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ERRATUM: "BOUNDS ON BLACK HOLE SPINS" (2009, ApJL, 696, L32)

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IOP Publishing introduced a serious error during the production of this article, which resulted in eight of the values of the beam power in Column 3 of Table 1 being modified. Table 1 with the author's original content, which contains the correct numbers, is reproduced below. IOP Publishing accepts full responsibility for, sincerely regrets, and apologizes for this error.

Table 1
FRIIb Black Hole Properties

Source	z	L_j (10^{44} erg s^{-1})	M ($10^8\ M_\odot$)	B_E (10^4 G)	jb (BZ)	jb (M)	j (BZ)
3C 405	0.056	47 ± 8	25 ± 7	1.2 ± 0.2	0.51 ± 0.08	0.23 ± 0.04	0.72 ± 0.06
3C 244.1	0.43	14 ± 4	9.5 ± 6.6	1.9 ± 0.7	0.44 ± 0.16	0.2 ± 0.07	0.67 ± 0.12
3C 172	0.519	31 ± 8	7.8 ± 5.4	2.2 ± 0.7	0.74 ± 0.27	0.33 ± 0.12	0.86 ± 0.16
3C 330	0.549	80 ± 20	13 ± 9	1.7 ± 0.6	0.93 ± 0.34	0.41 ± 0.15	0.96 ± 0.18
3C 427.1	0.572	31 ± 8	14 ± 10	1.6 ± 0.5	0.55 ± 0.2	0.25 ± 0.09	0.74 ± 0.14
3C 337	0.63	20 ± 6	9.1 ± 6.2	2 ± 0.7	0.56 ± 0.2	0.25 ± 0.09	0.75 ± 0.14
3C34	0.69	65 ± 9	16 ± 11	1.5 ± 0.5	0.74 ± 0.27	0.33 ± 0.12	0.86 ± 0.15
3C441	0.707	65 ± 12	18 ± 12	1.4 ± 0.5	0.72 ± 0.26	0.32 ± 0.12	0.85 ± 0.15
3C 55	0.72	180 ± 50	14 ± 10	1.6 ± 0.6	1.3 ± 0.5	0.58 ± 0.22	1.14 ± 0.22
3C 247	0.749	35 ± 9	26 ± 18	1.2 ± 0.4	0.43 ± 0.17	0.19 ± 0.07	0.66 ± 0.13
3C 289	0.967	85 ± 19	27 ± 21	1.2 ± 0.4	0.66 ± 0.27	0.3 ± 0.12	0.82 ± 0.16
3C 280	0.996	53 ± 15	27 ± 21	1.2 ± 0.4	0.52 ± 0.22	0.23 ± 0.1	0.72 ± 0.15
3C 356	1.079	250 ± 85	28 ± 22	1.1 ± 0.5	1.12 ± 0.49	0.5 ± 0.22	1.06 ± 0.23
3C 267	1.144	190 ± 50	24 ± 20	1.2 ± 0.5	1.04 ± 0.45	0.47 ± 0.2	1.02 ± 0.22
3C 324	1.21	150 ± 55	37 ± 30	1 ± 0.4	0.76 ± 0.35	0.34 ± 0.15	0.87 ± 0.20
3C 437	1.48	710 ± 180	24 ± 22	1.2 ± 0.5	2.03 ± 0.95	0.91 ± 0.42	1.42 ± 0.33
3C 68.2	1.575	210 ± 68	35 ± 32	1 ± 0.5	0.91 ± 0.45	0.41 ± 0.2	0.96 ± 0.23
3C 322	1.681	510 ± 140	32 ± 30	1.1 ± 0.5	1.48 ± 0.73	0.66 ± 0.33	1.22 ± 0.30
3C 239	1.79	480 ± 170	37 ± 36	1 ± 0.5	1.35 ± 0.69	0.6 ± 0.31	1.16 ± 0.30

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BOUNDS ON BLACK HOLE SPINS

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ABSTRACT

Beam powers and black hole masses of 48 extended radio sources are combined to obtain lower bounds on the spins and magnetic field strengths of supermassive black holes. This is done in the context of the models of Blandford & Znajek (the "BZ" model) and Meier; a parameterization for bounds in the context of other models is suggested. The bounds obtained for very powerful classical double radio sources in the BZ model are consistent with black hole spins of order unity for sources at high redshift. The black hole spins are largest for the highest redshift sources and decrease for sources at lower redshift; the sources studied have redshifts between zero and two. Lower-power radio sources associated with central dominant galaxies may have black hole spins that are significantly less than one. Combining this analysis with other results suggests that the maximum values of black hole spin associated with powerful radio galaxies decline from values of order unity at a redshift of 2 to values of order 0.7 at a redshift of zero, falling roughly as $\sqrt{(1+z)}$, while lower power radio sources have spin values that range from about 0.1 to 0.8. These black hole spin values decrease if the data are considered in the context of the Meier model rather than the BZ model.

