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RADIO-LOUD AND RADIO-QUIET ACTIVE GALACTIC NUCLEI

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ABSTRACT

We have generated a sample of 409 active galactic nuclei (AGNs) for which both the radio luminosity at 5 GHz and the line luminosity in [O III] λ5007 have been measured. The radio luminosity spans a range of 10 orders of magnitude, and the [O III] line luminosity spans a range of 8 orders of magnitude—both considerably larger than the ranges in previous studies. We show that these two quantities are correlated in a similar way for both radio-loud and radio-quiet AGNs. We demonstrate that the observed correlation can be explained in terms of a model in which jets are accelerated and collimated by a vertical magnetic field.

Key words: galaxies: active — galaxies: elliptical and lenticular, cD — galaxies: nuclei — galaxies: spiral — quasars: general — radio continuum

1. INTRODUCTION

The "unified" scheme of active galactic nuclei (AGNs) has been very successful in explaining a variety of AGN properties on the basis of the viewing angle θ (see, e.g., review by Urry & Padovani 1995). It is very clear, however, that more physical parameters are required to construct a truly "unified" model of all AGNs (e.g., Blandford 1990). In particular, it is by now well established that AGNs fall into two families in terms of their radio power (as measured, for example, by their 5 GHz luminosities), the "radio loud" and "radio quiet" AGNs (e.g., Baum & Heckman 1989; Miller, Rawlings, & Saunders 1993). Phenomenologically, radio-loud AGNs are always associated with large-scale radio jets and lobes, while the radio-quiet sources have very little or weak radio-emitting ejecta. Radio-loud AGNs are almost always associated with early-type galaxies, while the radio-quiet ones are mostly found in spirals and S0's.

One of the ways to tackle observationally the question of the additional fundamental parameters (other than the viewing angle θ) is to examine the AGN luminosities in a variety of wave bands. In particular, it has been shown that a correlation exists between the radio luminosity ($L_{5\ \rm GHz}$) and the [O III] 5007 Å narrow-line luminosity ($L_{[\rm O\ III]}$) (e.g., Rawlings & Saunders 1991; Baum & Heckman 1989).

In the present work, we study the $L_{5\ \rm GHz}$-$L_{[\rm O\ III]}$ and related correlations for a much larger data set, covering a very wide range of luminosities. We then use the obtained results in combination with recent theoretical developments in an attempt to place constraints on possible scenarios for the nature of radio-loud and radio-quiet AGNs.

In § 2, we describe the samples used and the data. The results are presented in § 3 and discussed in § 4. A summary and conclusions follow.

2. SAMPLES AND DATA HANDLING

All the data were compiled from the literature and through the NASA Extragalactic Database (NED). Our original sample included four categories of AGNs: (1) radio sources (Bennett 1962; Smith & Spinrad 1980; Zirbel & Baum 1995; Condon, Frayer, & Broderick 1991), (2) Seyfert galaxies (Lipovetsky, Neizvestny, & Neizvestnara 1988; Dahari & De Robertis 1988; Whittle 1992), (3) BL Lacertae objects (Véron-Cetty & Véron 1996; Padovani & Giommi 1995), and (4) quasars (Schmidt & Green 1983; Brotherton 1996; Boroson & Green 1992). To these we added many sources found individually in the literature, thus generating a sample of about 2000 AGNs. From this sample we selected all the objects for which measurements of both the radio luminosity at 5 GHz and the luminosity in the [O III] 5007 Å forbidden line existed. We have thus generated a sample of 409 sources, including 162 Seyfert galaxies, 136 quasars, 107 radio galaxies, and four BL Lac objects.

Table 1 gives a list of all the sources used, with the relevant information for each object. Specifically, we list in columns (1)–(6) respectively the object's IAU name, its catalog name, its identification (a galaxy [G] or a quasar [Q]), the nature of its activity (Seyfert or radio galaxy), its morphological type, and its redshift. In columns (7)–(10) we list respectively its luminosity in the [O III] 5007 Å line, the total radio power at 5 GHz, the core radio power at 5 GHz, the X-ray luminosity in the 2–10 keV band, and the corresponding references. In the last column (col. [11]), we remark whether the object is regarded as radio-loud (L) or radio-quiet (Q) in our study. A more detailed notation is attached at the end of Table 1. Almost all the data presented on the luminosities represent actual measurements, with very few (e.g., core radio powers from Zirbel & Baum 1995) upper and lower limits. As a rule, if a certain quantity was found to have several different quoted values, the one closest to the mean was taken.

The radio powers at 5 GHz given in Table 1 were either taken directly from the literature or calculated from the given fluxes. A value of the Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1} has been assumed throughout. In calculating the radio power of sources for which the spectral index was not available (assuming a power law $S_\nu \propto \nu^{-\alpha}$), a mean index of 0.75 was adopted.

The luminosities in the [O III] 5007 Å line were mostly calculated from the fluxes found in the literature (without reddening corrections, since very few of the latter are available, e.g., Koski 1978). In a case in which only the combined fluxes of [O III] λ5007 and λ4959 were given (Steiner 1981), the flux in the 5007 Å line was taken to be three-quarters of the combined flux. In two cases in which only equivalent

