## PROPERTIES OF RADIO-SELECTED BROAD ABSORPTION-LINE QUASARS FROM THE FIRST BRIGHT QUASAR SURVEY

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# ABSTRACT

In a spectroscopic follow-up to the VLA FIRST survey, the FIRST Bright Quasar Survey (FBQS) has found 29 radio-selected broad absorption line (BAL) quasars. This sample provides the first opportunity to study the properties of radio-selected BAL quasars. Contrary to most previous studies, we establish that a significant population of radio-loud BAL quasars exists. Radio-selected BAL quasars display compact radio morphologies and possess both steep and flat radio spectra. Quasars with low-ionization BALs have a color distribution redder than that of the FBQS sample as a whole. The frequency of BAL quasars in the FBQS is significantly greater, perhaps by as much as factor of two, than that inferred from optically selected samples. The frequency of BAL quasars appears to have a complex dependence on radio-loudness. The properties of this sample appear inconsistent with simple unified models in which BAL quasars constitute a subset of quasars seen edge-on.

Subject headings: quasars: radio — quasars: broad absorption line — quasars: evolution — surveys

### 1. INTRODUCTION

Until recently, a search of the astronomical literature would have revealed that broad absorption lines (BAL) are seen in approximately 10% of optically selected quasars (Foltz et al. 1990; Weymann et al. 1991) and in exactly 0% of radio-loud quasars (Stocke et al. 1992). This dichotomy has puzzled astronomers for years. The BAL quasars can be divided into two classes, high-ionization and low-ionization, which are primarily defined by the presence of broad absorption by C IV  $\lambda$ 1549 and Mg II  $\lambda$ 2800, respectively. (Note that all low-ionization BAL quasars also show high ionization absorption). The highionization BAL (HiBAL) quasars are more common, including 10% of all optically selected quasars, while the rarer lowionization BAL (LoBAL) quasars make up only 1% of optically selected quasars.

Prior to the FIRST survey there was only a single example of a LoBAL quasar whose spectrum shows strong absorption by metastable excited states of Fe II (Q 0059-2735, Hazard et al. 1987). Becker et al. (1997) reported the discovery of two more objects resembling Q0059-2735 (FIRST J084044.5+363328 and J155633.8+351758), the second of which is radio-loud. We will refer to these as FeLoBAL quasars. Both of the new unusual quasars were found by making optical identifications of radio sources from the VLA FIRST survey (Faint Images of the Radio Sky at Twenty-cm, Becker, White, & Helfand 1995; White et al. 1997). Subsequently, Brotherton et al. (1998) identified five more radio-loud BAL quasars (two Hi-BAL and three LoBAL quasars) from a complete sample of radio-selected ultraviolet excess guasars, firmly establishing the existence of radio-loud BAL quasars. Lastly, Wills, Brandt, and Laor (1999) have recently suggested that the radio-loud quasar PKS 1004+13 is also a BAL guasar.

For the past five years we have been developing several new radio-selected samples of quasars based on the VLA FIRST survey. The most extensive of these is the FIRST Bright Quasar Survey or FBQS (Gregg et al. 1996, hereafter FBQS1; White et al. 2000, hereafter FBQS2). The goal of the FBQS is to identify all quasars in the FIRST survey brighter than 17.8 on the POSS-I E (red) plate. In the initial 2700 square degrees of the FIRST survey, we defined a sample of 1238 quasar candidates based on positional coincidence between a FIRST source and a POSS-I stellar object (see FBQS1 and FBQS2 for a detailed discussion of the candidate selection criteria). Spectra have been collected for 90% of these candidates, 636 of which have been identified as quasars. Among these are 29 which display BAL characteristics. We present the optical spectra and radio spectral indices of these BAL quasars, comparing their radio and optical properties to previous samples of optically selected BAL quasars. We discuss the selection biases inherent in the survey results and discuss why our sample differs from those based on optically selected samples.

#### 2. IDENTIFICATION AND CLASSIFICATION OF BAL QUASARS

The FBQS BAL quasars are defined to be any quasar which shows significant broad absorption blueward of either Mg II  $\lambda 2800$  or C IV  $\lambda 1549$ . We have chosen not to employ any strict definition of a BAL, such as the "BALnicity" index of Weymann et al. (1991), which requires continuous absorption of at least 10% in depth spanning more than 2000 km s<sup>-1</sup>, discounting absorption closer than 3000 km s<sup>-1</sup> blueward of the emission peak. Weymann's highly conservative definition has the advantage of unambiguously distinguishing between associated absorbers and "classical BALs" but could unnecessarily exclude several potentially very interesting members of the class. We advocate classification of absorption systems based on their physical characteristics such as variability and partial coverage (c.f. Barlow et al. 1997) and so we choose not to exclude any likely BAL quasars.