Key words: black hole physics – galaxies: active – galaxies: nuclei

1. INTRODUCTION

Quasars and other types of active galactic nucleus (AGN) activity are believed to be powered by supermassive black holes. The AGN activity may produce highly collimated outflows from the immediate vicinity of the black hole (e.g., Rees 1984; Blandford 1990), which can power a large-scale radio source. Two defining properties of astrophysical black holes that can be measured in principle are the black hole mass and spin. A significant amount of progress has been made toward measuring the masses of supermassive black holes (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Ferrarese & Ford 2005), though measuring the spin has been more challenging.

General theoretical studies suggest that the merger and accretion history of a supermassive black hole is encoded in the spin of the hole. For example, successive mergers are likely to produce black holes that are spinning at a moderate rate ($j \sim 0.7$), while powerful accretion events are likely to produce rapidly rotating black holes (Berti & Volonteri 2008). Alternatively, most black holes may grow due to many short-lived, uncorrelated accretion episodes, which would lead to lower spin values (King & Pringle 2006, 2007). Numerous uncorrelated accretion episodes tend to cause the spin of the hole to decrease over time with substantial fluctuations in spin caused by each episode (King et al. 2008).

At present, only a few observations allow black hole spins to be studied directly. Observations of Seyfert galaxies suggest rapidly rotating black holes in these systems (Wilms et al. 2001; Fabian et al. 2002). A large spin is indicated by observations of the Galactic center black hole (Genzel et al. 2003; Aschenbach et al. 2004). And, X-ray observations of active galaxies suggest rapidly rotating black holes in these systems (Crummy et al. 2006). Outflows from AGN that produce extended radio sources allow a lower bound to be placed on the spin of the black hole that powers the outflow. Assuming only that the outflow is powered by the spin energy of the black hole, Daly (2008) showed that the outflow energy and the black hole mass may be combined to obtain a lower limit on the spin of the black hole. For a sample of 19 very powerful classical double sources, the lower bound was about the same for each source in the sample, and indicated $j_{\min} \approx 0.12 \pm 0.01$.

Here, beam powers and black hole masses of radio sources are combined to study black hole spins in the contexts of the models of Blandford & Znajek (1977), Meier (1999), and models with similar functional forms. It is shown that the spin and magnetic field strength of a supermassive black hole can be rather tightly constrained in the contexts of these models. The method is described in Section 2. It is applied to two samples of sources, and the results are presented in Section 3, discussed in Section 4, and summarized in Section 5. A standard cosmological model with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and zero space curvature is assumed throughout.

2. THE METHOD

The well-known model of Blandford & Znajek (1977), referred to as the "BZ" model, and other models to power highly collimated outflows from AGN are considered here. In the BZ model, the beam power L_j that will be produced is related to the dimensionless black hole spin $j \equiv Sc/(GM^2)$, the black hole horizon $r_H = 2GM/c^2$, and the poloidal magnetic field strength B_{p0} at the horizon, where S is the black hole spin angular momentum, M is the black hole mass, G is Newton's constant, and c is the speed of light (e.g., Macdonald & Thorne 1982; Thorne et al. 1986)

$$L_j(BZ) = \left(j^2 B_{p0}^2 r_H^2 \omega_F^2 c\right)/32 \approx 2 \times 10^{43} j^2 M_8^2 B_4^2 \text{ erg s}^{-1}. \quad (1)$$

Here B_4 is the value of B_{p0} in units of 10^4 G, M_8 is the black hole mass in units of $10^8 M_\odot$, and the factor $\omega_F^2 \equiv \Omega_F(\Omega_h - \Omega_F)/\Omega_h^2$ depends on the angular velocity of the field lines Ω_F relative to that of the hole Ω_h and is taken to have its maximum value of $\omega_F^2 = (0.5)^2$ (e.g., Blandford 1990). The magnetic field strength is not expected to exceed the Eddington magnetic field strength, given by $B_E \approx 6 \times 10^4 M_8^{-1/2}$ G (e.g., Dermer et al. 2008). Rewriting Equation (1) in terms of the black hole spin j and