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TABLE 1

AGN List

Object (1)	Name (2)	ID (3)	Class (4)	Morphology (5)	z (6)	log $L_{[O III]}$ (7a)	Ref. (7b)	log $L_{5 GHz}$ (8a)	Ref. (8b)	log L_{core} (9a)	Ref. (9b)	L_X (10a)	Ref. (10b)	Remark (11)
0000+21......	Mrk 334	G	Sy 1.8	Pec	0.0220	34.426	PBMP	21.266	PBMP	...		43.303	CPPB	Q
0003+15......	PG 0003+15	Q	...	...	0.4499	36.543	BG	25.492	KSSS	24.968	KSSS	45.631	CPPB	L
0003+19......	Mrk 335	Q	Sy 1.0	E/S0	0.0258	34.830	W	20.960	KSSS	20.840	KSSS	43.569	CB	Q
0007+10......	PG 0007+10	Q	Sy 1.0	E/S0	0.0890	35.648	DR	23.967	KSSS	23.611	KSSS	45.081	CPPB	I
0007+25......	NGC 0023	G	...	SB(s)a	0.0152	33.081	DR	21.420	KTDD	...		...		Q
0008−12......	NGC 0034	G	Sy 2.0	Pec	0.0198	33.274	PBMP	21.795	PBMP	...		...		Q
0023−26......	PKS 0023−26	G	NLRG	...	0.3220	35.397	TMDF	26.180	MKT	...		...		L
0026+12......	PG 0026+12	Q	...	...	0.1420	36.110	DR	22.590	KSSS	21.140	KSSS	45.260	CPPB	Q
0034−01......	3C 15	G	NLRG	E	0.0730	33.750	TMDF	24.490	MKT	23.760	ZB	...		L
0035−02......	3C 17	G	NLRG	N	0.2200	35.318	TMDF	25.710	MKT	25.043	MKT	...		L
0038+09......	3C 18	G	NLRG	...	0.1880	35.268	TMDF	25.390	MKT	24.080	ZB	...		L
0039−44......	PKS 0039−44	G	...	...	0.3459	36.299	TMDF	25.830	MKT	...		...		L
0042+10......		Q	...	...	0.5830	36.164	JB1	25.181	BSRF	...		...		L
0043+03......	PG 0043+03	Q	...	...	0.3840	34.798	BG	22.199	KSSS	...		...		Q
0043−42......	PKS 0043−42	G	NLRG	E	0.1160	33.960	TMDF	25.180	MKT	22.480[a]	ZB	...		L
0045−25......	NGC 0253	G	...	Sc	0.0010	30.493	TMDF	20.930	MKT	19.650	ZB	...		I
0046+31......	NGC 0262	G	Sy 2.0	S0	0.0149	34.608	W	22.265	CFB	...		43.234	PBMP	Q
0049+17......	PG 0049+17	Q	Sy 1.0	...	0.0640	35.139	MRSE	20.972	KSSS	20.965	KSSS	44.266	CPPB	Q
0050+12......	PG 0050+12	G	Sy 1.0	S0	0.0610	34.872	DR	21.538	KSSS	21.359	KSSS	...		Q
0052+25......	PG 0052+25	Q	Sy 1.5	...	0.1550	35.898	MRSE	21.832	KSSS	21.539	KSSS	45.693	CB	Q
0055+30......	NGC 0315	G	...	E	0.0173	32.684	HFS	23.271	CFB	22.710	ZB	...		L
0055−01......	3C 29	G	...	E	0.0450	33.198	TMDF	24.200	MKT	22.480	ZB	...		L
0056−00......	PHL 9234	Q	...	...	0.7170	36.650	JB1	26.596	BSRF	...		...		L
0105−16......	3C 32	Q	NLRG	...	0.4000	35.625	TMDF	25.980	MKT	23.210[a]	ZB	...		L
0106+13......	3C 33	G	NLRG	E	0.0600	35.332	RSEM	24.820	HR	22.470		...		L
0106+72......	3C 33.1	G	...	...	0.1810	35.049	JB2	25.070	HR	23.270	ZB	...		L
0107−03......		Q	Sy 2.0	...	0.0546	35.730	PBMP	21.906	PBMP	...		...		Q
0109−38......	Tol 0109−383	G	Sy 2.0	(R)SB0/a	0.0117	34.394	PBMP	20.846	PBMP	...		...		Q
0110+29......	4C 29.02	Q	...	...	0.3630	36.043	JB1	25.257	BSRF	...		...		L
0111−15......	Mrk 1152	G	Sy 1.0	S/Pec	0.0527	34.711	W	20.948	ULWE	...		44.592	CB	Q
0113+32......	NGC 449	G	Sy 2.0	(R)SB0/a	0.0167	34.604	DR	21.564	NED	...		...		Q
0115+02......	3C 37	Q	...	...	0.6719	36.487	JB1	26.177	BSRF	...		...		L
0116+31......	B2 0116+31	...	...	...	0.0590	33.500	GW	24.252	HR	24.240[a]	ZB	...		L

Note.—The columns list (1) IAU name; (2) frequently used name; (3) identification: G = galaxy, Q = quasar; (4) AGN classification: Sy = Seyfert galaxy, NLRG = narrow-line radio galaxy, BLRG = broad-line radio galaxy, GPS = gigahertz-peaked radio galaxy; (5) morphological type of the host galaxy; (6) redshift; (7a, 7b) log [O III] 5007 Å line luminosity (in watts) and corresponding reference; (8a, 8b) log total 5 GHz radio power (in W Hz^{-1} sr^{-1}) and corresponding reference; (9a, 9b) log core 5 GHz radio power (in W Hz^{-1} sr^{-1}) and corresponding reference; (10a, 10b) log 2–10 keV X-ray luminosity (in ergs s^{-1}) and corresponding reference; (11) remarks: L = radio-loud, Q = radio-quiet, I = intermediate. Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

[a] Upper limit.

