Discovery of Radio-loud Broad Absorption Line Quasars Using Ultraviolet Excess and Deep Radio Selection[1]

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ABSTRACT

We report the discovery of five broad-absorption-line (BAL) QSOs in a complete sample of 111 ultraviolet excess (UVX) QSO candidates also detected in the NRAO VLA Sky Survey. All five BAL QSOs, which include two high-ionization BAL QSOs and three low-ionization BAL QSOs, are formally radio-loud. Of QSOs with $z > 0.4$, 3±2% show low-ionization BALs, and of QSOs with $z > 1.5$, all radio-loud, 9±5% show BALs; these frequencies are consistent with those of optical surveys. While the first reported radio-loud BAL QSO, FIRST J155633.8+351758, is likely to be heavily dust reddened and thus less radio-loud than indicated by its observed radio-to-optical luminosity, these QSOs are UVX selected and probably free of significant dust along the line of sight. We point out unusual features in two of the BAL QSOs and discuss the significance finding these heretofore rare objects.

Subject headings: quasars: absorption lines, quasars: emission lines, quasars: general

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[1]Based on observations at the W. M. Keck Observatory.

1. Introduction

The nature of the central engines of AGNs and the mechanisms by which they produce their enormous luminosities and radio jets are not yet well understood. The power of these jets differs by orders of magnitude in quasars that appear similar at UV and optical wavelengths. The distribution of radio-to-optical power ranges over nearly six orders of magnitude and appears bimodal (e.g., Kellermann et al. 1989; Stocke et al. 1992; Hooper et al. 1995). Why are only a fraction of quasars "radio-loud?" Why is this fraction about a tenth?

One previously strong result that seemed to be a clue to understanding this radio-loud/radio-quiet dichotomy was that broad-absorption-line (BAL) QSOs appeared to be exclusively radio-quiet (e.g., Stocke et al. 1992). This suggested that outflows in radio-quiet QSOs are not well collimated and either formed or accelerated BAL material, while outflows in radio-loud QSOs are confined to well collimated relativistic jets.

Becker et al. (1997a) reported the discovery of an exception to the above result in the radio-loud BAL QSO FIRST J155633.8+351758, hereafter FIRST 1556+3517. While the radio flux is high ($S_{1400} = 30.6$ mJy) for its redshift (z=1.48), making its radio luminosity consistent with those of radio-loud QSOs, the BAL QSO appears optically reddened and relativistically beamed in the radio, making it unclear just how radio-loud the object truly is. Near-IR photometry shows that FIRST 1556+3517, with $B - K = 6.57$, is among the reddest QSOs known (Hall et al. 1997). ISO observations are also consistent with significant dust causing a line-of-sight reddening of $A_V = 1.6$, which indicates $4M_{\odot}$ of dust and 800 $M_{\odot}$ of associated gas (Clavel 1998); correcting the optical magnitude for the reddening would bring FIRST 1556+3517 within approximately 1 sigma of the radio-loud/radio-quiet division. Furthermore, Brotherton et al. (1997) showed that much of the blue light is scattered, making the direct light from FIRST 1556+3517 even more red than apparent.

While just how radio-loud FIRST 1556+3517 is remains an open issue, Becker et al. (1997b) report the discovery of other radio-loud BAL QSOs from the FIRST Bright Quasar Survey (FBQS; Gregg et al. 1995), which selects stellar objects to a limiting magnitude of $E \sim 17.5$ with $O - E < 2.0$ that appear in the FIRST, a deep radio survey that reaches 1 mJy at 20 cm (Becker et al. 1995). While none of these new radio-loud BAL QSOs are as red as FIRST 1556+3517, the FBQS has a weak color selection. Therefore the prospect of reddening in FBQS radio-loud BAL QSOs remains an issue, especially because none are overly powerful radio sources.

As a result of the discovery of these new objects, Weymann (1997) has refined the statement of the anticorrelation between radio-loudness and the exhibition of BALs: "The observed radial terminal velocity of thermal gas being ejected from luminous QSOs is strongly anticorrelated with the radio power of the QSO." BAL QSOs that are formally radio-loud are interesting transition objects, which may display related properties that will shed light on the radio-loud/radio-quiet dichotomy.