Even though we did not use "BALnicity" to define our sample, we have calculated the BALnicity index for each of our

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BALs. The values are given in Table 1. In all, seven of our BALs fail the BALnicity test, i.e., they have zero BALnicity. Three of these are LoBALs for which by necessity the BALnicity was calculated from the Mg II absorption line, a line for which the test was never meant to be applied (Weymann et al 1991). For example, Voit et al (1993) found that Mg II absorption troughs are usually narrower than the C IV absorptions troughs in LoBALs. Two of these LoBALs are in fact FeLoBALs and the correctness of their inclusion is almost beyond question in so far as the conditions necessary for absorption by excited states of Fe strongly indicate an intrinsic system local to the active nucleus (FIRST J084044.5+363328 and FIRST 121442.3+280329). The inclusion of the third (FIRST J112220.5+312441) is problematical and will only be resolved with an observation of C IV. Inclusion of the four HiBALs which fail the test can be justified as follows. Two of them (FIRST J095707.4+235625 and J141334.4+421202) have nearly black C IV absorption spanning 4000 km/sec which is very unlikely to break up into a blend of narrow lines. FIRST J115023.6+281908 has three C IV absorption systems with velocities up to 11700 km/sec. Even though none of the absorbers individually is 2000 km/sec broad, the three taken together are very suggestive of being an intrinsic BAL outflow. Lastly, the Si IV absorption lines in FIRST J160354.2+300209 show clear evidence of partial covering which is normally taken to be a property of BALs (Arav et al. 1999).

The typical wavelength coverage of the FBQS spectra is 3800 to 8000 Å. For quasars with 0.5 < z < 1.7, the MgII 2800 feature is shifted into the observed range, permitting identification of LoBALs. Somewhat higher redshift LoBALs can be identified through broad absorption by Al III  $\lambda$ 1860 as in the case of FIRST J105427.1+253600. HiBAL quasars can be identified only for  $z \ge 1.4$  which brings CIV  $\lambda$ 1549 well into the observed spectral range. (Since the observed wavelength coverage is not uniform for all the FBQS spectra, the redshift range over which C IV is observable differs from quasar to quasar.) Some of our HiBAL quasars, since LoBALs also exhibit broad CIV  $\lambda$ 1549 and other high-ionization species.

Table 1, partially excerpted from Table 2 in FBOS2, lists FIRST catalog RA and Dec (J2000), recalibrated and extinction-corrected E and O magnitudes, red extinction corrections A(E), FIRST peak and integrated radio flux densities, the computed BALnicity index (as defined in Weymann et al. 1991), the maximum outflow velocity in the absorption lines, and redshifts for the 29 BAL quasars identified to date in the FBQS. Also in Table 1 are the radio luminosity  $L_R$  at a rest frequency of 5-GHz (calculated using the observed radio spectral indices from Table 2 and hence different from the values given in FBQS2), the absolute B magnitude  $M_B$ , and the radio loudness,  $R^*$ , the ratio of the 5 GHz radio flux density to the 2500 Å optical flux in the quasar rest frame (using  $\alpha_{radio}$  from Table 2 and assuming  $\alpha_{opt} = -1$ , Stocke et al. 1992). We use the (APS-calibrated) APM O magnitude (White et al. 2000) as a direct estimate of B, and we do not correct the optical magnitude for the emission-line contribution. The cosmological parameters  $H_0 = 50 \,\mathrm{km \, s^{-1} Mpc^{-1}}$ ,  $\Omega = 1$ , and  $\Lambda = 0$  are adopted. In the last column, we give the type of BAL. Our spectra for FIRST J112220.5+312441 and J115023.6+281908, while suggestive that these objects are BAL QSOs, are not definitive; this uncertainty is indicated by question marks next to the type in Table 1. Figures 1 and 2 show the spectra of the BAL quasars, plotted in the rest frame to facilitate the recognition of the sometimes complex absorption features.

The BAL quasars in Table 1 divide nearly evenly into 15 Hi-BALs and 14 LoBALs. Both FIRST J105427.2+253600 and J132422.5+245222 are classified as LoBALs solely by the presence of Al III  $\lambda$ 1860, since their Mg II is redshifted into the near IR. Four of the LoBALs belong to the rare class of FeLoB-ALs (Becker et al. 1997), characterized by the metastable FeII absorption bands centered at ~ 2350 and ~ 2575 Å. These four FeLoBAL quasars vary markedly in the depth of their absorption features. Two of the other LoBAL quasars (FIRST J140806.2+305449 and J152350.4+391405) are unusual insofar as the spectra appear suppressed blueward of 2500 Å in the rest frame. Several of the BAL quasars, both high and low ionization, are almost devoid of obvious emission lines (e.g., FIRST J142703.6+270940, J142013.1+253404).

## 3. RADIO PROPERTIES OF THE FIRST BAL QUASARS

The FIRST Survey provides 20 cm maps with 5 arcsec angular resolution taken with the NRAO VLA<sup>5</sup> in the Bconfiguration. To investigate the radio spectral indices and radio morphologies of the radio-selected BAL quasars, we have reobserved nearly all of the objects with the VLA in either A or D configurations (sometimes both) at 20 and 3.6 cm wavelength. The observed flux densities of the quasars at 20 cm from the three different VLA configurations (A, B, and D) are given in Table 2, along with the A and D configuration 3.6 cm flux densities. These are supplemented by data from the WENSS (Westerbork Northern Sky Survey, Rengelink et al. 1997) survey at 92 cm, the Green Bank 6 cm survey (Becker, White, & Edwards 1991), and the NVSS 20 cm survey (Condon et al. 1998). Angular resolutions for all the observations are listed in Table 2. Spectral indices are given for 28 of the BAL quasars; the sources have a mix of flat spectra (9 sources,  $\alpha > -0.5$ ) and steep spectra (19 sources,  $\alpha \leq -0.5$ ), with 9 of the sources falling close to the dividing line ( $-0.6 \le \alpha \le -0.4$ ). Where possible, the spectral indices are based on simultaneous observations at two frequencies.