References.—(B) Brotherton 1996; (BG) Boroson & Green 1992; (BKSD) Bicay et al. 1995; (BM) Browne & Murphy 1987; (BSRF) Brinkmann et al. 1995; (BWH) Braatz, Wilson, & Henkel 1997; (CB) Ceballos & Barcons 1996; (CFB) Condon et al. 1991; (CPPB) Della Ceca et al. 1990; (DR) Dahari & De Robertis 1988; (FGGP) Feretti et al. 1984; (GC) Gregory & Condon 1991; (GW) Gelderman & Whittle 1994; (GWBE) Griffith et al. 1994; (HFS) Ho, Filippenko, & Sargent 1993; (HOBL) Heckman et al. 1994; (HR) Herbig & Readhead 1992; (JB1) Jackson & Browne 1991; (JB2) Jackson & Browne 1990; (KKA) Kaastra, Kunieda, & Awaki 1991; (KPWS) Kühr et al. 1981; (KSSS) Kellermann et al. 1989; (KTDD) Kojoian et al. 1980; (KW) Keel & Windhorst 1991; (MKT) Morganti, Killeen, & Tadhunter 1993; (MRS) Miller et al. 1993; (MRSE) Miller et al. 1992; (NED) NASA Extragalactic Database; (P) Pounds 1990; (PBMP) Polletta et al. 1996; (PG) Padovani & Giommi 1995; (PK1) Pauliny-Toth & Kellermann 1968; (PK2) Pauliny-Toth & Kellermann 1972; (PKDF) Pauliny-Toth et al. 1972; (PWP) Pauliny-Toth et al. 1978; (RSEM) Rawlings et al. 1989; (S1) Steiner 1981; (S2) Sramek 1975; (S3) Stephens 1989; (SB) Shimmins & Bolton 1972; (SBMT) Siebert et al. 1996; (SMGM) Stocke et al. 1991; (SWCR) Simpson et al. 1996; (TI) Tabara & Inoue 1980; (TMDF) Tadhunter et al. 1993; (TWSS) Turner et al. 1989; (ULWE) Unger et al. 1987; (UM) Ulrich & Meier 1984; (UW1) Ulvestad & Wilson 1984b; (UW2) Ulvestad & Wilson 1989; (UW3) Ulvestad & Wilson 1984a; (W) Whittle 1992; (ZB) Zirbel & Baum 1995.

widths of [O III] λ5007 were given (Brotherton 1996; Boroson & Green 1992), the continua were determined from the corresponding spectra.

The X-ray luminosities in the 2–10 keV band were calculated from the integrated fluxes. In a case in which only the *HEAO* A-2 count rate was given (Della Ceca et al. 1990), the fluxes were calculated assuming a mean energy index of 0.65. The redshifts were obtained from the literature and cross-checked through NED.

While clearly the use of many sources for the data makes our sample inhomogeneous in terms of the errors involved, this has very little effect on our conclusions, since the data now span 8 orders of magnitude in [O III] luminosity and 10 orders of magnitude in the radio luminosity.

3. ANALYSIS AND RESULTS

In Figure 1, we present the radio luminosity at 5 GHz, $L_{5\ \mathrm{GHz}}$, as a function of the [O III] 5007 Å line luminosity, $L_{[\mathrm{O\ III}]}$, for all the sources in our sample. The separation into the two families of radio-loud and radio-quiet AGNs with a significant gap between them is immediately apparent. The radio luminosities are different by a factor of 10^3–10^4 between the two groups (at a given [O III] luminosity). We do find a small group ($\sim 3\%$ of the sample) of objects that appear to occupy the region between the two main families. These tentative "intermediate" objects have been represented by filled circles in Figure 1.

Linear fits to the radio-loud and radio-quiet AGNs (excluding the intermediate objects) yield

$$\log L_{5\ \mathrm{GHz}} = \begin{cases} (0.61 \pm 0.07) \log L_{[\mathrm{O\ III}]} + (3.7 \pm 0.6) & \text{(radio-loud)}, \\ (0.45 \pm 0.07) \log L_{[\mathrm{O\ III}]} + (5.6 \pm 0.6) & \text{(radio-quiet)}. \end{cases} \quad (1)$$

Here $L_{5\ \mathrm{GHz}}$ is the radio luminosity in W Hz^{-1} sr^{-1}, and $L_{[\mathrm{O\ III}]}$ is the [O III] line luminosity in watts. In determining whether an object belongs to the radio-loud, radio-quiet, or intermediate group, we first selected out two distinct groups of objects (namely, radio-loud and radio-quiet) based on the distribution in the $L_{5\ \mathrm{GHz}}$-$L_{[\mathrm{O\ III}]}$ diagram (Fig. 1). We then found linear fits to the two groups, respectively. We considered the objects whose radio luminosities (at 5 GHz) are higher than the "radio loud" fitting minus 2.75 σ as radio-loud, those whose radio luminosities are less than the "radio quiet" fitting plus 2.5 σ as radio-quiet, and those that lie between the two groups as intermediate. This way of defining radio-loud and radio-quiet is to some extent semi-empirical. The reason we chose slightly different criteria in determining the radio-loud and radio-quiet membership was to achieve the best visual representation of the two groups in Figure 1.

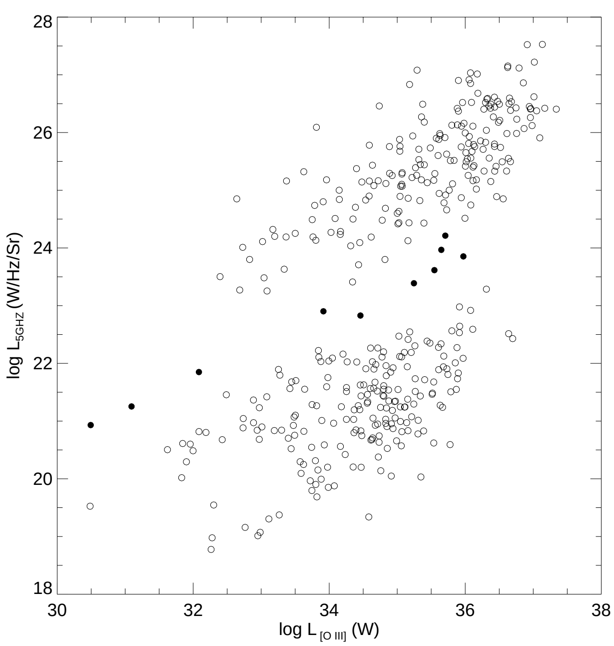

FIG. 1.—Total 5 GHz luminosity vs. [O III] 5007 Å line luminosity for our sample of AGNs. The filled circles represent the intermediate sources.