In this Letter, we report the discovery of five radio-loud BAL QSOs, selected as stellar objects with an ultraviolet excess (UVX), and detected by the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), within a complete sample of 111 QSO candidates. Because of the UVX selection, these QSOs are unlikely to be reddened significantly. Section 2 describes the sample selection and observations. Section 3 tabulates the new BAL QSOs and their properties and gives their statistics with respect to the rest of the sample. Section 4 discusses the potential importance of these BAL QSOs and how our results compare with other surveys. As recommended by Weymann (1997), we adopt log R* as the formal measure of radio-loudness with log

R* = 1.0 dividing radio-loud and radio-quiet QSOs, where R* is the K-corrected ratio of radio-to-optical power (Sramek & Weedman 1980; Stocke et al. 1992).

2. The Sample and Observations

The UVX-NVSS sample includes quasar candidates from the UVX (AAT-2dF) quasar survey (Smith et al. 1996) that are within 10″ of a radio source from the NVSS. To make the matches, we extracted our own radio catalog from the NVSS images using the HAPPY algorithm (White et al. 1997).

The UVX catalog includes just over 46000 stellar objects that meet the following selection criteria. The primary color selection is $U - B_j \leq -0.12$, which accounts for 90% of the QSO candidates. Additional color selection using R extends the redshift range of QSOs selected to $2.2 < z < 2.9$, about 10% of the catalog. The magnitude limits are $18.25 < B_j < 20.85$. The area surveyed covers approximately 740 square degrees in two strips: (1) between declination $+2.5°$ and $-2.5°$ and right ascension 9.8 hours to 14.8 hours and (2) between declination $-27.5°$ and $-32.5°$ and right ascension 21.7 hours to 3.3 hours. Preliminary 2dF observations demonstrate that the UVX catalog is approximately 50% contaminated by non-AGN sources, predominantly stars and narrow-line galaxies. The additional restriction that candidates also have a 20 cm radio flux density $S_{20cm} \gtrsim 2.5$ mJy (5 σ limit) reduces the contamination to $\sim 5\%$ based on results below. The $z < 2.2$ QSO sample is expected to be $> 90\%$ complete with respect to previous QSO surveys, with a lower level of completeness for $2.2 < z < 2.9$; additional details of the multicolor selection and completeness will be given by Smith et al. (1998).

We obtained spectra of all 111 quasar candidates from the equatorial UVX-NVSS catalog with $18.25 \leq B_j \leq 20.00$ and right ascensions from 10 hours to 13 hours. Observations were conducted with the Keck II telescope during 1998 February 9 and 1998 March 7 (UT), using the Low Resolution Imaging Spectrometer (Oke et al. 1995). The 300 line mm^{-1} grating blazed at 5000 Å with a 1″ slit gave an effective resolution ≤ 10 Å (FWHM of comparison lamp lines); the dispersion was 2.5 Å pixel^{-1} covering approximately 4000 Å to 9000 Å. All exposure times were four minutes. We employed standard data reduction techniques within the NOAO IRAF package.

3. Results

Of the 111 candidates, 103 are quasars (93%), five are BL Lacertae objects, one is a Seyfert 2 galaxy, and two are stars. Given our observed wavelength range, low-ionization BALs are visible when present in quasars with $z > 0.4$ (Mg II λ2800 enters the window; 101 objects), and high-ionization BALs are visible when present in quasars with $z \gtrsim 1.5$ (C IV λ1549 enters the window; 33 objects). Given the selection criteria, all quasars in our sample with $z > 1.5$ will be formally radio-loud (log R* > 1); in the case of these specific objects, due to the combination of the properties of the quasar population, the selection criteria, and chance, all 103 quasars are formally radio-loud.

We find three low-ionization BAL QSOs (3±2% of the quasars with $z > 0.4$) and two high-ionization BAL QSOs (6±4% of the quasars with $z > 1.5$; one of the low-ionization BAL QSOs also has $z > 1.5$ making a total of 9±5% BAL QSOs in the high-z category). All are formally radio-loud, three solidly with log R* $\gtrsim 2$. Figure 1 shows their spectra, and Table 1 lists their properties, including the means and standard deviations for the sample. As seen in the radio-loud BAL QSOs found in the FBQS, none are powerful radio sources. Table 2 summarizes the BAL properties. All BAL identifications are unambiguous, as the velocity widths ($V_{max} - V_{min}$) are > 2000 km s^{-1} and, except for 1252+0053, we observe troughs of multiple species. All the QSOs have a positive "balnicity," a conservative definition of a BAL QSO (Weymann et al. 1991), although a number of lower velocity dispersion and associated systems are now recognized to be intrinsic in a handful of QSOs.

