The Optical/Near-IR Colors of Broad Absorption Line Quasars, Including the Candidate Radio-Loud BAL Quasar 1556+3517

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ABSTRACT

A candidate radio-loud broad absorption line quasar (RLBAL) has been reported by Becker et al. (1997). We present JHK observations of this object and three other radio-detected BALs taken with the new Michigan-Dartmouth-MIT/Ohio State/Aladdin IR Camera (MOSAIC) on the KPNO 4-meter. The candidate RLBAL 1556+3517 has $B-K$=6.63, redder than all but one or two known z>1 quasars. This strongly suggests the observed continuum of this quasar is reddened by dust. Even when this extreme reddening is taken into account 1556+3517 is still probably radio-loud, although near-IR spectroscopy to measure its Balmer decrement will be needed to verify this. In addition, since it is a flat-spectrum object, VLBI observations to determine the extent (if any) to which beaming affects our estimate of its radio luminosity will be needed before 1556+3517 can be unequivocally declared a radio-loud BAL.

We also use our data and data from the literature to show that optically selected BALs as a class have $B-K$ colors consistent with the observed distribution for optically selected quasars as a whole. Thus there is currently no evidence that the tendency of optically selected BALs to be preferentially radio-intermediate (Francis, Hooper, & Impey 1993) is due to extinction artificially lowering estimated BAL optical luminosities. However, as most quasar surveys, both radio and optical, would be insensitive to a population of reddened radio-quiet BALs, the existence of a large population of reddened BALs similar to 1556+3517 cannot yet be ruled out.

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

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1. Introduction

Broad absorption line quasars (BALs) exhibit absorption troughs blueward of high-ionization (and occasionally low-ionization) emission lines in their rest-frame UV continua. Since the definitive work of Stocke et al. (1992, hereafter S92) it has been held that no BALs are radio-loud quasars (RLQs), defined as having either an absolute radio power $P \gtrsim 10^{32.5}$ ergs s^{-1} Hz^{-1} or a ratio of radio to optical luminosities $R \gtrsim 10$. However, Francis, Hooper & Impey (1993, hereafter F93) have shown that BALs are preferentially "radio-intermediate" quasars (RIQs), with $0.2 < \log(R) < 1$. This may be because BALs are radio-quiet quasars (RQQs) with higher than average optical extinction. In principle this can be tested by measuring near-IR fluxes, which are less sensitive to extinction and thus provide a better measurement of the quasar luminosity.

Recently Becker et al. (1997, hereafter B97) reported the discovery of a candidate radio-loud BAL (RLBAL) 1556+3517 in the FIRST Bright Quasar Survey (FBQS; Gregg et al. 1996). This object shows strong absorption below 2800 Å rest (B97, Fig. 1). Extinction from dust associated with the BAL gas of $\sim 5^{\mathrm{m}}$ at 2500 Å (equivalent to $E(B-V) \sim 1$; Sprayberry & Foltz 1992, hereafter SF92) would be sufficient to make the quasar appear a RLQ even if it were actually a RQQ, as mentioned by B97. This is a large amount of extinction, but Egami et al. (1996, hereafter E96) find $E(B-V) \sim 0.41-0.84$ for the unusual BALs 0059−2735 and Hawaii 167 based on their large Balmer decrements. Again, this hypothesis can be tested with near-IR fluxes.

Since the confirmed existence of an RLBAL would have an impact on theoretical models, and since near-infrared observations are useful for understanding the overabundance of BALs among RIQs, we have obtained such observations for several BALs and report the results in this Letter. We adopt H_0=50 km s^{-1} Mpc^{-1}, q_0=0.1, Λ=0, consistent with B97.