We note that the samples used by previous authors (e.g., radio-quiet quasars by Miller et al. 1993; radio-loud objects by Rawlings 1994) represent subgroups of our sample. These authors found a relation with a somewhat steeper slope ($\sim$0.85–1.0) for the subgroups.

In Figure 2*a*, we present the same data, now indicating the different classes of AGNs (note that a few of the objects might have been misclassified in the literature). What becomes immediately clear from this figure is that by plotting $L_{5\ \mathrm{GHz}}$ versus $L_{[\mathrm{O\ III}]}$ only for some *individual classes* of AGNs (e.g., quasars), one could obtain a distribution of points that would have looked like a relation with a rather different slope (see Fig. 2*b*). In such a case it would have been difficult to determine whether this indeed represents a different functional dependence of $L_{5\ \mathrm{GHz}}$ or $L_{[\mathrm{O\ III}]}$, or whether this is merely an artifact of examining, for example, only the rightmost edges of two separate linear relations (as in the case of quasars; Figs. 2*a*, 2*b*). For the moment we will assume that the latter interpretation is correct, since our basic assumption is one of an underlying "unified" scheme. We do note however that extreme caution should be exercised in attempts to determine the properties of subclasses of AGNs and that, in principle, the former interpretation may be valid (e.g., that radio-loud and radio-quiet QSOs are more fundamentally associated).

In order to examine the question of whether the distinction between the radio-loud and radio-quiet families is mainly a result of the extended radio emission, we plot in Figure 3 the 5 GHz core radio luminosity against the [O III] line luminosity. As one can see from the figure, the gap between the radio-loud and radio-quiet groups is much less pronounced in this case (although instrumental effects introduce uncertainties; see also Nelson & Whittle 1996 and Sadler et al. 1995), but the two groups are still discernible. Interestingly, most of the "intermediate" sources of Figure 1 become essentially indistinguishable from the radio-loud sources in Figure 3. This may indicate a close relation between the intermediate sources and the radio-loud ones. A linear fit to the core radio luminosity of the radio-loud sources yields

$$\log L_{\mathrm{core}} = (0.78 \pm 0.07) \log L_{[\mathrm{O\ III}]} - (3.3 \pm 1.1) , \quad (2)$$

where L_{core} is the core radio luminosity (at 5 GHz) in W Hz^{-1} sr^{-1}.

In order to further clarify the properties of the [O III] emission, we plot in Figure 4 the X-ray luminosity in the 2–10 keV band as a function of the [O III] luminosity. As can be seen from the figure, a clear positive correlation exists, and a linear fit yields

$$\log L_{\mathrm{HX}} = (1.01 \pm 0.08) \log L_{[\mathrm{O\ III}]} + (8.6 \pm 0.7) , \quad (3)$$

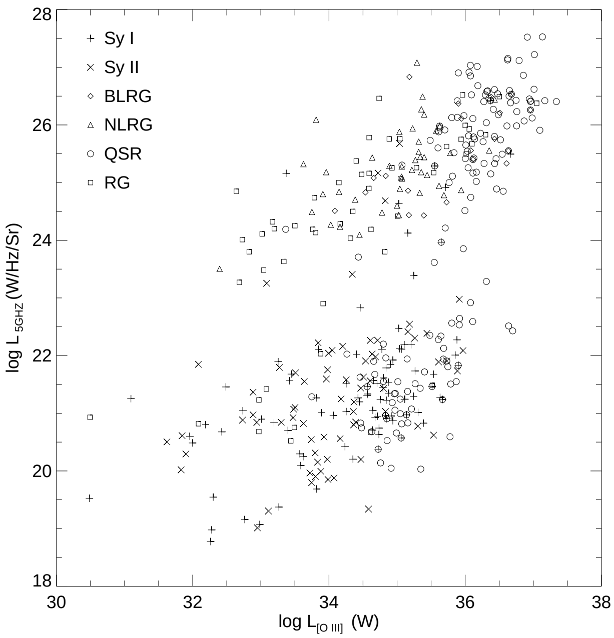

FIG. 2*a*

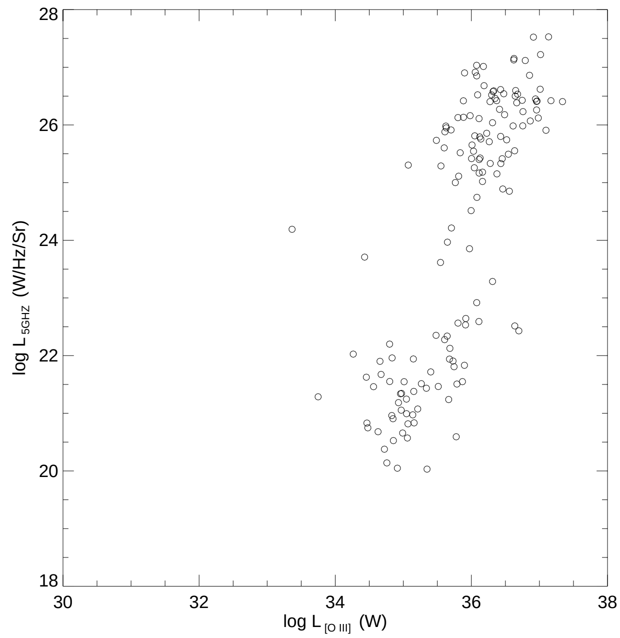

FIG. 2*b*

FIG. 2.—Same as Fig. 1, but with (*a*) the types of the AGNs indicated and (*b*) only the quasars presented

where L_{HX} is the X-ray luminosity (in the 2–10 keV range) in ergs s^{-1}. Individual fits to the radio-loud (plus intermediate) sample and the radio-quiet sample yield slopes of 0.89 ± 0.19 and 0.95 ± 0.10, respectively.