This heterogeneous set of radio observations spans a wide range of angular resolutions, so the measured flux densities may not be directly comparable; any spectral index derived from data with different angular resolutions is uncertain unless the radio source is effectively a point source at the highest resolution available. In that case, the flux densities from all the observations can be directly compared, assuming a nonvariable source. If all the flux density measurements at a given frequency for an object are the same independent of angular resolution, then the point source assumption is probably valid. If the flux density measured with low resolution is less than that at high-resolution, then the source is probably variable. If the low-resolution flux density is higher than the high-resolution value, the difference could arise from either resolution effects or variability.

The VLA observations provide some indication of the radio brightness distribution and morphology. Roughly 90% of the BAL quasars appear point-like at the FIRST resolution of  $\sim 5''$ . This is in sharp contrast to the parent population of quasars in the FBQS, which are evenly split between point-like and extended (based on a subset of several hundred quasars with a similar range of parameters to the BAL quasars: z > 0.5 and

TABLE 1 FIRST BROAD ABSORPTION LINE QUASARS

RA	Dec	E	0	O-E	A(E)	$S_p$	Si	BALnicity	V <sub>max</sub>	$M_B$	$\log L_R$	$\log R^*$	Z	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
07 24 18.492	+41 59 14.40	17.65	18.71	1.05	0.24	7.89	7.90	1300	18300	-26.6	32.7	1.60	1.552	LoBAL
07 28 31.661	+40 26 15.85	15.13	15.26	0.14	0.13	16.96	16.79	200	20600	-28.0	32.0	0.37	0.656	LoBAL
08 09 01.332	+27 53 41.67	17.17	17.58	0.40	0.10	1.17	1.67	7000	27400	-27.7	31.9	0.40	1.511	HiBAL
08 40 44.457	+36 33 28.41	16.20	17.53	1.34	0.10	1.63	1.00	0	4900	-27.2	31.8	0.45	1.230	FeLoBAL
09 10 44.902	+26 12 53.71	17.78	19.26	1.48	0.09	7.84	7.46	320	6100	-27.6	33.1	1.64	2.920	HiBAL
09 13 28.260	+39 44 44.17	17.16	17.99	0.83	0.05	2.06	2.09	10700	27000	-27.4	32.0	0.63	1.580	HiBAL
09 34 03.978	+31 53 31.47	17.43	17.83	0.39	0.05	4.68	4.41	1200	27000	-28.5	32.8	0.88	2.419	HiBAL
09 46 02.299	+27 44 07.04	16.89	17.65	0.76	0.06	3.54	3.63	260	9900	-27.9	32.4	0.74	1.748	HiBAL
09 57 07.367	+23 56 25.32	17.63	18.47	0.84	0.09	136.10	140.49	0	5200	-27.4	34.1	2.63	1.995	HiBAL
10 31 10.647	+39 53 22.81	17.73	18.66	0.92	0.03	2.45	2.03	20	5900	-25.8	31.9	1.11	1.082	LoBAL
10 44 59.591	+36 56 05.39	16.51	17.23	0.72	0.04	14.61	15.00	400	6600	-26.2	32.2	1.29	0.701	FeLoBAL
10 54 27.150	+25 36 00.33	16.93	18.38	1.45	0.07	2.99	3.02	1200 <sup>a</sup>	25000	-28.0	32.6	0.91	2.400	LoBAL
11 22 20.462	+31 24 41.19	17.08	18.19	1.11	0.04	12.64	12.87	0	4300	-26.9	32.8	1.52	1.448	LoBAL? <sup>b</sup>
11 50 23.570	+28 19 07.50	16.46	18.00	1.54	0.06	13.96	14.22	0	11700	-29.0	33.5	1.43	3.124	HiBAL? <sup>c</sup>
12 00 51.501	+35 08 31.41	15.21	16.45	1.24	0.05	2.03	1.46	4600	13500	-29.1	32.1	-0.02	1.700	HiBAL
12 14 42.303	+28 03 29.01	15.87	17.03	1.16	0.06	2.61	2.90	0	3500	-26.3	31.4	0.39	0.698	FeLoBAL
13 04 25.543	+42 10 09.66	16.33	17.08	0.75	0.04	1.52	0.99	2900	27000	-28.7	32.2	0.23	1.916	HiBAL
13 12 13.560	+23 19 58.51	16.95	17.84	0.89	0.03	43.27	44.12	1400	25000	-27.4	33.3	1.88	1.508	HiBAL
13 24 22.536	+24 52 22.25	17.40	18.87	1.47	0.04	4.89	4.41	1300 <sup>a</sup>	6900	-27.4	32.7	1.31	2.357	LoBAL
14 08 00.454	+34 51 25.11	17.03	18.44	1.41	0.04	2.91	2.87	260	9600	-26.3	31.9	0.99	1.215	LoBAL
14 08 06.207	+30 54 48.67	17.30	19.00	1.69	0.03	3.34	3.21	4800	22000	-24.8	31.7	1.28	0.842	LoBAL
14 13 34.404	+42 12 01.76	17.60	18.40	0.80	0.02	17.79	18.74	0	3800	-28.3	33.5	1.68	2.810	HiBAL
14 20 13.072	+25 34 03.71	16.78	18.24	1.47	0.05	1.27	1.17	4500	26000	-27.9	32.1	0.46	2.200	HiBAL
14 27 03.637	+27 09 40.29	17.68	19.05	1.37	0.05	2.58	2.98	30	5900	-25.6	31.9	1.23	1.170	FeLoBAL
15 23 14.434	+37 59 28.71	17.37	18.41	1.04	0.04	1.67	1.83	3700	17000	-26.5	31.8	0.76	1.344	HiBAL
15 23 50.435	+39 14 04.83	15.93	16.93	1.00	0.05	3.75	4.07	3700	19000	-26.3	31.6	0.66	0.657	LoBAL
16 03 54.159	+30 02 08.88	17.36	18.02	0.65	0.10	53.69	54.18	0	3200	-27.9	33.7	2.04	2.026	HiBAL
16 41 52.295	+30 58 51.79	17.57	18.70	1.14	0.07	2.14	2.66	10600	22000	-27.2	32.4	1.09	2.000	LoBAL
16 55 43.235	+39 45 19.91	17.74	18.11	0.37	0.05	10.15	10.16	4500	22000	-27.5	32.9	1.41	1.747	HiBAL