2. Observations and Data Reduction

We observed the first two published BALs from the FIRST survey (B97), 0840+3633 and 1556+3517, and two flat-radio-spectrum RQQ BALs (1212+1445 and 1246−0542) from Barvainis & Lonsdale (1997, hereafter BV97). The observations were obtained on 20 & 24 March 1997 at the 4-meter Mayall telescope at Kitt Peak National Observatory with MOSAIC, the Michigan-Dartmouth-MIT/Ohio State/Aladdin Infrared Camera. MOSAIC employs a 512×1024 Aladdin (InSb) array as detector and has both imaging and spectroscopic capabilities. For these observations we used the $f/7.6$ camera which results in a plate scale of $0\farcs18$ pixel^{-1}. Typical seeing during these nights was $1''$ and $2''$ for 20 & 24 March, respectively. We obtained JHK photometry of these four targets by employing a five-position dither pattern on the array in each filter. The median of the five images in each filter was used as a sky frame and subtracted from each individual frame. We then flatfielded the images with the difference of dome flats taken with the lights on and the lights off. Standard stars were observed and reduced in the same manner. Measurements were made using a $2\farcs5$ synthesized circular beam. The mean of each set of five measurements is presented in Table 1, along with literature data on 0059−2735 (Hazard et al. 1987) and Hawaii 167 (Cowie et al. 1994). Our data on 1246−0542 agree well with Hyland & Allen (1982), although the object appears ∼0.1 mag brighter in epoch 1997.23.

3. Analysis and Discussion

The colors of our objects, corrected for galactic extinction, are given in Table 1. These corrections were determined using $E(B-V)$ from Burstein & Heiles (1978, 1982) and R_λ from Mihalas & Binney (1981). The colors are also shown in Fig. 1, which consists of three $B-K$ histograms. The bottom histogram (dashed) is predominantly optically selected $z>1$ quasars from Francis (1996) and Srianand & Kembhavi (1997). The middle histogram consists of our six objects (solid) and the six other $z>1$ BALs with $B-K$ values in the literature (dotted). 1556+3517 is one of the reddest quasars known, even redder than Hawaii 167. A two-sided Kolmogorov-Smirnov (K-S) test using the STATISTICS package in STSDAS under IRAF[2] gives P=64.65% that the $B-K$ distributions of our 12 BALs matches that of optically selected quasars. However, if we exclude from the set of BALs Hawaii 167, 1556+3517, and 0840+3633, none of which were optically selected, we obtain P=99.95% that the $B-K$ distributions of optically selected BALs and optically selected quasars match.[3] Thus there is no evidence for optically selected BALs as a class to have redder $B-K$ colors than other optically selected quasars. Therefore the observed tendency of optically selected BALs to be radio-intermediate (F93) does not seem to be due to extinction artificially lowering estimated BAL optical luminosities. This extends to a longer wavelength baseline the finding of Weymann et al. (1991) that the observed-frame optical continua of high-ionization BALs and non-BALs are essentially identical.

However, the fact that neither of the two known examples of extremely red BALs (Hawaii 167 and 1556+3517) were optically selected casts doubt on the applicability of this conclusion to the entire BAL population, as distinct from the known optically selected BAL population. A strong claim has been made by Webster et al. (1995) that the color distribution of radio-selected quasars extends to much redder colors than that of optically-selected quasars. To illustrate this, in the top histogram of Fig. 1 we plot the $B-K$ distribution for a subsample of radio-selected quasars from the Parkes 0.5 Jy survey (Webster et al. 1995, Drinkwater et al. 1997), including 23 objects with $z>1$ and 11 objects of unknown redshift. The $B-K$ distribution of radio-selected quasars spans a range of $B-K$ colors that includes those of 1556+3517 and Hawaii 167. A two-sided K-S test gives P=5.11% that the $B-K$ distributions of BALS and radio-selected quasars match, but P=0.83% that the $B-K$ distributions of optically selected BALs and radio-selected quasars match.

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[2]The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories, which is operated by AURA, Inc., under contract to the National Science Foundation.

[3]This probability is correct but unusually high. Resampling simulations show that a dataset of B-K colors of nine randomly chosen optically selected quasars would almost certainly give a lower but still significant P.

