifying assumption of similar emitting volumes for the radio and X-ray sources, we find that $l_R \propto l_x^{7/8}$. This almost linear relationship is consistent with the slope of the correlation found between l_R and l_x in our radio-quiet sample. The observed linear slope could then be the result of thermal confinement of the radio source by the X-ray gas. If this is true, we would expect that elliptical and S0 galaxies with radio luminosities significantly in excess of this linear relationship should present extended components, exceeding in size the parent galaxy. This is certainly the case in Fornax A and 3C 296.

c) Comparison with High-Luminosity Objects (3CR Galaxies)

Dressel and Wilson (1985) compared the X-ray to radio-nuclear flux ratios of a sample of low radio luminosity ellipticals with those of 3CR radio galaxies (Fabbiano *et al.* 1984) and noticed that the ratios were similar in the two samples. This led them to suggest that their sample of low radio luminosity galaxies could be considered as the low-luminosity extension of the X-ray and radio nuclear relationship of 3CR radio galaxies. Here we extend this comparison to a larger sample of normal radio-quiet early-type galaxies, in the light of the recent X-ray results (Paper II; Forman, Jones, and Tucker 1985; Trinchieri, Fabbiano, and Canizares 1986) that suggest a predominant extended gaseous component for their X-ray emission.

In Figure 6 we compare the X-ray and radio properties of the normal radio-quiet galaxies discussed in this paper with those of radio-loud (3CR) galaxies and quasars. The locus of the X-ray/radio luminosities of the radio-quiet galaxies falls about one order of magnitude above the extrapolation of the linear relationship between the X-ray and radio nuclear (5 GHz) luminosities of double-lobed 3CR galaxies found by Fabbiano *et al.* (1984). The X-ray emission of bright 3CR galaxies, however, is typically in excess of that of normal elliptical galaxies (Paper II) and is likely to be dominated by a nuclear source (Fabbiano *et al.* 1984). The radio-quiet elliptical galaxies of our sample could have nuclear properties consistent with the low-luminosity extrapolation of the 3CR galaxy properties, if the nuclear component of their X-ray emission contributes to $\lesssim 1/10$ of the observed luminosity and their radio sources are comparable in nature with the core components of the 3CR radio galaxies. The latter point is supported by the results of Feretti *et al.* (1984), who found that in the range of radio luminosities of our sample the core component is dominant or of the same order as the extended emission (see below). We also plot the 5 GHz core component of Fornax A (Birkinshaw and Davies 1985) versus its total X-ray luminosity, which is dominated by an extended gaseous component (Forman, Jones, and Tucker 1985). This point is consistent with the low end of the 3CR distribution and suggests that in less bright radio galaxies the X-ray emission could still be dominated by the gaseous component. An analogous point for 3C 296 is also plotted. No information on the extent of this X-ray source is available.

In the double-lobed 3CR radio galaxies the radio emission is dominated by the extended steep-spectrum lobes, which are a factor of $\sim 10^{2-3}$ brighter than the cores. Core and lobe (or total) radio power are linearly correlated in these galaxies ($P_c \propto P_t^{\sim 1}$) (Fabbiano *et al.* 1984), suggesting a link between nuclear activity and continuous feeding of the lobes. If this correlation were extended to radio-quiet elliptical galaxies, one would expect to see relatively bright radio lobes (~ 100 mJy) associated with them, contrary to observations. As discussed above (§ IV*b*), thermal confinement by the hot X-ray emitting interstellar gas could explain the absence of extended radio lobes. In bright isolated double-lobed 3CR galaxies instead, the X-ray data show that the radio lobes are not thermally confined by an external medium (Miller *et al.* 1985).

Feretti *et al.* (1984) studied the core-lobe correlation in a sample of elliptical galaxies covering a large range of radio luminosities (10^{29}–10^{35} ergs s^{-1} Hz^{-1} at 408 MHz) and