<sup>a</sup>The BALnicity was computed from C IV for these LoBAL quasars. Other LoBAL quasars have the BALnicity computed from Mg II, and all HiBAL quasars have BALnicities from C IV.

<sup>b</sup>Absorption line depth barely exceeds 10% limit for BALnicity criterion.

<sup>c</sup>Identification as BAL quasar is less secure; see text for discussion.



FIG. 1.— Spectra of low ionization broad absorption line quasars from the FIRST Bright Quasar Survey, sorted by decreasing redshift, plotted against rest wavelength. The dotted lines show expected positions of prominent emission lines: Ly $\alpha$  1216, N V 1240, Si IV 1400, C IV 1549, C III] 1909, and Mg II 2800. The positions of the atmospheric A and B band absorption at observed wavelengths of ~ 6880 Å and 7620 Å are marked.



FIG. 1.— Continued. Spectra of FBQS low-ionization BAL quasars. Note that the wavelength range differs from previous panel.



FIG. 2.— Spectra of FBQS high-ionization BAL quasars.



FIG. 2.— Continued. Spectra of FBQS high-ionization BAL quasars.

		VLA S	S(20 cm)	V	VLA S	S(3.6 cm)			
Name (1)	A (2)	B (FIRST) (3)	D (NVSS) (4)	D (5)		A (6)	D (7)	Spectral Index (8)	Notes (9)
0724+4159		7.9	12.1	9.9			10.6	+0.0	
0728+4026	18.0	17.0	17.6			2.7		-1.1	$S_{92} = 19$
0809+2753		1.7	<						
0840+3633	0.9	1.6	5.2	4.9		0.5	1.1	-0.2	
0910+2612		7.8	7.0	9.4			4.2	-0.5	
0913+3944	2.3	2.1	<	1.5		0.4	0.5	-0.6	
0934+3153	5.1	4.7	6.5			3.5	3.6	-0.2	
0946+2744		3.6	3.9	2.6			< 0.2	< -1.5	
0957+2356		140.	137.	139.			51.3	-0.6	$S_6 = 84$
1031+3953	1.7	2.5	3.0	1.6		1.2	1.2	-0.2	
1044+3656	15.6	15.0	15.8	14.1		5.2	5.9	-0.5	$S_{92} = 39$
1054+2536	3.0	3.0	2.9	2.6		0.9	1.1	-0.5	
1122+3124		12.9	10.9	10.			3.6	-0.6	$S_{92} = 23$
1150+2819		14.2	11.0	9.7		•••	1.3	-1.2	
1200+3508	1.8	2.0	2.9	1.6	<	< 0.2	0.4	-0.8	
1214+2803	<1.8	2.9	<	2.1	<	< 0.4	0.5	-0.8	
1304+4210		1.5	<	0.9		•••	2.8	+0.7	
1312+2319	46.5	44.1	46.9	45.5		12.6	12.3	-0.8	
1324+2452		4.9	4.4	4.3			1.2	-0.7	
1408+3451	2.7	2.9	3.1	1.7		0.4	0.6	-0.6	
1408+3054	3.0	3.3	4.2	1.3		0.4	0.4	-0.7	
1413+4212		18.7	17.3	17.0			11.3	-0.2	$S_{92} = 22$
1420+2534	0.5	1.3	<		<	< 0.2	0.2	-1.1	
1427+2709	<3.	3.0	<	1.9		0.3	0.6	-0.7	
1523+3759	1.3	1.8	<	0.6	<	< 0.2	0.2	-0.6	
1523+3914	4.1	4.1	4.3	2.8		1.5	1.5	-0.4	$S_{92} = 18$
1603+3002	54.2	54.2	54.6	50.7		18.1	18.6	-0.6	$S_{92} = 43$
1641+3058		2.7	3.4	1.1			2.5	+0.5	
1655+3945		10.2	10.5	4.8			3.4	-0.2	

TABLE 2 RADIO PROPERTIES OF FIRST BAL QUASARS

NOTE.—All flux densities are in mJy. Descriptions of table columns:

Col 2: 20 cm flux density measured by VLA in A-configuration (resolution 1.8").