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FRIIb Black Hole Properties

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3C 405	0.056	47 ± 8	25 ± 7	1.2 ± 0.2	0.51 ± 0.08	0.23 ± 0.04	0.72 ± 0.06
3C 244.1	0.43	14 ± 4	9.5 ± 6.6	1.9 ± 0.7	0.44 ± 0.16	0.2 ± 0.07	0.67 ± 0.12
3C 172	0.519	31 ± 8	7.8 ± 5.4	2.2 ± 0.7	0.74 ± 0.27	0.33 ± 0.12	0.86 ± 0.16
3C 330	0.549	80 ± 20	13 ± 9	1.7 ± 0.6	0.93 ± 0.34	0.41 ± 0.15	0.96 ± 0.18
3C 427.1	0.572	31 ± 8	14 ± 10	1.6 ± 0.5	0.55 ± 0.2	0.25 ± 0.09	0.74 ± 0.14
3C 337	0.63	20 ± 6	9.1 ± 6.2	2 ± 0.7	0.56 ± 0.2	0.25 ± 0.09	0.75 ± 0.14
3C34	0.69	65 ± 9	16 ± 11	1.5 ± 0.5	0.74 ± 0.27	0.33 ± 0.12	0.86 ± 0.15
3C441	0.707	65 ± 12	18 ± 12	1.4 ± 0.5	0.72 ± 0.26	0.32 ± 0.12	0.85 ± 0.15
3C 55	0.72	1.0 ± 50	14 ± 10	1.6 ± 0.6	1.3 ± 0.5	0.58 ± 0.22	1.14 ± 0.22
3C 247	0.749	35 ± 9	26 ± 18	1.2 ± 0.4	0.43 ± 0.17	0.19 ± 0.07	0.66 ± 0.13
3C 289	0.967	85 ± 19	27 ± 21	1.2 ± 0.4	0.66 ± 0.27	0.3 ± 0.12	0.82 ± 0.16
3C 280	0.996	53 ± 15	27 ± 21	1.2 ± 0.4	0.52 ± 0.22	0.23 ± 0.1	0.72 ± 0.15
3C 356	1.079	2.0 ± 85	28 ± 22	1.1 ± 0.5	1.12 ± 0.49	0.5 ± 0.22	1.06 ± 0.23
3C 267	1.144	1.0 ± 50	24 ± 20	1.2 ± 0.5	1.04 ± 0.45	0.47 ± 0.2	1.02 ± 0.22
3C 324	1.21	1.0 ± 55	37 ± 30	1 ± 0.4	0.76 ± 0.35	0.34 ± 0.15	0.87 ± 0.20
3C 437	1.48	7.0 ± 180	24 ± 22	1.2 ± 0.5	2.03 ± 0.95	0.91 ± 0.42	1.42 ± 0.33
3C 68.2	1.575	2.0 ± 68	35 ± 32	1 ± 0.5	0.91 ± 0.45	0.41 ± 0.2	0.96 ± 0.23
3C 322	1.681	5.0 ± 140	32 ± 30	1.1 ± 0.5	1.48 ± 0.73	0.66 ± 0.33	1.22 ± 0.30
3C 239	1.79	4.0 ± 170	37 ± 36	1 ± 0.5	1.35 ± 0.69	0.6 ± 0.31	1.16 ± 0.30

normalized magnetic field strength $b \equiv B_{p0}/B_E$, we have

$$jb_{BZ} \approx (B_{E,4}M_8)^{-1}\sqrt{(5L_{44})} \approx \sqrt{(17.5L_j/L_E)}, \qquad (2)$$

where $B_{E,4}$ is the Eddington magnetic field strength in units of 10^4 G, $B_{E,4} \approx 6M_8^{-1/2}$, L_{44} is the beam power in units of 10^{44} erg s^{-1}, and L_E is the Eddington luminosity, $L_E \approx 1.26 \times 10^{46} M_8$ erg s^{-1}.