It is important to note right away that the radio-loud and radio-quiet sources share the same L_{HX}-$L_{[O\,III]}$ relation, probably implying that the same physical process relates these quantities in the two families (we will return to this point below).

In order to examine the potential effects of the environment, we also plotted the data of Figure 1 distinguishing among the different types of host galaxies (in cases in which the latter have been identified). This is presented in Figure 5. This figure confirms that *all* the radio-loud sources are elliptical or S0 galaxies, while almost all of the spirals are radio-quiet. It is interesting to note though that some of the "intermediate" objects are spirals. We should note, however, that quite a few of the morphologies are ambigu-

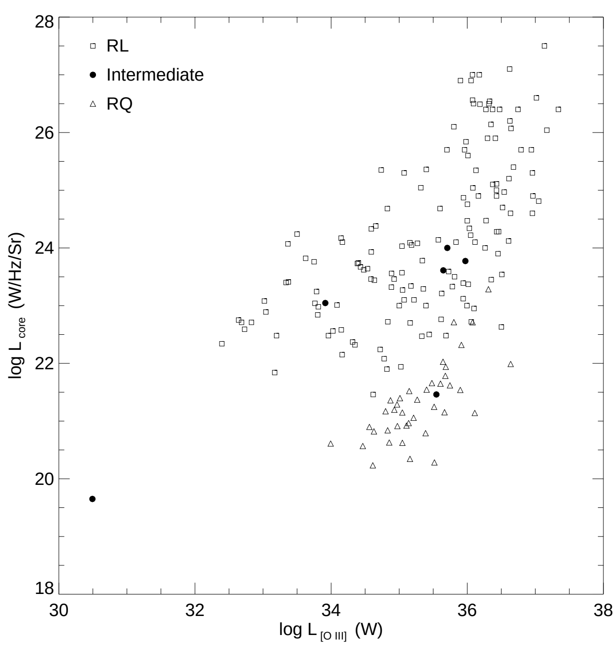

FIG. 3.—Core 5 GHz luminosity vs. [O III] λ5007 luminosity. Most of the objects presented here are radio-loud.

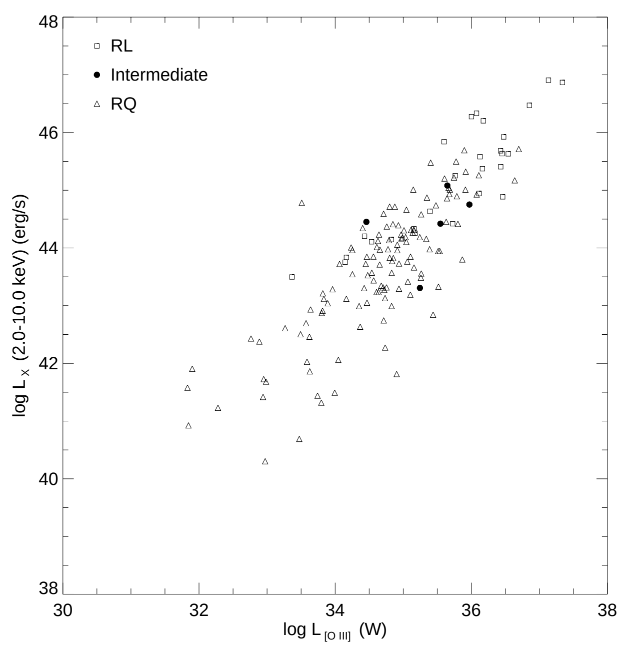

FIG. 4.—Hard X-ray luminosity (2–10 keV) vs. [O III] λ5007 luminosity.

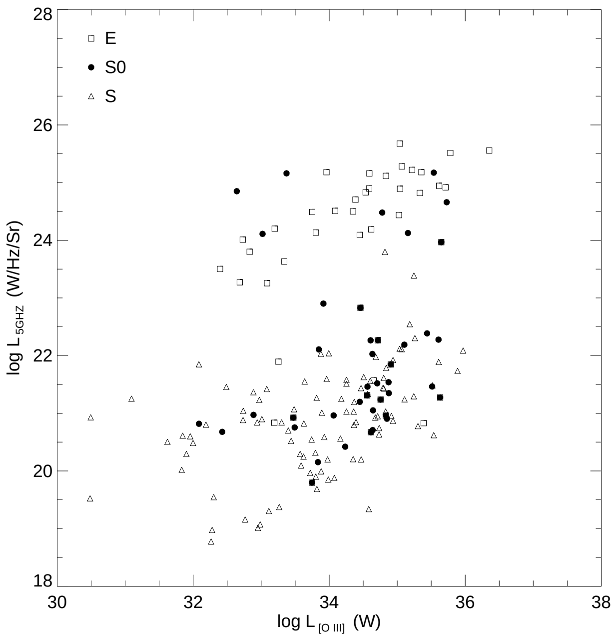

FIG. 5.—Same as Fig. 1, but with the morphological type of the host galaxies of the AGNs indicated (note that the symbols that appear as filled squares are actually filled circles residing in open squares, in cases in which an ambiguity exists).

ous (in particular, the distinction between elliptical galaxies and S0's), and therefore caution should be exercised in attempts to draw conclusions on the basis of morphology.