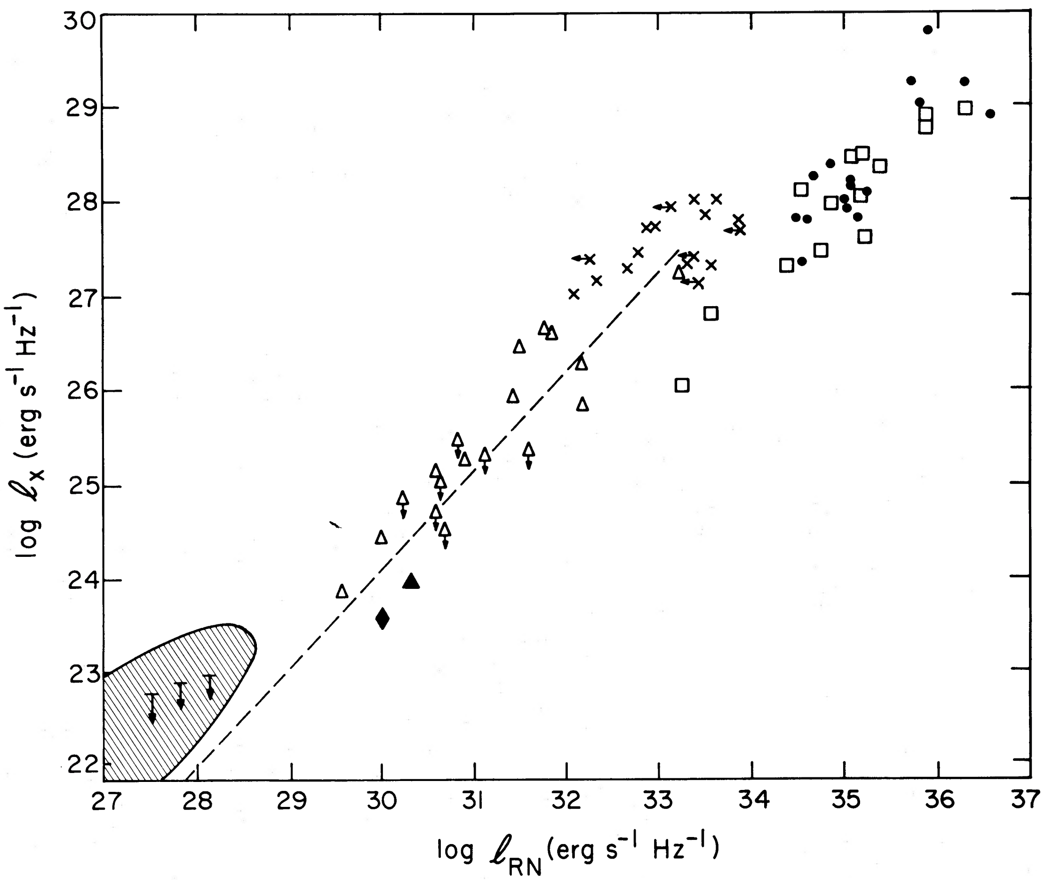

FIG. 6.—Locus of the X-ray/radio luminosities of the radio-quiet elliptical and S0 galaxies (*dashed area*) plotted on the log l_x, log l_{RN} (5 GHz core power) correlation of 3CR galaxies (*triangles*), 3CR quasars (*crosses*) and compact quasars (*dots and squares*) (Fabbiano *et al.* 1984). Filled diamond represents the 5 GHz core component of NGC 1316 (Fornax A) from Birkinshaw and Davies (1985) plotted vs. its total l_x, and filled triangle is the analogous point for NGC 5532 (3C 296) (see Fabbiano *et al.* 1984).

found a power-law dependence for this correlation of the form $P_c \propto P_t^{0.57}$, less strong than the linear one reported in bright double-lobed 3CR galaxies. We might attempt to understand this relationship as the result of the interaction of a nuclear radio source of increasing power first with the interstellar and then with the intracluster hot gaseous medium (e.g., Burns and Balonek 1982) that could be effective in inhibiting the formation of powerful extended lobes in less powerful radio sources. In this picture, there would be no intrinsic physical difference between radio-loud and radio-quiet galaxies, except for the strength of the nuclear source.

As discussed in § IV*a*, gravitational accretion of the radiatively cooling gas seen in the X-rays could account for the fueling of the nuclear radio source. Hummel, Kotanyi, and Ekers (1983) remarked that, in the accretion picture, bright radio galaxies should be more efficient accreters and suggested that, for a given mass, rounder galaxies could be more efficient accreters. More recent dynamical evidence suggests that a galaxy merger could have triggered activity (Heckman *et al.* 1985).