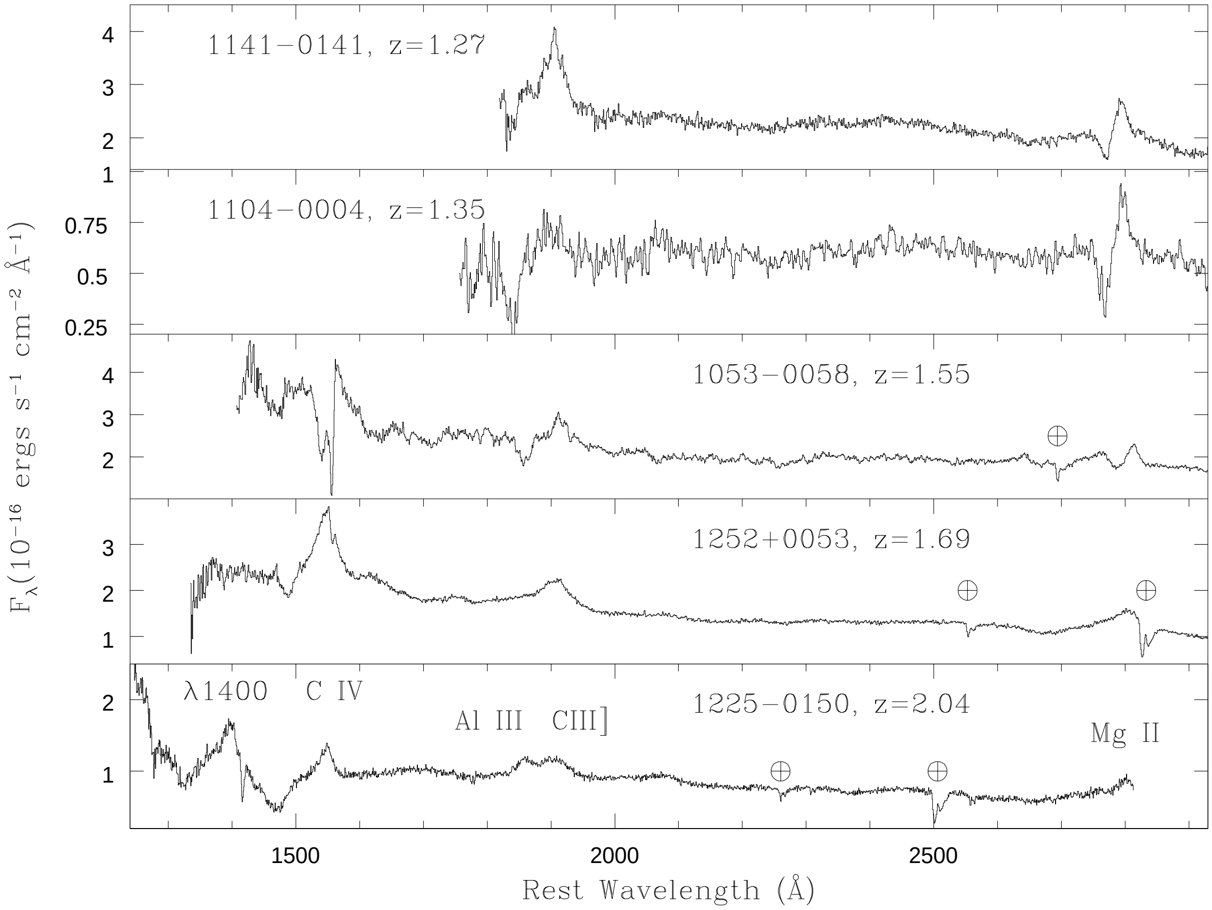

Fig. 1.— Rest-frame spectra of the UVX radio-loud BAL QSOs. Telluric A and B band absorption has been marked (⊕), and features of interest are labeled in the bottom panel. The spectrum of 1104−0004 has been smoothed by 3 pixels. Note that the bottoms of the flux scales do not start at zero.