4. DISCUSSION

We have found that over a very wide range in luminosities, AGNs separate into two classes of objects, radio-loud and radio-quiet, and that the two classes obey two parallel relations between their radio and [O III] luminosities, of the form

$$L_{5\ \mathrm{GHz}} \sim L_{[\mathrm{O\ III}]}^{\beta}\,, \tag{4}$$

with $\beta \sim 0.5$ (Fig. 1 and eq. [1]). At this point we need to consider whether the observed relationships are true correlations or whether selection effects can be dominating what we are seeing. First we need to ask, are there really two distinct classes of radio-quiet and radio-loud types of AGN or is the apparent gap region merely an artifact of the selection process? In particular, many, though not all, of the radio-loud objects come from radio flux density–selected samples and many, though not all, of the radio-quiet objects come from optically selected samples.

We do not think that selection effects are responsible for the apparent population of the L_{radio}-$L_{[\mathrm{O\ III}]}$ plane, for the following reasons:

1. Radio flux density–selected samples always include objects of low radio luminosity at low redshift and of progressively higher radio luminosity with increasing redshift. For example, the 3CR cutoff in radio flux is about 9 Jy at 178 MHz (Bennett 1962); if we take the spectral index as 0.75 (which is a typical value for AGNs), then the extrapolated radio flux at 5 GHz is 0.74 Jy. This corresponds to $L_{5\ \mathrm{GHz}} \sim 2.3 \times 10^{21}$ W Hz^{-1} sr^{-1} at $z = 0.003$ and $L_{5\ \mathrm{GHz}} \sim 2.56 \times 10^{22}$ W Hz^{-1} sr^{-1} at $z = 0.01$. These values lie within the radio-quiet group in our classification (Fig. 1). Actually, we do find sources from the 3CR catalog that are indeed radio-quiet (3C 71, for example). Likewise, purely optically selected samples of AGNs (e.g., Padovani 1993; Miller, Peacock, & Mead 1990; Kellermann et al. 1989) also show the radio-quiet–radio-loud dichotomy, with roughly one in 10 of optically selected quasars falling into the radio-loud category.

2. Perhaps more importantly, the apparent dichotomy in properties we have found is not a dichotomy of either L_{radio} or $L_{[\mathrm{O\ III}]}$, but the *ratio* of these two quantities. It is clear that selection effects can cause us to find sources with high, on average, radio luminosity when we select radio flux density–limited samples; however, there is no a priori reason why such samples should show a limited and specific ratio of radio to line luminosity. The absence of identified sources with high radio luminosity and low line luminosity in radio flux density–selected samples has been known for years (e.g., Baum & Heckman 1989); sources with high radio luminosity invariably have high accompanying line luminosities. The real surprise is then that the *converse* does not also appear to be true. That is, if one selects AGNs of high line luminosity at any given redshift, one finds two distinct classes of objects: those with high radio luminosity and those without. Said in a different way, there are sources with very high line luminosity that do not have accompanying very high radio luminosity. This is the radio-quiet–radio-loud dichotomy that has been known for many years (e.g., Antonucci 1993 and references therein), and the fundamental paradox: the nuclei of active galaxies can produce copious amounts of line luminosity (and UV through X-ray luminosity) without producing large amounts of radio luminosity, however, the nuclei of active galaxies cannot produce large amounts of radio luminosity without producing concomitantly large amounts of line and UV/X-ray luminosity.

4.1. *Physical Origin of the L_{radio}-$L_{[\mathrm{O\ III}]}$ Relation*

We will now attempt to understand the origin of this relation in terms of the physical processes involved. There exists strong observational evidence that suggests that $L_{[\mathrm{O\ III}]}$ is one of the best orientation-independent measures of the intrinsic luminosity of the nuclei of AGNs (e.g., Miller et al. 1992; Jackson & Browne 1991; Mulchaey et al. 1994). This fact, in combination with the data presented in Figure 4, suggests that $L_{[\mathrm{O\ III}]}$ is proportional to the accretion rate through the accretion disk, $\dot{M}_{\mathrm{acc}}$. We will therefore assume that $L_{[\mathrm{O\ III}]}$ is proportional to $\dot{M}_{\mathrm{acc}}$, i.e., $L_{[\mathrm{O\ III}]} \propto \dot{M}_{\mathrm{acc}}$.

We will now attempt to obtain a general relation between the accretion rate through the disk and the mass flux into the jet, $\dot{M}_j$ (see, e.g., Pringle 1993; Tout & Pringle 1996; Livio 1997).

To this goal, we first note that the most promising models for jet acceleration and collimation involve an accretion disk that is threaded by a large-scale, vertical magnetic field (e.g., Blandford & Payne 1982; Königl 1989; see Livio 1997 for a review). We will now make the following simple assumptions: (1) The accretion disk is largely a standard (geometrically thin), Shakura-Sunyaev (1973) disk. (2) The jet velocity, V_j, is of the order of the Keplerian velocity in the inner disk. (3) The vertical magnetic field component is of the order of the azimuthal one, $B_z \sim B_\phi$. A detailed justification of these assumptions can be found in Livio (1999) and references therein. Realizing that the back-pressure from the jet on the disk is given by $P_{\rm jet} \sim \dot{M}_j V_j/R^2$, where R is the radius from which the jet originates, and using assumptions 1–3 above, we obtain

$$\frac{B_z^2/8\pi}{P_g} \sim \frac{\dot{M}_j}{\dot{M}_{\rm acc}} \frac{H}{R} \alpha . \quad (5)$$