Col 3: 20 cm flux density measured by VLA in B-configuration (resolution 5.4") from FIRST catalog (White et al. 1997).

Col 4: 20 cm flux density measured by VLA in D-configuration (resolution 45'') from NVSS catalog (Condon et al. 1998). "<" indicates source is not detected.

Col 5: 20 cm flux density measured by VLA in D-configuration in November 1997. Col 6: 3.6 cm flux density measured by VLA in A-configuration (resolution 0.3"). Col 7: 3.6 cm flux density measured by VLA in D-configuration (resolution 9").

Col 8: Spectral index between 3.6 and 20 cm ( $F_{\nu} \propto \nu^{\alpha}$ ).

Col 9: Notes: S<sub>92</sub> is 92 cm flux density from WENSS survey (Rengelink et al. 1997). S<sub>6</sub> is 6 cm flux density from Green Bank survey (Becker, White, & Edwards 1991).

a 20 cm flux density less than 50 mJy). Of 13 BAL quasars observed in the A configuration of the VLA, 11 are still unresolved at the level of  $\sim 1.5''$ .

## 3.1. Comments on Individual Radio Sources

FIRST J072418.4+415914 – Appears to be variable at 20 cm. FIRST J080901.3+275342 – Slightly resolved in FIRST.

FIRST J084044.5+363328 – A second radio source positioned  $\sim 27''$  away from 0840+3633 has a FIRST flux density of 2.5 mJy and appears extended. This source is too close for the NVSS to resolve from 0840+3633 and probably explains the higher NVSS flux density. The lower B-configuration 20 cm flux density was used to determine the spectral index in Table 2.

FIRST J093404.0+315331 – Appears to be variable at 20 cm. FIRST J115023.6+281907 – Appears to be variable at 20 cm.

FIRST J140806.2+305449 – Possibly a triple source, although a chance alignment of sources is more likely since both of the other sources break up into double sources in higher resolution images.

FIRST J152350.4+391405 – Appears to be variable at 20 cm. FIRST J160354.2+300209 – Possibly a GigaHertz-peaked radio spectrum.

FIRST J164152.3+305852 – Partially resolved by FIRST, consistent with the higher NVSS flux density but subsequent D configuration data suggests variability.

FIRST J165543.2+394520 - Appears to be variable at 20 cm.

# 4. THE FBQS BAL QUASAR FRACTION AND ITS DEPENDENCE ON RADIO-LOUDNESS

The frequency of BALs within the FBQS can be derived by comparing the number of BAL quasars found to the number of quasars with rest-frame wavelength coverage (determined by the redshift and observed spectral range) that would have allowed absorption to be seen had it been present. For the redshift range relevant to LoBAL quasars,  $0.5 \le z \le 1.7$ , there are  $\sim$  350 quasars in the FBQS in which LoBALs could have been confirmed had they been present. In this same redshift range, we find 11 are LoBAL or FeLoBAL quasars  $(3\pm 1\%)$ , where the uncertainty is the standard deviation of a binomial distribution). There are 100 quasars in the redshift range relevant to HiBALs,  $z \gtrsim 1.4$ , in which the wavelength coverage would have permitted C IV absorption to be seen had it been present. Of these 100 quasars, eighteen show high-ionization broad absorption. This includes the 3 high-redshift LoBALs, so designated because they also show Al III absorption; the other 15 objects show only high-ionization absorption. Our BAL rate is therefore  $18 \pm 3.8\%$ . If we exclude from this those objects with zero BALnicity, our rate is reduced to 14% which is roughly a 50% increase over the rate seen in optically selected samples ( $\sim 9\%$ in the LBQS; Foltz et al. 1990). It is worth noting of the unambiguous BAL quasars, i.e., those with nonzero BALnicity, one third are either LoBALs or FeLoBALs while the comparable number for the LBQS is 10%. This is very suggestive that the frequency of LoBAL quasars is highly dependent on radio luminosity as was already postulated in Becker et al. 1997.