This suggests that optically selected BALs may have a $B-K$ distribution indistinguishable from that of optically selected quasars simply because BALs have been almost exclusively optically selected to date. Whatever produces the bluer average $B-K$ colors of optically-selected quasars (selection effect or lack of a red spectral component seen in RLQs) would then naturally affect the colors of optically selected BALs as well. This does not change our conclusion that extinction is unlikely to be responsible for the observed preferential radio-moderateness of optically selected BALs, but it should be kept in mind that the observed distribution of BAL $B-K$ colors may not represent the true distribution. Radio surveys such as the FBQS (Gregg et al. 1996) which are sensitive to RQQs and RIQs to fairly high z may help remedy this situation, since such surveys can in principle select BALs regardless of their optical/IR colors.

There are three obvious explanations for the extreme redness of 1556+3517: dust, a beamed red synchrotron component, and/or contamination from its host galaxy. The latter possibility can be almost completely ruled out, as it would require a galaxy at z=1.48 with $K \lesssim 15$. This is two magnitudes brighter than the brightest radio galaxies at $z \sim 1.5$ (McCarthy 1993). The possibility of a beamed red synchrotron component (Serjeant & Rawlings 1996) in this flat-spectrum source cannot be ruled out with photometry alone. However, Francis et al. (1997) show that for the Parkes radio-selected quasars the equivalent width of Mg II does not anticorrelate with continuum redness, as expected if a red synchrotron component were present. Thus there is good reason to believe that a red synchrotron component is not present in most red quasars. To determine this for certain for 1556+3517 specifically will require measurement of its near-IR polarization (which should be low if such a component is absent) or of its Balmer decrement (which should be high if dust is instead the reddening agent).

Assuming that the extreme redness of 1556+3517 is due to dust, is its RLQ status due just to extinction? We can test this by calculating R, the ratio of radio to optical luminosity. Two specific definitions are in use: R^*, the ratio of rest-frame 5 GHz to 2500 Å flux densities (S92), and $R_{8.4}$, the ratio of rest-frame 8.4 GHz to B flux densities (Hooper et al. 1995, hereafter H95).

To calculate the radio flux densities, we ignore the likelihood of variability since we have only single-epoch data. To change our conclusions, however, would require extreme radio variability of a factor $\gtrsim 3$, unusual for quasars (Hughes, Aller, & Aller 1992). We also assume isotropic radio emission, a point we shall return to later. B97 use radio spectral index $\alpha_{\rm rad}=-0.1$ based on 1.4 and 5 GHz detections of 1556+3517. We use $\alpha_{\rm rad}=-0.1$ for consistency except for 1212+1445 and 1246−0542, for which multiwavelength radio data is available (BV97). We calculate $\alpha_{\rm rad}=-0.259\pm0.009$ for 1212+1445 and $\alpha_{\rm rad}=+0.097\pm0.021$ for 1246−0542. Flux densities and luminosities at 1400, 5000 and 8400 MHz are given in Table 2.

To calculate the true optical/UV flux densities, we again ignore variability because of our lack of multi-epoch data. We incorporate the differential k-correction between BALs and non-BALs from S92, which is $\leq 0^{\rm m}_{.}05$ except for 1246−0542 ($0^{\rm m}_{.}25$) and Hawaii 167 ($0^{\rm m}_{.}3$). For Hawaii 167 and 1556+3517, because of the anomalously red $B-K$ colors we assume that the observed B