Here P_g is the gas pressure, H is the disk half-thickness, and α is the Shakura-Sunyaev (1973) viscosity parameter. If we assume in addition that the disk viscosity is generated by a dynamo, which in turn is powered by magnetohydrodynamic turbulence (e.g., Hawley, Gammie, & Balbus 1995; Stone et al. 1996; Brandenburg et al. 1995), then $\alpha \sim B_D^2/(4\pi P_g)$, where B_D is the magnetic field in the disk. Substituting this into equation (5) gives

$$\frac{B_z}{B_D} \sim \left(\frac{\dot{M}_j}{\dot{M}_{\rm acc}} \frac{H}{R}\right)^{1/2} . \quad (6)$$

An independent relation between B_z and B_D can be obtained if we make an assumption about the origin of the large-scale vertical field. In principle, such a field can either be advected inward by the accreting matter (e.g., Blandford & Payne 1982; Königl 1989; Pelletier & Pudritz 1992) or it can be generated locally by the same dynamo processes that generate the disk viscosity (Tout & Pringle 1996). If we assume the latter to be true, then the large-scale field may be obtained through the reconnections of magnetic loops (leading to an inverse cascade process), which have a length distribution of the form $n(l) \sim l^{-\delta}$. In such a case, it can be easily shown that

$$\frac{B_z}{B_D} \sim \left(\frac{H}{R}\right)^{\delta - 1} \quad (7)$$

(Tout & Pringle 1996; Livio 1997). Combining equations (6) and (7), we obtain

$$\frac{\dot{M}_j}{\dot{M}_{\rm acc}} \sim \left(\frac{H}{R}\right)^{2\delta - 3} . \quad (8)$$

Observations of accretion disks, jets and outflows in young stellar objects, supersoft X-ray sources, and cataclysmic variables and theoretical models suggest that δ is in the range 1.7–3.4 (Livio 1997; Tout & Pringle 1996). Therefore, assuming that the jet formation mechanism is similar in all the classes of objects that produce jets, and noting that H/R is approximately constant in standard disks (Shakura & Sunyaev 1973), we find that $\dot{M}_j$ is roughly proportional to $\dot{M}_{\rm acc}$, i.e., $\dot{M}_j \propto \dot{M}_{\rm acc}$.

The final ingredient that is needed to explain the relation obtained in Figure 1 is a relation between $L_{5\ \rm GHz}$ and $\dot{M}_j$. Since we have shown that $L_{[\rm O\ III]} \propto \dot{M}_{\rm acc}$ and that $\dot{M}_j \propto \dot{M}_{\rm acc}$, it is clear that the dependence observed in Figure 1 (and by Rawlings 1994) would be obtained if $L_{5\ \rm GHz} \propto \dot{M}_j^{\beta}$, with $\beta \sim 0.5$–1.0. Observations of individual Galactic jets in systems containing black hole accretors (e.g., Hjellming & Rupen 1995; Mirabel & Rodríguez 1994; Tavani et al. 1996) indeed suggest that the radio luminosity is proportional to some power (of order unity) of the mass flow rate into the jet. Simple models of radio emission from jets also predict radio luminosities that are roughly proportional to the mass flux into the jet (with the constant of proportionality depending on some power of the magnetic field strength and on the age of the source; e.g., Bicknell, Dopita, & O'Dea 1997). We therefore conclude that the general correlation in Figure 1 is entirely consistent with a model in which jets are formed by accretion disks (around supermassive black holes) that are threaded by a vertical magnetic field (e.g., Blandford & Payne 1982; Königl 1989; Ostriker 1997; Matsumoto et al. 1996; see Livio 1997 for a review).

A question that needs to be asked at this point is, can there be important selection effects that are skewing the slope of the $L_{5\ \rm GHz}$-$L_{[\rm O\ III]}$ correlation to be less than unity? This could occur, most naturally, if we were missing a class of high radio luminosity, high [O III] luminosity objects or if we have systematically underestimated the line luminosity of the high-luminosity objects. However, there is no evidence that this is the case. A fit to the slope for only $z \geq 0.2$ radio-loud sources indicates, if anything, a slightly flatter slope (0.37 ± 0.12) than that found either at low ($z \leq 0.2$) redshifts or taking the sample as a whole (0.61 ± 0.07), though the differences are not statistically significant. Similarly, the slope of the radio-quiet class is more dominated by low-redshift objects but shows no evidence of a change for redshifts less than 0.2 (slope 0.44 ± 0.07) or greater than 0.2 (slope 0.45 ± 0.55).

It is important to note that the fact that the $L_{5\ \rm GHz}$-$L_{[\rm O\ III]}$ relation *has almost the same slope* for both the radio-quiet and radio-loud AGNs probably indicates that the jet formation mechanism is the same in both of these subclasses.

4.2. *Black Hole Mass*

Another consequence of Figure 1 that should be pointed out is the following (see also Livio 1997): The mass of the central black hole determines the Eddington luminosity and, therefore, the maximum accretion rate that the system can sustain (this translates into how far to the right in Fig. 1 the system can be found). Hence, we can expect that the AGNs containing the most massive black holes will occupy the upper right corner of the distribution for each subclass (radio-loud and radio-quiet). Interestingly, we find that the distribution of the radio-loud AGNs extends to somewhat higher values of $L_{[\rm O\ III]}$ (larger $\dot{M}_{\rm acc}$). In order to further examine the implications of this fact, we show in Figure 6 the distribution of the sources with respect to their redshifts. We find that the sources at low redshifts ($z \leq 0.2$) exhibit the same range in $\dot{M}_{\rm acc}$ ($L_{[\rm O\ III]}$) in both radio-loud and radio-quiet AGNs, but that the radio-loud sources at higher redshifts extend to larger values of $\dot{M}_{\rm acc}$. Therefore, if the Eddington luminosity is indeed the limiting factor, then this finding can be regarded as suggestive that the maximum mass of the black holes found in radio-loud sources is higher than that in radio-quiet ones. This result would be consistent with the fact that the measured black hole masses appear to correlate with the bulge luminosities (Kormendy & Richstone 1995).