Equation (2) allows a determination of the quantity jb_{BZ} when observations allow determinations of the beam power of the source, L_j, and the black hole mass, M. The parameter jb_{BZ} provides a lower bound on j and a lower bound on b in the context of the BZ model since the maximum value of j is unity and the maximum value of b is unity. When this parameter, referred to as the "j–b" parameter, is equal to one, it suggests that both j and b are close to one. If the "j–b" parameter exceeds one, it suggests a problem with the underlying model (in this case, the BZ model). Thus, the "j–b" parameter indicated by Equation (2) provides a lower bound on j and a lower bound on b in the context of the BZ model, and provides a test of the BZ model.

Models may be characterized by comparison with BZ model predictions by writing $L_j = \kappa L_j(BZ)$. Then jb of that model is $jb = jb_{BZ}/\sqrt{\kappa}$. If jb_{BZ} exceeds unity, then models with values of κ with $\kappa \geqslant [jb_{BZ}]^2$ would be indicated. Consider, for example, the hybrid model proposed by Meier (1999). This model includes characteristics of the Blandford–Payne (Blandford & Payne 1982) and Blandford–Znajek (Blandford & Znajek 1977) models. The beam power produced in this model is $L_j(M) \approx 10^{44} j^2 M_8^2 B_4^2$ erg s^{-1} (Meier 1999), or $\kappa(M) \simeq 5$, and $jb_M \simeq jb_{BZ}/\sqrt{5}$.

Requiring that jb satisfy $jb \leqslant 1$ allows constraints to be placed on κ, and this indicates which models can account for the characteristics of these systems.

3. RESULTS

The method is applied to the samples of 19 very powerful FRII radio galaxies (referred to as FRIIb sources) and 29 central dominant galaxies (CDGs) studied by Daly (2008). The FRIIb sources have radio powers at least a factor of 10 above the classical FRI/FRII transition (Fanaroff & Riley 1974). Black hole masses and beam powers are available for all of these sources; the masses are listed in Tables 1 and 2 of Daly (2008). Beam powers for the powerful classical double radio galaxies are obtained from Guerra et al. (2000), Wan et al. (2000), and O'Dea et al. (2008) note that these beam powers are independent of offsets of the extended radio source from minimum energy conditions (O'Dea et al. 2008). Beam powers for the CDGs are obtained from Rafferty et al. (2006), and also are independent of offsets from minimum energy conditions. Almost all of the radio sources associated with CDGs have an FRI radio source structure or amorphous radio structure, with a few exceptions such as Cygnus A (Birzan et al. 2008). The name, redshift, total beam power, black hole mass, and Eddington magnetic field strength are listed for each source in Tables 1 and 2 for the FRIIb and CDG sources, respectively. The beam powers and black hole masses were combined to solve for jb_{BZ} using Equation (2) and are listed in Tables 1 and 2. Values of jb_M were obtained explicitly for the FRIIb sources using $\kappa(M) \approx 5$ so $jb_M \approx jb_{BZ}/\sqrt{(5)}$, and are included in Table 1. The value of $\sqrt{(jb_{BZ})}$ is listed in the final column of Tables 1 and 2, and is discussed below. For simplicity, the average values of asymmetric error bars was used.

The parameter jb_{BZ} is shown as a function of black hole mass in Figure 1. Analyzing the two samples separately, there is no indication of a dependence of jb_{BZ} on black hole mass (see Figure 1). Since jb_{BZ}, and jb_M, are proportional to $\sqrt{L_j/L_E}$ (see Equation (2)), this is equivalent to finding no dependence of L_j/L_E on black hole mass.

The parameter jb_{BZ} is shown as a function of redshift in Figure 2. Each sample clearly exhibits a dependence of jb on redshift (see Figure 2). The sample of 19 powerful FRIIb sources has the dependence $\mathrm{Log}(jb_{BZ}) = (0.92 \pm 0.24)\,\mathrm{Log}\,(1 + z) - (0.34 \pm 0.06)$. Given that these are the most powerful radio sources at each redshift and that they are drawn from a complete sample of sources, this represents the envelope of the distribution of jb values as a function of redshift. Thus, this redshift dependence can be interpreted as