Until the discovery of FIRST J155633.8+351758 by Becker et al. (1997) and several additional objects by Brotherton et al. (1998), it was believed that the BAL phenomenon did not occur in radio-loud quasars, i.e., those with  $R^* > 10$ . The 29 FBQS BALs demonstrate otherwise. In Figure 3 we plot log  $R^*$  vs *z* (where  $R^*$  is taken from FBQS2). Consistent with the Becker et al. (1997) and Brotherton et al. (1998) results, the BAL quasars are not confined to the radio-quiet regime. Our data do suggest that the incidence of BALs decreases for radio-loud quasars with  $R^* > 100$ . For the LoBALs in particular,  $R^*$  never exceeds 35. In comparison, 38% of the quasars in the FBQS over the same redshift range (z > 0.5) have  $R^* > 35$ . The incidence of LoBALs is 5% for quasars with  $R^* < 35$ . While based on a rather small sample, these statistics suggest that the frequency of LoBAL quasars is dependent on radio loudness. The likelihood of a quasar being a HiBAL, however, shows no obvious dependence on radio loudness. HiBALs are slightly underrepresented in quasars with  $R^* > 100$ , but this is not statistically significant. A better delineation of the frequency of BALs as a function of  $R^*$  will have to wait until more sky is surveyed by the FBQS, but the existence of a population of radio-loud BALs, both low and high ionization, is now firmly established.

Using  $R^*$  as a measure of radio loudness may be a little misleading for BAL quasars in so far as the BAL quasars are affected by reddening which would reduce the optical magnitude and hence inflate the value of  $R^*$ . As we point out in section 4.2 (see Figure 6), if we use the alternative definition of radioloud, ie,  $L_R > 10^{32}$  erg s<sup>-1</sup> Hz<sup>-1</sup> (Miller, Rawlings, and Saunders 1993), which is independent of the observed optical magnitude, we still find that a significant number of the FBQS BAL quasars are radio-loud.

The traditional measure of the significance of the broad absorption lines in a quasar spectrum is the BALnicity index (BI; Weymann et al. 1991). In Figures 4(a) and 4(b) we plot the dependence of BI on the observed radio luminosity, for HiBAL and LoBAL quasars respectively. For HiBAL quasars, there is an anticorrelation between BI and  $L_R$  (The Spearman rank correlation coefficient is -0.85 which would arise by chance with a probability of only  $6 \times 10^{-5}$ ). No such anticorrelation is apparent for the LoBAL quasars in Figure 4(b). In Figures 4(c) and 4(d), we plot the dependence of the maximum outflow velocity  $V_{max}$  against  $L_R$  for HiBAL and LoBAL quasars. There is a suggestion of an anticorrelation for HiBAL quasars (the Spearman rank correlation coefficient is -0.70; probability of only 0.0037), though it is considerably less convincing than that with BI.

The lack of correlation between BI or  $V_{max}$  and  $L_R$  for the LoBAL quasars may simply reflect the lack of high radio luminosity LoBAL quasars. If HiBAL quasars with luminosities greater than  $10^{33}$  ergs/s/Hz are omitted from the plots, at most a weak correlation is detectable in the less luminous objects.

# 4.1. Why the FBQS BAL Quasar Fraction is High

There are several possible reasons for the higher frequency of BAL quasars in the FBQS. One possible explanation is the looser definition of BAL used in this paper, a definition divorced from the BALnicity index. Since the fraction of BALs seen in the LBQS has only appeared as an AAS abstract (Foltz et al. 1990), it is difficult to evaluate the magnitude of this effect. Another possible explanation is that the frequency of the BAL phenomenon depends on the radio emission, albeit a reversal of the old thesis that only radio-quiet quasars can have BALs (Stocke et al. 1992). The FBQS quasars span the radioquiet/radio-loud boundary, filling in what used to be considered a bimodal distribution which was perhaps the result of selection effects in other surveys (White et al. 2000). Based on a limited sample, Francis, Hooper, & Impey (1993) found that BAL quasars in the LBQS appeared primarily in this radiointermediate regime; accepting their result as correct, the FBQS naturally includes BALs passed over, for whatever reasons, by



FIG. 3.— Radio-optical ratio  $R^*$  (rest-frame ratio of the 5 GHz radio flux density to the 2500 Å optical flux; Stocke et al. 1992) versus redshift for FBQS quasars. BAL quasars are indicated with the heavy symbols, with low-ionization (LoBALs) and high-ionization (HiBALs) object distinguished. The dotted lines show redshifts where Mg II  $\lambda$ 2800 and C IV  $\lambda$ 1549 fall at 4000 Å in the observed spectrum, so that their absorption is observable in most of our spectra (which vary in their wavelength coverage.) It is difficult or impossible to identify any BAL systems in quasars with redshifts below ~ 0.4, and HiBALs typically cannot be detected when  $z \leq 1.4$ . Many FIRST-selected BAL quasars are found above the traditional radio-loudness threshold at log  $R^* = 1$ . There also is an evident excess of LoBAL quasars at radio-intermediate log  $R^* \sim 1$ .



FIG. 4.— (a) BALnicity index (BI) versus radio luminosity  $L_R$  for HiBAL quasars. (b) BI versus  $L_R$  for LoBAL quasars. (c) Maximum outflow velocity  $V_{max}$  versus  $L_R$  for HiBAL quasars. (d)  $V_{max}$  versus  $L_R$  for LoBAL quasars. The FeLoBAL quasars are indicated as lower limits in (b) and (d) because their complex absorption spectra make it very difficult to determine these quantities.

optical surveys. It is easy to imagine that the objects in Figure 1 that do not have strong emission lines or that have significantly redder continua than typical quasars would be overlooked in surveys with optical selection criteria.