4. Discussion

4.1. Individual Features

There are interesting features in two BAL QSOs. First, the absorption profiles in 1053−0058 are unusual, appearing to extend to the red of the emission peak as well as to the customary blue: based on the redshift of the peak of C III] λ1909, the Mg II λ2800 emission should peak near the center of the absorption,

Table 1. Radio-loud UVX BAL QSO Properties[a]

Name	R.A. (J2000)	Decl. (J2000)	z	B_j[b]	$U - B_j$[b]	$B_j - R$[b]	M_B	S_{1400}[c] (mJy)	log L_{1400} (ergs s^{-1} Hz^{-1})	log R*[d]
UN J1053−0058	10 53 52.83	−00 58 53.63	1.55	18.72	−0.20	0.87	−26.8	23.4±1.2	33.5	1.98
UN J1104−0004	11 04 40.81	−00 04 42.55	1.35	19.55	−0.32	0.76	−25.6	33.1±1.4	33.5	2.49
UN J1141−0141	11 41 06.54	−01 41 08.48	1.27	19.84	−0.83	0.39	−25.1	4.3±0.5	32.6	1.73
UN J1225−0150	12 25 23.18	−01 50 35.02	2.04	19.37	−0.96	1.16	−26.8	3.6±0.5	32.9	1.38
UN J1252+0053	12 52 43.78	+00 53 19.69	1.69	19.22	−0.76	0.49	−26.5	16.3±1.1	33.4	2.01
Sample[e] Mean	11.5 hr	0.0°	1.4	19.3	−0.53	0.45	−25.8	116	33.5	2.41
Std. Dev.	···	···	0.6	0.4	0.42	0.36	1.1	334	0.7	0.64
Minimum	10 hr	−2.5°	0.4	18.5	−1.66	−0.70	−22.2	3	31.8	1.25
Maximum	13 hr	+2.5°	2.9	20.0	0.99	1.16	−28.1	3092	35.7	4.13

[a]Assuming $H_0 = 50, q_0 = 0, \alpha_{rad} = -0.1, \alpha_{opt} = 0.3, (S_\nu \propto \nu^\alpha)$.

[b]UVX Survey (Smith et al. 1996). We have used $B = B_j - 0.1$ for calculating M_B and log R*.

[c]NVSS (Condon et al. 1998).

[d]For ease of comparison, as defined by Sramek & Weedman (1980) and extensively used by Stocke et al. (1992) with their choice of $\alpha_{rad} = -0.3$ and $\alpha_{opt} = -1.0$ for K-corrections.

[e]Properties of the complete sample of 103 quasars. Note that several properties, like the radio flux, are not normally distributed.

Table 2. BAL Properties[a]

Name	Line	EW[a] (Å)	Balnicity[b] (km s^{-1})	V_{min} (km s^{-1})	V_{max} (km s^{-1})
UN J1053−0058	C IV	14	255	2100	−5300
	Al III	5	50	1400	−3600
	Mg II	5	40	1100	−4600
UN J1104−0004	Al III	13	1100	−800	−6000
	Mg II	9	400	−1100	−5000
UN J1141−0141	Al III	4	400	−1500	−5200
	Mg II	1	170	−1100	−5000
UN J1225−0150	C IV	23	3900	−8400	−24300
	Si IV	12	2300	−8000	−22000
UN J1252+0053	C IV	5	130	−8400	−15400

[a]Rest-frame lower limit based on a linear interpolation.

[b]Defined by Weymann et al. (1991) who tabulate many balnicities for C IV.

and the C IV λ1549 emission should peak near the local maximum in its corresponding absorption trough. This suggests an unusual flow pattern or significantly blueshifted emission lines (e.g., Brotherton et al. 1994).

Second, in 1225−0150 the emission-line spectrum is unusual and there is a "mini-BAL" candidate. The intensity ratio of Al III λ1857 to C III] λ1909 is 0.88 (based on a two-Gaussian fit), significantly larger than nearly all other known QSOs, including other BAL QSOs, which have enhanced Al III/C III] compared to radio-quiet QSOs (Weymann et al. 1991). (An exception might be the handful of QSOs like H0335−336 (Hartig & Baldwin 1986), which show strong Al III λ1857 and a strong Fe III in place of C III] λ1909.) C IV λ1549 emission appears weak relative to emission from C III] λ1909 and the λ1400 feature (a blend of Si IV λ1397 and O IV] λ1402; see Wills et al. 1993); the C IV λ1549 emission line does not appear to be affected by the BAL trough, which appears detached by more than 8000 km s^{-1}. What these unusual line ratios mean is not clear, although strong Al III λ1857 is an important coolant for very dense gas (e.g., Ferland et al. 1996). Because C IV λ1549 is likely to have a very high optical depth, the line may become an ineffective emitter at high density (e.g., Zheng & Puetter 1990). Additionally, there is a smooth, intermediate width ($\sim$ 900 km s^{-1}) absorption system at −27,000 km s^{-1} seen in both C IV λ1549 and Si IV λ1397 (the latter line is not commonly seen in interstellar systems); we suggest that this may be an intrinsic "mini-BAL" system (e.g., Hamann et al. 1997), but higher resolution spectroscopy, perhaps at multiple epochs, would be needed to confirm our suggestion.