Table 2
CDG Black Hole Properties

Source	z	L_j (10^{44} erg s^{-1})	M ($10^8\,M_\odot$)	B_E (10^4 G)	jb (BZ)	j (BZ)
M84	0.0035	0.01 ± 0.011	3.4 ± 0.9	3.2 ± 0.4	0.02 ± 0.022	0.14 ± 0.08
M87	0.0042	0.06 ± 0.026	8.6 ± 2.9	2 ± 0.3	0.031 ± 0.017	0.18 ± 0.05
Centaurus	0.011	0.074 ± 0.038	8.6 ± 2.9	2 ± 0.3	0.035 ± 0.021	0.19 ± 0.06
HCG 62	0.014	0.039 ± 0.042	5.7 ± 2.9	2.5 ± 0.6	0.031 ± 0.037	0.18 ± 0.10
A262	0.016	0.097 ± 0.051	8.6 ± 2.9	2 ± 0.3	0.04 ± 0.025	0.20 ± 0.06
Perseus	0.018	1.5 ± 0.7	17 ± 7	1.4 ± 0.3	0.11 ± 0.07	0.33 ± 0.10
PKS 1404-267	0.022	0.2 ± 0.18	5.7 ± 2.9	2.5 ± 0.6	0.07 ± 0.07	0.26 ± 0.13
A2199	0.03	2.7 ± 1.6	20 ± 9	1.3 ± 0.3	0.14 ± 0.1	0.37 ± 0.13
A2052	0.035	1.5 ± 1.4	17 ± 7	1.4 ± 0.3	0.11 ± 0.11	0.33 ± 0.16
2A 0335+096	0.035	0.24 ± 0.15	14 ± 7	1.6 ± 0.4	0.048 ± 0.038	0.22 ± 0.09
MKW 3S	0.045	4.1 ± 2.3	8.6 ± 2.9	2 ± 0.3	0.26 ± 0.17	0.51 ± 0.17
A4059	0.048	0.96 ± 0.62	29 ± 14	1.1 ± 0.3	0.068 ± 0.056	0.26 ± 0.11
Hydra A	0.055	4.3 ± 1.3	11 ± 4	1.8 ± 0.3	0.23 ± 0.11	0.48 ± 0.11
A85	0.055	0.37 ± 0.24	29 ± 14	1.1 ± 0.3	0.042 ± 0.035	0.21 ± 0.08
Cygnus A	0.056	13 ± 7	29 ± 14	1.1 ± 0.3	0.25 ± 0.18	0.50 ± 0.18
Sersic 159/03	0.058	7.8 ± 5.4	17 ± 9	1.4 ± 0.4	0.25 ± 0.21	0.50 ± 0.21
A133	0.06	6.2 ± 1.4	20 ± 10	1.3 ± 0.3	0.21 ± 0.11	0.46 ± 0.13
A1795	0.063	1.6 ± 1.4	23 ± 11	1.3 ± 0.3	0.099 ± 0.099	0.31 ± 0.16
A2029	0.077	0.87 ± 0.27	60 ± 36	0.77 ± 0.23	0.045 ± 0.03	0.21 ± 0.07
A478	0.081	1 ± 0.5	26 ± 14	1.2 ± 0.3	0.073 ± 0.055	0.27 ± 0.10
A2597	0.085	0.67 ± 0.58	8.6 ± 2.9	2 ± 0.3	0.1 ± 0.1	0.32 ± 0.15
3C 388	0.092	2 ± 1.8	17 ± 7	1.4 ± 0.3	0.13 ± 0.13	0.36 ± 0.18
PKS 0745-191	0.103	17 ± 9	31 ± 16	1.1 ± 0.3	0.27 ± 0.19	0.52 ± 0.19
Hercules A	0.154	3.1 ± 2.5	20 ± 11	1.3 ± 0.4	0.15 ± 0.14	0.38 ± 0.19
Zw 2701	0.214	60 ± 62	17 ± 9	1.4 ± 0.4	0.7 ± 0.8	0.84 ± 0.48
MS 0735.6+7421	0.216	69 ± 51	20 ± 11	1.3 ± 0.4	0.69 ± 0.65	0.83 ± 0.39
4C 55.16	0.242	4.2 ± 3	14 ± 7	1.6 ± 0.4	0.2 ± 0.18	0.45 ± 0.20
A1835	0.253	18 ± 13	54 ± 36	0.81 ± 0.27	0.21 ± 0.21	0.46 ± 0.22
Zw 3146	0.291	58 ± 42	74 ± 53	0.7 ± 0.25	0.33 ± 0.33	0.57 ± 0.29