A related reason for the high incidence of BAL quasars is that our sample was selected using the red E magnitude of the optical counterparts while most quasar surveys (including the LBQS) are based on bluer B magnitudes. A plot of the color of the FBQS quasars as a function of redshift is shown in Figure 5. The reddest objects in the figure are low-redshift objects, in which there is undoubtedly a large contribution of starlight. The BALs in general and the LoBALs in particular are predominant among the reddest quasars with  $z \ge 0.5$ , accounting for over 50% of the quasars redder than O-E of 1.3. The BAL quasars are redder than the average FBQS quasar by  $\sim 0.5$  magnitude. Hence samples based on *B* magnitudes have an effective magnitude cutoff 0.5 magnitudes higher for BAL quasars than for the non-BAL quasars which, owing to the steep quasar number counts would substantially reduce the observed incidence of BAL quasars. This effect is tantamount to a differential k-correction between BAL and non-BAL quasars and has been discussed in earlier studies (Boroson & Meyers 1992; Sprayberry & Foltz 1992). It is possible that the red FBQS BAL quasars represent the tip of the iceberg and that there remains a large population of BAL quasars that are yet redder and do not make it into the FBQS despite its weak color selection (O - E < 2) (Becker at al. 1997).

The red colors of the BAL quasars are not simply the effect of broad absorption lines suppressing the flux in the O band (typically  $\sim 0.2$  mag), although this contributes part of the difference. The unabsorbed continuum itself appears red, especially in the LoBAL quasars, which is suggestive of dust (Brotherton et al. 1999; Yamamoto & Vansevicius 1999). The color difference extends to the infrared (Hall et al. 1997). Egami et al. (1996) presented the near-IR spectrum of Q 0059-2735, which displays a very large Balmer decrement (H $\alpha$ /H $\beta$  = 7.6), almost the same as that seen in FIRST J155633.8+351758 (Dey 1998, priv. comm.). For case B recombination,  $H\alpha/H\beta = 2.85$ ; and "normal" blue quasars usually show  $H\alpha/H\beta < 4$ . (While case B is not likely to apply to Balmer lines and the Balmer decrement, the empirical result is that the smallest Balmer decrements are consistent with case B and that the Balmer decrement has been shown to correlate with the continuum slope in a manner consistent with an intrinsic case B ratio and dust reddening (Baker 1997)). The observed Balmer decrements of these extreme objects then imply  $A_V \sim 3$ , which is consistent with the Brotherton et al. (1997) estimate for J155633.8+351758 based on spectropolarimetry. Because of the bright magnitude limit of the FBQS (E = 17.8), and the redshifts required to see BALs in the optical, modest reddening will remove BAL quasars from the sample (especially the LoBAL quasars which appear redder than other classes, e.g., Sprayberry and Foltz (1992)). If it suffered no intrinsic reddening, FIRST J155633.8+351758 would likely have been selected for inclusion in the FBOS.

# 4.2. Why the FBQS BAL Quasar Fraction is Low

The FBQS certainly misses BAL quasars. The magnitude limit discriminates against BAL quasars when the heavily absorbed spectral regions fall within the *E* bandpass ( $\sim 6250 \pm 180$  Å). While less affected than the *O* bandpass, *E* magnitudes are still affected by dust reddening. The BAL quasar fraction we find,  $\sim 18\%$ , is then a lower limit to the actual BAL quasar fraction for radio-intermediate quasars. The LoBAL quasars,

which can be significantly dust reddened, are more susceptible to color selection effects than HiBAL quasars.

Goodrich (1997) and Krolik & Voit (1998) have argued that the true fraction of BAL quasars is much higher ( $\gtrsim$ 30%). While we would agree that the true fraction is possibly this high, the FBQS sample undermines their position that BAL quasars are radio-moderate (Francis, Hooper, & Impey 1993) because of optical attenuation rather than intrinsically strong radio emission. Figure 6 plots the radio luminosity of the FBQS quasars as a function of redshift, clearly showing that at least some BAL quasars are intrinsically strong radio sources.

Goodrich (1997) (see also Goodrich & Miller 1995) had a second reason for arguing that the optical continuum was suppressed and the true fraction of BAL quasars was underestimated: high polarization. The idea is that scattered and polarized light is present in all quasars, but only becomes noticeable when the direct light is somehow attenuated. Hutsemekers, Lamy, & Remy (1998) found that, on average, LoBAL quasars are more polarized than HiBAL quasars, which are in turn (slightly) more polarized than non-BAL quasars. This is consistent with the idea that LoBAL quasars possess more absorbing material and dust along the line of sight.

Estimating the true fraction of BAL quasars remains a difficult problem given the many unknowns that must be assumed or derived with incomplete information. What we can say with some certainty is that the true fraction of BAL quasars among radio-selected quasars is greater than 18%.

# 4.3. Radio Properties and Unified Schemes

The similarity of the emission lines in BAL quasars and normal quasars (Weymann et al. 1991) suggests that BAL quasars are normal quasars seen at a viewing angle that intersects an outflow common to all quasars. The spectropolarimetry results have often been interpreted in terms of a preferred orientation: Goodrich & Miller (1995), Hines & Wills (1995), and Cohen et al. (1995) all suggest that BAL quasars are normal quasars seen along a line of sight skimming the edge of a disk or torus, with BAL clouds accelerated from its surface by a wind, and polarized continuum light scattered above along a less obscured path. LoBAL quasars are those seen at the largest inclinations, thus presenting the largest column densities.