Although our results do not bear directly on this question, in light of our previous discussion we suggest that the radio source itself, once established, could help furnishing the regulating mechanism needed for its existence. The weaker radio jets and small lobes of radio-quiet galaxies could be effective in considerably reducing the accretion flow by partially reheating the cooling gas by conduction (e.g., Tucker and Rosner 1983). In the very active nuclei, the cooling flows might be less disrupted, if activity results in well-collimated energetic directional jets that are not affected by (and thus do not affect) most of the hot gas. Cyg A could be a good example of this type of galaxies, given the presence of very collimated jets (Perley, Dreher, and Cowan 1984) and of fast cooling X-ray emitting gas (Fabbiano *et al.* 1979) which could give rise to a strong cooling flow (Arnaud *et al.* 1984).

V. SUMMARY AND CONCLUSIONS

In order to explore the relationships between radio, optical, and X-ray emission of normal elliptical and S0 galaxies, we have observed 20 galaxies of the LVS sample with the 100 m radio telescope of the MPIfR at Bonn.

The principal results of this paper can be summarized as follows:

1. Eleven galaxies, including the radio-loud NGC 5532, were detected at 4.75 GHz. The 4.75 GHz fluxes for the radio-quiet galaxies range between ~45 and ~1 mJy. Four of the galaxies (NGC 936, NGC 4636, NGC 4649, and NGC 586) were also observed and detected at 10 GHz, and one, NGC 4649, was still visible at 32 GHz. The 5–10 GHz power-law indices ($F_\nu \propto \nu^{+\alpha}$) of three of these galaxies are flat ($\alpha \approx -0.1$–0.0). NGC 4636 could also have a high-frequency flat component.

2. Using both detections and upper limits of the Bonn survey and data from the literature for eight additional galaxies, we have performed a maximum likelihood correlation analysis between radio, optical (B), and X-ray fluxes and luminosities. We find that the most significant correlation is the one between X-ray and B luminosities, already discussed in Paper II. Also significant is the correlation between radio and X-ray luminosities. If we exclude the two radio-loud galaxies (NGC 1316 and NGC 5532), this correlation is consistent with being linear. The radio and the B luminosities instead are only weakly correlated, or not correlated if we exclude the two radio-loud galaxies from the analysis.

The above results are consistent with the picture that the radio sources in radio-quiet E and S0 galaxies could be associated with an accreting nuclear compact object. The fuel could be provided by the radiatively cooling X-ray emitting gas present in these galaxies (Paper II; Forman, Jones, and Tucker 1985), flowing inward in the galaxy potential (Nulsen, Stewart, and Fabian 1984; White and Chevalier 1984). This picture could explain the correlation between the radio and X-ray emission in these galaxies. The hot X-ray emitting gas could also provide an effective means for thermally confining the radio sources, thus explaining the lack of extended radio lobes in radio-quiet galaxies.

A comparison between the X-ray and radio properties of radio-quiet and radio-loud double-lobed (3CR) galaxies suggests that the radio-quiet nuclei could just be a scaled-down version of the bright radio nuclei. The strength of the central radio source could help in providing a self-regulatory mechanism for the nuclear accretion. A weak radio source, as in the radio-quiet galaxies, could reduce the accretion rate by partially heating by conduction the cooling gas (e.g., Tucker and Rosner 1983). A strong radio source with powerful collimated jets would have little or no effect on the accreting cooling flows, thus providing the nuclear engine with a larger quantity of fuel.

Our results were derived from the analysis of a sample of radio-faint elliptical and S0 galaxies ($l_R < 10^{29}$ ergs s^{-1} Hz^{-1} at 5 GHz). The sample needs to be extended to include a significant number of low- luminosity radio galaxies ($l_R \approx 10^{29}$–10^{32} ergs s^{-1} Hz^{-1}) in order to explore the statistical relationships in this intermediate range of radio power. This will be the subject of future work. Future X-ray observations (with the *ROSAT* and *AXAF* satellites) will also be needed in order to study a carefully selected statistically complete sample of E and S0 galaxies.

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G. Fabbiano: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

U. Klein: Radioastronomisches Institut der Universität auf dem Hügel 71, D-5300 Bonn 1, Federal Republic of Germany

G. Trinchieri: Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy

R. Wielebinski: Max-Planck-Institut für Radioastronomie, auf dem Hügel 69, D-5300 Bonn 1, Federal Republic of Germany