DISCOVERY OF RADIO-LOUD BROAD ABSORPTION LINE QUASARS USING ULTRAVIOLET EXCESS AND DEEP RADIO SELECTION

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Received 1998 June 9; accepted 1998 July 22; published 1998 August 24

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

1. INTRODUCTION

The nature of the central engines of active galactic nuclei (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 6 orders of magnitude and appears bimodal (see, 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 (see, 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 BAL QSOs known (Hall et al. 1997). Infrared Space Observatory observations are also consistent with significant dust causing a line-of-sight reddening of $A_V = 1.6$, which indicates 4 $M_\odot$ 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) show 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. 1996), which selects stellar objects to a limiting magnitude of $E < 17.5$ with $O - E < 2.0$ that appear in the Faint Images of the Radio Sky at Twenty centimeters (FIRST), a deep radio survey that reaches 1 mJy at 20 cm (Becker, White, & Helfand 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. In § 2, we describe the sample selection and observations. In § 3, we tabulate the new BAL QSOs and their properties and give their statistics with respect to the rest of the sample. In § 4, we discuss 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. Sample and Observations

The UVX-NVSS sample includes quasar candidates from the UVX (AAT-2dF) quasar survey (Smith et al. 1997) 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 46,000 stellar objects that meet the following selection criteria. The primary color selection is \( U - B \leq -0.12 \), 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 deg\(^2\) in two strips: (1) between declination \( +2.5^\circ \) and \(-2.5^\circ\) and right ascension 9.8 and 14.8 hr and (2) between declination \(-27.5^\circ\) and \(-32.5^\circ\) and right ascension 21.7 and 3.3 hr. 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 \( S_{20\,\text{cm}} \geq 2.5\,\text{mJy} \) (5σ limit) reduces the contamination to \( \sim 5\% \), based on results below. The \( z < 2.2 \) QSO sample is expected to be greater than 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 to 13 hr. Observations were conducted with the Keck II telescope during 1998 February 9 and 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 \( \leq 10 \) Å (FWHM of comparison lamp lines); the dispersion was 2.5 Å pixel\(^{-1}\), covering approximately 4000–9000 Å. All exposure times were 4 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 \( \lambda 2800 \) enters the window; 101 objects), and high-ionization BALs are visible when present in quasars with \( z \geq 1.5 \) (C IV \( \lambda 1549 \) 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 \( z > 0.4 \)); 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 \( R^* \geq 2 \). 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, since the velocity widths \( V_{\text{max}} - V_{\text{min}} \) are greater than 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

![Fig. 1.—Rest-frame spectra of the UVX radio-loud BAL QSOs. Telluric A- and B-band absorption has been marked (encircled crosses), 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.](Image)
TABLE 1
Radio-Loud UVX BAL QSO Properties

| Name       | R.A. (J2000) | Decl. (J2000) | z  | $B_{\alpha}$ | $U-B_{\alpha}$ | $B_{\gamma}$ | $M_a$ | $S_{900}$ (mJy) | $\log L_{900}$ (ergs s$^{-1}$ Hz$^{-1}$) | $\log R^{\ast}$ |
|------------|--------------|---------------|----|--------------|----------------|-------------|-------|-----------------|-------------------------------------|-----------------|
| 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 21.38 | −01 50 35.02 | 2.04 | 19.93 | −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 mean a* …… | 11.5 hr | 0.0 | 1.4 | 19.3 | −0.53 | 0.45 | 25.8 | 116 | 33.5 | 2.41 |
Standard deviation …… | ... | ... | 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 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
a* Assuming $H_0 = 50$, $q_0 = 0$, $\alpha_{gal} = −0.1$, and $\alpha_{ref} = 0.3$ ($S \propto r^7$).

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 iv $\lambda$1909, the Mg ii $\lambda$2800 emission should peak near the center of the absorption, and the C iv $\lambda$1549 emission should peak near the local maximum in its corresponding absorption trough. This suggests an unusual flow pattern or significantly blueshifted emission lines (see, 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 $\lambda$1857 to C iv $\lambda$1909 is 0.88 (based on a two-Gaussian fit), significantly larger than that of nearly all other known QSOs, including other BAL QSOs, which have enhanced Al iii/C iv compared with radio-quiet QSOs (Weymann et al. 1991). (An exception might be the handful of QSOs like Al iii QSOs, including other BAL QSOs, which have enhanced Al iii/C iv.)

C iv $\lambda$1549 emission appears weak relative to emission from C iv $\lambda$1909 and the Ly$\alpha$ feature (a blend of Si iv $\lambda$1397 and O iv $\lambda$1402; see Wills et al. 1993); the C iv $\lambda$1549 emission line does not appear to be affected by the BAL trough, which appears detached by more than 8000 km s$^{-1}$. What these unusual line ratios mean is not clear; although Al iii $\lambda$1857 is an important coolant for very dense gas (see, e.g., Ferland et al. 1996). Because C iv $\lambda$1549 is likely to have a very high optical depth, the line may become an ineffective emitter at high density (see, e.g., Zheng & Puetter 1990). Additionally, there is a smooth, intermediate width (~900 km s$^{-1}$) absorption system at ~27,000 km s$^{-1}$ seen in both C iv $\lambda$1549 and Si iv $\lambda$1397 (the latter line is not commonly seen in interstellar systems); we suggest that this may be an intrinsic mini-BAL system (see, e.g., Hamann, Barlow, & Junkkarinen 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 as to 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 (see, 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 § 1. While our results suggest that the incidence of BALs is independent of whether $\log R^{\ast}$ is greater than or less than unity, it appears that there is some value of $\log R^{\ast}$ above which BALs are not seen. The answer to this issue will likely emerge with the growth of the FBQS (see, e.g., Gregg et al. 1996). 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 $R^*$ of 2.5.

The second method of discovering radio-loud QSOs, while searching deep enough in the radio, failed apparently because of 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 one 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 one-third of the ~2600 UVX QSOs have $z > 1.6$, for which the high-ionization C iv $\lambda 1549$ BAL trough can be seen at wavelengths greater than 4000 Å, the observed radio-loud BAL QSO fraction is greater than about one in 200. At the lower limit of these detection rates, the LBQ was too small to be sure of finding such an object. Because Becker et al. (1997b) find radio-loud BAL QSOs within the FBQ, the fact that the UVX-NVSS sample is optically fainter than the LBQS probably is not important.

Despite differences in selection criteria, 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, Sherwood, & Patnaik (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 sample of 103 deep radio-detected UVX QSOs that are unlikely to be significantly dust reddened. The 9% ± 5% BAL QSOs in the high-redshift sample ($z \geq 1.5$, entirely radio loud) are consistent with the frequency in purely optically selected QSOs (9%). We find three (3% ± 2%) low-ionization BAL QSOs, a result that is 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.

We thank Carlos De Breuck and the Keck staff for their excellent assistance. We thank Nahum Arav and Fred Hamann for their comments on the manuscript. The W. M. Keck Observatory is a scientific partnership between the University of California and the California Institute of Technology, which made possible by the generous gift of the W. M. Keck Foundation. This work has been performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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