4.2. Sample Features

Foltz et al. (1990) find that 9% of the optically selected Large Bright Quasar Survey (LBQS; Foltz et al. 1987, 1989; Hewett et al. 1991; Chaffee et al. 1991; Morris et al. 1991; Francis et al. 1992) QSOs with $z > 1.5$ are BAL QSOs, the same fraction we find for our $z > 1.5$ radio-loud UVX sample. One of the three BAL QSOs in our high-redshift subsample displays low-ionization BALs. While this result is not statistically unlikely given the expected 0.1 fraction of low-ionization BALs in optically selected samples, it is suggestive of an excess because this is a strongly color-selected sample. Previous work has shown that low-ionization BAL QSOs tend to be more dust reddened than either high-ionization BAL QSOs or the bulk of radio-quiet QSOs (Sprayberry & Foltz 1992).

The question remains why radio-loud BAL QSOs were not identified sooner. Two methods have been employed: searching the spectra of radio-loud QSOs for BALs, and measuring the radio-loudness of optically selected BAL QSOs (e.g., Stocke et al. 1992). The first method failed apparently because of the shallowness of radio surveys given the persistent but unexplained anticorrelation stated in section 1. While our results suggest that the incidence of BALs is independent of whether log R* is greater than or less than unity, it appears that there is some value of log R* above which BALs are not seen. The answer to this issue will likely emerge with the growth of the FBQS (e.g., Gregg et al. 1995). The best current limits are discussed by Weymann (1997), who finds no BALs among 20 QSOs with 6 cm flux densities between 30 and 100 mJy. The radio-loud BAL QSOs reported here and by Becker et al. (1997b) have 20 cm flux densities of no higher than approximately 30 mJy. Given the optical fluxes of the QSOs, the radio-loudness above which BALs are not seen appears to be near to our largest log R* = 2.5.

The second method of discovering radio-loud QSOs, while searching deep enough in the radio, failed apparently through insufficient numbers. There are about 5200 UVX quasar candidates that meet the present selection criteria independent of NVSS detection, half of which should be QSOs, and five of which we found to be radio loud BAL QSOs. Therefore, the fraction of radio-loud BAL QSOs found with pure optical selection is at least 1 in 500 (at least because the NVSS does not detect all the radio-loud QSOs in the sample, and because we do not know how many of the low-redshift QSOs may show BALs in the unobserved ultraviolet). Assuming that 1/3 of the ∼2600 UVX QSOs have $z > 1.6$, for which the high-ionization C IV λ1549 BAL trough can be seen at wavelengths greater than 4000 Å the observed radio-loud BAL QSO fraction is greater than about 1 in 200. At the lower limit of these detection rates, the LBQS was too small to be sure of finding such an object. Because Becker et al. (1997b) find radio-loud BAL QSOs within the FBQS (Gregg et al. 1995), the fact that the UVX-NVSS sample is optically fainter than the LBQS probably is not important.

Despite differences in selection criterion, there are similarities that bias both the FBQS and the UVX-NVSS sample toward finding radio-loud BAL QSOs. Both samples preferentially select large numbers of radio-intermediate and radio-loud but low log R* QSOs. Furthermore, the radio selection is at a relatively high frequency, 1400 MHz. If Falcke et al. (1996) are correct that radio-quiet QSOs possess relativistic radio-emitting jets and that some fraction of radio-loud but low log R* QSOs are actually beamed radio-quiet QSOs, the pure anticorrelation between radio-loudness and the presence of BALs may still be preserved. Radio maps with high spatial resolution or spectral indices are needed for these radio-loud BAL QSOs to rule out strong beaming. Such a face-on geometry with BAL outflow along a radio-quiet jet axis could explain the overabundance of BALs seen among radio-intermediate QSOs by Francis, Hooper, & Impey (1993).

5. Conclusions

We have discovered five radio-loud BAL QSOs in a complete sample of 103 deep-radio detected UVX QSOs which are unlikely to be significantly dust reddened. The 9±5% BAL QSOs in the high-redshift sample ($z \gtrsim 1.5$, entirely radio-loud) is consistent with the frequency in purely optically selected QSOs (9%). We find three (3±2%) low-ionization BAL QSOs, also consistent with pure optical selection (∼ 1%). While BALs are not seen in the most radio-loud QSOs, the incidence of BALs appears to be independent across the conventional radio-loud/radio-quiet division.

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