The jets of quasars provide a way to measure orientation. The relativistic beaming model for radio sources (e.g., Orr & Browne 1982) unifies core-dominated (flat spectrum) and lobedominated (steep spectrum) radio sources by means of orientation: core-dominant objects are those viewed close to the jet axis, while lobe-dominant objects are those viewed at larger angles. Indeed, relativistic jets appear to be present in at least some radio-quiet quasars (e.g., Blundell & Beasley 1998), and a flat radio spectral index in a radio-quiet quasar may indicate a beamed source (e.g., Falcke, Sherwood, & Patnaik 1996).

We find that about two thirds of the FBQS BAL quasars have steep radio spectra ( $\alpha < -0.5$ ), as expected for edge-on systems, but that the remaining third have flat spectra (including clearly radio-loud sources such as FIRST J141334.4+421202, as well as J155633.8+351758 which is not in this sample). This is inconsistent with the simple unified scheme, which predicts only steep spectrum sources for an edge-on geometry.

Similarly, Barvainis & Lonsdale (1997) found that the radio spectra of radio-quiet BAL quasars have a range of slopes, again including both flat and steep spectra, suggesting that BAL quasars are seen for a range of orientations with respect to the system (jet) axis.



FIG. 5.— Extinction-corrected O-E (roughly B-R) color of FBQS quasars as a function of redshift. BAL quasars are marked as in Fig. 3. The error bars show the mean and standard deviation of the mean for the FBQS sample as a whole in redshift bins. The boxes show the same for the BAL quasars, which are substantially redder. BAL quasars constitute the majority of FBQS quasars redder than O-E = 1.3 with  $z \ge 0.5$ . BALs cannot be observed in lower *z* quasars, but they are also reddened by the starlight visible in lower-luminosity AGN.



FIG. 6.— Radio luminosity at a rest frequency of 5 GHz versus redshift, using spectral index  $\alpha = -0.5$  for the non-BAL quasars and the observed spectral indices from Table 2 for the BAL quasars.

The radio morphology of the FIRST BAL quasars is also unexpected for the unified edge-on scheme. VLA A array maps of our BALQSOs show that 80% of the sources are unresolved at the 0.2'' scale. This could be because they are small, "frustrated" or young sources, similar to compact steep spectrum sources, or because they are very core-dominated with the jet beamed toward us. The compactness of the radio emission. even in the radio-loud sources, favors their existence in gasrich interacting systems which can confine the radio emission to small scales.

There is an alternative to "unification by orientation," which may be described as "unification by time," with BAL quasars characterized as young or recently refueled quasars. Boroson & Meyers (1992) found that LoBAL quasars constitute 10% of IR-selected quasars, greater than the 1% found in optically selected samples, and that LoBALs show very weak narrow [O III]  $\lambda$ 5007 emission. Turnshek et al. (1997) found that 1/3 of weak [O III]  $\lambda$ 5007 quasars show BALs. Because [O III]  $\lambda$ 5007 is emitted from the extended narrow-line region (NLR), its weakness suggests that obscuring material with a large covering factor is present. We are unaware of any LoBAL quasars with significant [O III]  $\lambda$ 5007 emission. Voit et al. (1993) argue that low-ionization BALs are a manifestation of a "quasar's efforts to expel a thick shroud of gas and dust," consistent with the scenario of Sanders et al. (1988) in which quasars emerge from dusty, gas-rich merger-produced ultraluminous infrared galaxies. The warm *IRAS*-selected BAL quasars (0.25 < $F_{\nu}(25\mu m)/F_{\nu}(60\mu m) < 3)$  Markarian 231 (Smith et al. 1995), IRAS 07598+6508 (Boyce et al. 1996), and PG 1700+518 (Hines et al. 1999; Stockton et al. 1998) all show evidence for recent mergers or interactions, including young starbursts.

While the geometry of BAL quasars and their relationship to non-BAL quasars remains an open question, our results do not appear to favor the popular notion that all BAL quasars are normal quasars seen edge-on. The FBQS results are more consistent with the unification by time picture.

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### 5. SUMMARY

We have investigated the properties of 29 radio-selected BAL quasars found in the FBQS. The sample comprises 15 highionization BAL quasars, and 14 low-ionization BAL quasars, 4 of which are rare FeLoBALs. At least 13 are formally radioloud, unequivocally establishing the existence of a substantial population of radio-loud quasars exhibiting BAL spectral features.

The frequency of BAL quasars appears to be higher than that found in optically selected samples. Even so, because of selection effects and preferential reddening of LoBAL quasars, the FBQS almost certainly misses additional BAL guasars and the true frequency must be higher. The situation is complicated by indications that the frequency of BAL quasars peaks among the radio-moderate population and decreases for the extremes of radio-loudness. The BAL quasars show compact radio morphologies, and have a range in radio spectral indices. The radio properties do not support the popular scenario in which all BAL quasars are normal quasars seen edge-on. An alternative picture in which BALs are an early stage in the development of new or refueled quasars is preferred.

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