4.3. *The Distinction between Radio-loud and Radio-quiet Sources*

A more difficult and long-standing question is what distinguishes the upper group (radio-loud) from the lower one (radio-quiet). Recent discussions of this problem can be found, for example, in Blandford & Levinson (1995), Fabian & Rees (1995), Wilson (1996), and Livio (1997).

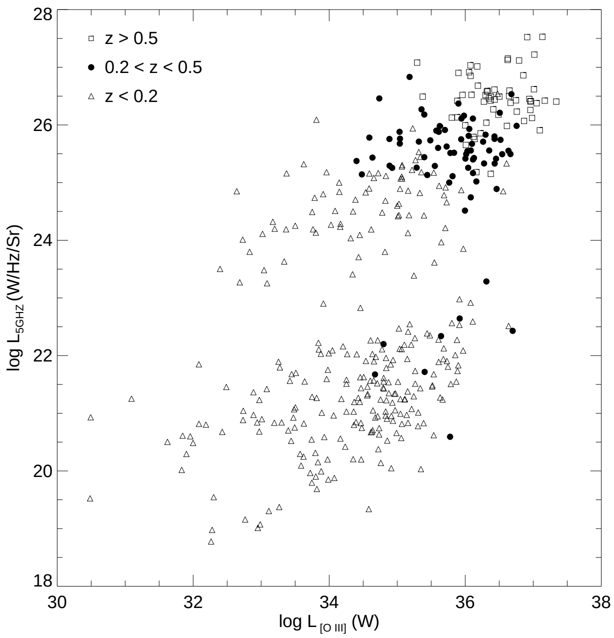

FIG. 6.—Same as Fig. 1, but with the redshift ranges indicated

Generally, explanations for the existence of these two classes fall into two different categories: (1) Those that assume that the central engines in radio-loud and radio-quiet AGNs are the same but that either the formation or the propagation of powerful jets is somehow prohibited in radio-quiet sources by some external circumstances. (2) Ones in which it is assumed that only the central engines of the radio-loud AGNs can produce truly *powerful* jets.

In recent work, Livio (1997, 1999) examined the formation of jets in *all* the classes of astrophysical objects that are observed to produce jets. On the basis of the assumption that the jet formation mechanism is *the same* in all the classes of objects, Livio has shown that the following *conjecture* is consistent with all the available observational data: the formation of *powerful* jets requires, in addition to an accretion disk threaded by a vertical field, an additional energy/wind source such as a corona or a source associated with the central object. More recently, Ogilvie & Livio (1998) solved for the local vertical structure of an accretion disk threaded by a poloidal magnetic field. By analyzing the dynamics of the transonic outflow in the disk corona, they showed that a certain potential difference must be overcome even when the inclination angle between the magnetic field and the vertical to the disk surface is larger than 30°. Thus, the launching of an outflow from an accretion disk indeed requires a hot corona or access to an additional source of energy, in accordance with Livio's above conjecture. Livio went on to attempt to identify the extra energy/wind source for every jet-producing class. In the case of black hole accretors, the general impression has been that this source may be the black hole spin (since rotational energy can be extracted, e.g., by the Blandford & Znajek 1977 mechanism). Observations suggesting that the spins of the two jet-producing Galactic black holes (GRS 1915+105 and GRO J1655−40) are high ($a_* = 0.998$ and $a_* = 0.93$, respectively, where a_* is the dimensionless specific angular momentum) while those of other stellar-mass black holes (which do not have jets) are very low ($a_* \sim 0$; Zhang, Cui, & Chen 1997) seemed consistent with this impression (although the spin determinations are rather uncertain). However, more recently, Ghosh & Abramowicz (1997), Livio, Ogilvie, & Pringle (1999), and Li (1999) have shown that the electromagnetic output from the inner disk is generally expected to dominate over that from the hole. Consequently, the spin of the hole may not be the "extra" energy source in Livio's conjecture. Rather, the role of the "wind" from the central source in Livio's conjecture may be played by gas pressure of the hot atmosphere in elliptical galaxies, as suggested by Fabian & Rees (1995). The latter possibility may be supported by the fact that Figure 5 shows that the high-$L_{5\,\mathrm{GHz}}$ group contains quite a few S0 galaxies (but no spirals), in which the central environments are generally similar to those in elliptical galaxies.

5. SUMMARY AND CONCLUSIONS

On the basis of the data collected in the present work and the discussion in § 4, we can draw the following (tentative) conclusions: (1) Both radio-quiet and radio-loud AGNs obey a linear log $L_{5\,\mathrm{GHz}}$-log $L_{[\mathrm{O\,III}]}$ relation, with a nearly identical slope (but with a shift toward higher radio power for the radio-loud sources, by a factor of $\sim 10^3$–10^4; see also Rawlings 1994). (2) The radio-loud and radio-quiet AGNs share the *same* linear correlation between log L_X and log $L_{[\mathrm{O\,III}]}$ (where L_X is the X-ray luminosity in the 2–10 keV range). (3) Consistently with previous studies, we find that radio-loud AGNs are found only in elliptical and S0 galaxies (although the distinction between S0 and elliptical is often ambiguous), while radio-quiet sources are mostly spirals and S0's. (4) The observationally determined $L_{5\,\mathrm{GHz}}$-$L_{[\mathrm{O\,III}]}$ correlation is consistent with a model in which the radio-emitting jets are formed by an accretion disk that is threaded by a vertical magnetic field. (5) It is still not entirely clear whether the distinction between radio-loud and radio-quiet AGNs is a consequence of differences in the central engines of these two classes or whether it merely reflects differences in the environments.

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