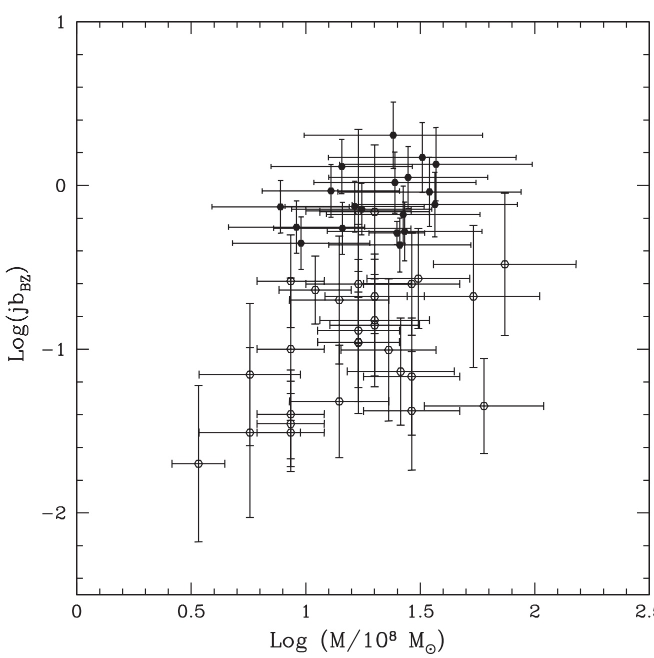

Figure 1. Distribution of "j–b" parameters obtained in the context of the BZ model as a function of black hole mass. The 19 sources associated with very powerful classical double radio galaxies are indicated by solid circles, and the 29 sources associated with CDGs are indicated by the open circles. One source, Cygnus A (3C 405), is included in both samples.

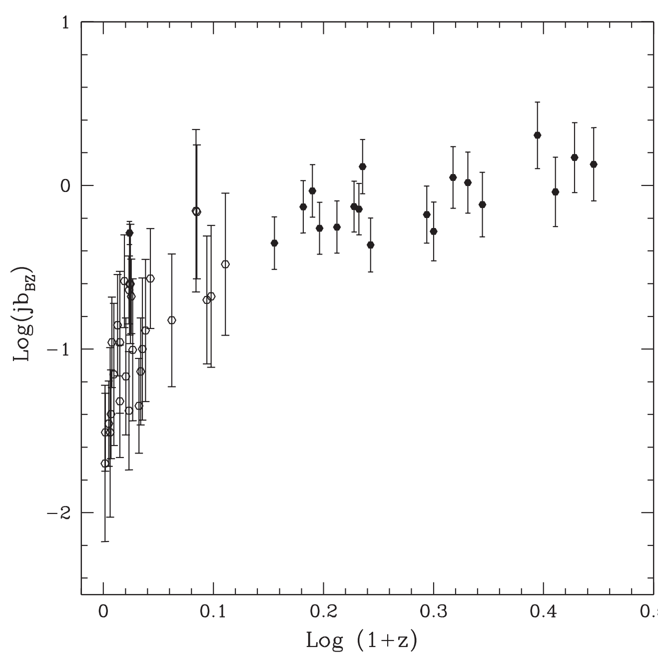

Figure 2. Distribution of "j–b" parameters obtained in the context of the BZ model as a function of redshift. The symbols are as in Figure 1.

the evolution of the maximum value of jb as a function of redshift, and is obtained in the context of the BZ model. The normalization of jb decreases by a factor of about $1/\sqrt(5)$ if the Meier model is considered, but the redshift behavior is unaffected.

The beam power is shown as a function of black hole mass in Figure 3. The CDGs have much lower beam powers than the

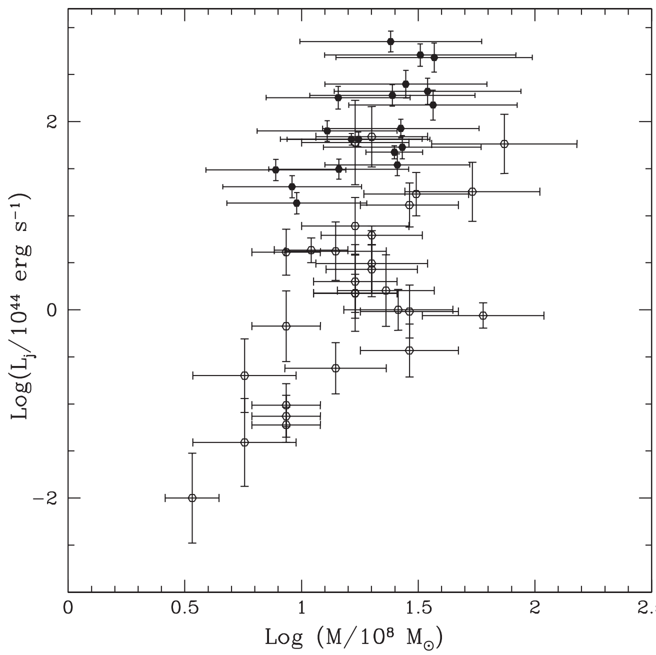

Figure 3. Beam powers as a function of black hole mass. The symbols are as in Figure 1.

FRIIb sources, though the sources are powered by black holes with similar mass.

The value of j and b may be independent, or the value of b could depend upon j. The results of Daly et al. (2009) and Daly & Guerra (2002) suggest that $B_{p0} \propto j$, that is, $b \propto j$. Setting $b = b_* j$, and noting that $j \leqslant 1$ and $b \leqslant 1$, the results for jb listed in Table 1 indicate that $0.4 \leqslant b_* \leqslant 1$ for the BZ model. Thus, b_* is of order unity, or $b \approx j$. In this case, $jb \approx j^2$, and the redshift evolution of the maximum value of j varies as $\text{Log}(j) = (0.46 \pm 0.12)\,\text{Log}\,(1+z) - (0.17 \pm 0.03)$. The values of j obtained using $j \approx \sqrt{(jb)}$ are listed in the final column of Tables 1 and 2 and are obtained in the context of the BZ model.

4. DISCUSSION

All of the empirically determined jb_{BZ} parameters are consistent with $jb_{BZ} \leqslant 1$ at about the 1σ level, thus the current data do not require modifications to the BZ model (see Tables 1 and 2 and Figure 1). It is interesting that many sources have $jb_{BZ} \simeq 1$, indicating that both j and b are close to one if the BZ model provides an accurate description of the physics of these systems. Almost all of the empirically determined $jb(M)$ parameters are less than one, indicating that either j or b is less than one if this model provides an accurate description of these systems.

As noted in Section 2, the parameter jb provides a lower bound on j and a lower bound on b since neither is expected to exceed unity. The lower bounds on j obtained for FRIIb sources in the BZ and the Meier models are about 0.4 and 0.2, respectively (see Table 1). These are larger than the lower bound of $j_{\min} = 0.12 \pm 0.01$ obtained for these same sources by Daly (2008) using a model-independent approach, assuming only that the large-scale outflow from the AGN is powered by the spin energy of the black hole. Combining the results obtained here with those obtained by Daly (2008) indicates that only a small fraction of the spin energy per unit black hole mass, r, of a system is extracted during one particular outflow event for the FRIIb sources studied and most of the CDGs. Thus, a single outflow event does not significantly reduce the spin of the black hole for FRIIb sources and most radio sources associated with CDGs.

The parameter jb_{BZ} is clearly increasing with redshift (see Figure 2), and is roughly $\propto (1+z)^{0.92\pm0.24}$ for the FRIIb sources. The fact that lower jb_{BZ} sources are missing at high redshift results from the radio power selection effect, since all of the higher redshift sources are from the 3CRR catalog (Laing et al. 1983); obviously, this does not explain the lack of high jb sources at low redshift. Given that the sources with high radio power have high beam power, and, for a fixed black hole mass, sources with high beam power have high spin (see Equation (1)), the FRIIb sources studied here are likely to have spin values that are close to the maximal values for sources at that redshift. Thus, the evolution of spin of these systems should be considered to be the envelope of the distribution, presenting the maximal spin as a function of redshift. That is, the black holes at the centers of massive elliptical galaxies that produce FRIIb radio sources have maximal spin values that are slowly decreasing as the universe evolves.

The results of Daly (2008) suggest that the energy extracted per unit black hole mass, r, during each outflow event is independent of source redshift and black hole mass, and is roughly constant for all of the FRIIb sources studied. Given the selection effects affecting the CDGs, the data were consistent with those sources having a value of $j_{\min}$ similar to that of the FRIIb sources. The lower bounds on j obtained here in the context of the BZ model are consistent with $j_{\min}$ of 0.12 ± 0.01 obtained for the FRIIb sources by Daly (2008) and with most of the CDGs at about 1 to 2σ.

In the case that $b \simeq j$, as discussed in Section 3 and as indicated by detailed studies of FRIIb sources (e.g., Daly et al. 2009), the value of j is obtained by taking the square root of the values of jb listed in Tables 1 and 2, and is listed in the final columns of each table. In this case, all of the FRIIb and CDG sources have values of j that are consistent with the "model-independent" minimum value $j_{\min} = 0.12 \pm 0.01$ obtained by Daly (2008). In addition, this implies that the maximum value of j evolves as $\text{Log}(j) = (0.46 \pm 0.12)\,\text{Log}(1+z) - (0.17 \pm 0.03)$. The evolution of the spins of supermassive black holes may be used to study the accretion and merger history of these sources, as discussed, for example, by King & Pringle (2006, 2007), Berti & Volonteri (2008), and King et al. (2008). It is particularly intriguing that the redshift evolution obtained here for FRIIb sources is very similar to that predicted by the detailed model of King et al. (2008) for spin down by gas accretion through a series of repeated accretion episodes. In comparing the results obtained here with theoretical predictions, it should be kept in mind that all of the CDGs are by definition associated with giant elliptical galaxies, and the FRIIb sources are likely to evolve into CDGs (Lilly & Longair 1984; Best et al. 1998; McLure et al. 2004). Due to the way each sample is selected, the CDGs allow a glimpse into the spin values of sources with low radio power and low beam power, while the FRIIb sources are the most powerful extended radio sources at their respective redshifts.

The combination of the results obtained here with those obtained earlier suggest that each source may undergo multiple outflow events. The energy extracted per outflow event is roughly constant, suggesting very similar physical conditions in the source when the outflow event is triggered, and the energy extracted per outflow event is a small fraction of the total available energy for most of the sources (Daly 2008).

Thus, each source may undergo numerous outflow events. These outflow events could significantly affect the gaseous medium in the vicinity of the radio source. This heating of the gaseous environment of the source could cause the radio source structure to shift from FRII to FRI structure. This is consistent with the ideas that very powerful 3CRR radio galaxies evolve into CDGs (Lilly & Longair 1984; Best et al. 1998; McLure et al. 2004), that different radio structures are determined by the source environment (e.g., Hardee et al. 1992; O'Donoghue et al. 1993; Burns et al. 1994; Bicknell 1995; Barai & Wiita 2007), and that the evolution of the gaseous environments could be due in part to the large-scale outflows (e.g., Silk & Rees 1998; Eilek & Owen 2002). The CDGs do have much lower beam powers than the FRIIb sources, which may also explain the differences in the radio source structures.

5. SUMMARY

Both the CDG and FRIIb samples are illustrative of outflows from massive black holes associated with giant elliptical galaxies since FRIIb sources are expected to evolve into CDGs (Lilly & Longair 1984; Best et al. 1998; McLure et al. 2004). The CDGs allow a study of black hole spins and magnetic field strengths of lower power radio sources that have a range of beam power, black hole spin, and magnetic field strengths. The FRIIb sources allow a study of black hole spins and magnetic field strengths of the most powerful sources with large-scale outflows at their respective redshifts; these are the sources that have the largest radio power, beam power, and black hole spin.

These sources were studied in the context of the BZ and Meier models, which allowed the beam power and black hole mass of each source to be combined to obtain lower bounds on the black hole spin and strength of the magnetic field close to the black hole. The lower bounds on the black hole spin obtained for FRIIb sources were significantly larger than those obtained by Daly (2008) by studying the outflow energy and black hole mass of each system. This implies that, if the black hole spin powers the large-scale outflows in these systems, then the energy extracted in each outflow event is a small fraction of the total spin energy available. Thus, the evolution of the spin with redshift is a reflection of the merger and accretion history of the source, and is not significantly affected by energy losses associated with the outflow. And, each source may undergo numerous outflow events.

Independent empirical work has shown that the magnetic field strength is proportional to the black hole spin (e.g., Daly et al. 2009). This means that the values of jb obtained here can be used to obtain estimates of the black hole spin j; the normalization between b and j is of order unity, but is not precisely known. Values of j were obtained in the context of the BZ model for the FRIIb and CDGs. The values obtained for FRIIb sources range from about 0.7 to 1, while those for CDGs range from about 0.14 to 0.8. If considered in the context of the Meier (1999) model, these values decrease by a factor of about 1.5. All the values are greater than or similar to the "model-independent" minimum value of $j_{\min} \approx 0.12 \pm 0.01$ obtained by Daly (2008). Losses due to outflows will affect the spin of the black hole when that spin is close to $j_{\min}$. Thus, this could affect the spins of black holes of CDGs with low values of j, but is unlikely to affect the those associated with FRIIb sources.

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