magnitudes do not reflect their intrinsic B luminosities, due to dust reddening and extinction. We want to find the *observed* (dereddened) B magnitudes the objects would have in the absence of dust. We assume that without dust the objects would have observed $B-K$=3. This is a plausible unreddened value for z>1 quasars (Fig. 1; cf. Webster et al. 1995, Francis 1996, Srianand & Kembhavi 1997), and just slightly bluer than the $B-K$ of 0059−2735 and 0840+3633 (cf. Table 1), two of the other three known "Iron low-ionization BALs" (the third is Mrk 231, Smith et al. 1995). We determine the rest-frame $E(B-V)$ necessary to produce the observed $B-K$ colors assuming the dust is at the quasar z, which gives a conservative $E(B-V)$. We use a SMC extinction law, in accordance with SF92 who found that LMC or MW reddening laws which have a 2200 Å bump could not explain the observed reddening of low-ionization BALs like Hawaii 167 and 1556+3517. We find $E(B-V)$=0.23 for Hawaii 167 and $E(B-V)$=0.63 for 1556+3517. The $E(B-V)$ for Hawaii 167 is ∼3.3 times lower than that derived by E96 from its Balmer decrement. This is expected if, as they suggest, the quasar is highly extincted and the observed rest-frame UV emission is actually from its host galaxy. From these $E(B-V)$ and Fig. 1 of SF92, we find that 1556+3517 and Hawaii 167 have extinctions of $4\overset{\mathrm{m}}{.}41$ and $2\overset{\mathrm{m}}{.}76$ in observed B respectively, corresponding to dereddened B magnitudes of 16.79 for 1556+3517 and 20.24 for Hawaii 167.

We then calculate R^* using S_{5000} and the dereddened B magnitudes in the formula log $f_{2500\mathring{A}} = -22.62-0.4B$ (S92). We follow H95 in calculating absolute B magnitudes (given in Table 1) from the dereddened B magnitudes using k-corrections for the composite Large Bright Quasar Survey spectrum of Francis et al. (1991), and then calculating $R_{8.4}$ using $L_{8.4}$ and the absolute rest-frame B-band luminosity L_B (calculated assuming a zeropoint of 4260 Jy). Values of R^* and $R_{8.4}$ are given in Table 2. 0840+3633 and 1212+1445 appear to be RIQs by either definition of R. 1556+3517 is still a RLQ with log(R)∼1.43 even after our reddening correction. However, if its true color was $B-K$=2 or 1 and we dereddened its B magnitude appropriately, 1556+3517 would be a RIQ with log(R)∼1.03 or 0.73. Thus a better estimate of the reddening for 1556+3517 is needed before it can be unequivocally declared a radio-loud quasar. This could come from near-IR spectra to determine its Balmer decrement or L (3.4μm) or M (5μm) data sampling rest-frame H and K, where extinction should be only $0\overset{\mathrm{m}}{.}32$ and $0\overset{\mathrm{m}}{.}16$ for $E(B-V)$=0.63.

The radio-loudness of 1556+3517 is in accord with its log(L)∼33.5 being above the usual divide of 32.5 between RLQs and RQQs based on radio power alone (B97). However, 1556+3517 is an unresolved flat-spectrum radio source, so the possibility remains that it is in fact a RQQ with a relativistically boosted jet pointed near our line of sight, and that we have overestimated its radio luminosity by assuming isotropic radio emission. This has been shown to be the case for several flat-spectrum RIQs with log(R) as high as 2.41 (Falcke, Patnaik, & Sherwood 1996).

4. Conclusions

We have shown that the candidate radio-loud BAL 1556+3517 has a redder $B-K$ color than almost every other quasar known. Despite this, it is still probably a RLQ by all common definitions, unless it has a true (unreddened) observed color of $B-K<2$ or its red color is due to a beamed red synchrotron emission component. Also, because it is a flat-spectrum radio source, its radio luminosity may be affected by relativistic beaming. Thus VLBI observations to determine the core dominance of 1556+3517 and near-IR spectroscopy to measure its Balmer decrement will be needed to definitively determine if 1556+3517 is a radio-loud BAL.

We have also shown that at $z>1$, optically selected BALs as a class have a $B-K$ color distribution consistent with that of all optically selected quasars. Thus there is currently no evidence that the tendency of optically selected BALs to be preferentially radio-intermediate (F93) is due to extinction artificially lowering our estimate of BAL optical luminosities. However, as most quasar surveys, both radio and optical, would not be sensitive to a population of reddened radio-quiet BALs, the existence of a large population of reddened BALs similar to 1556+3517 cannot yet be ruled out.

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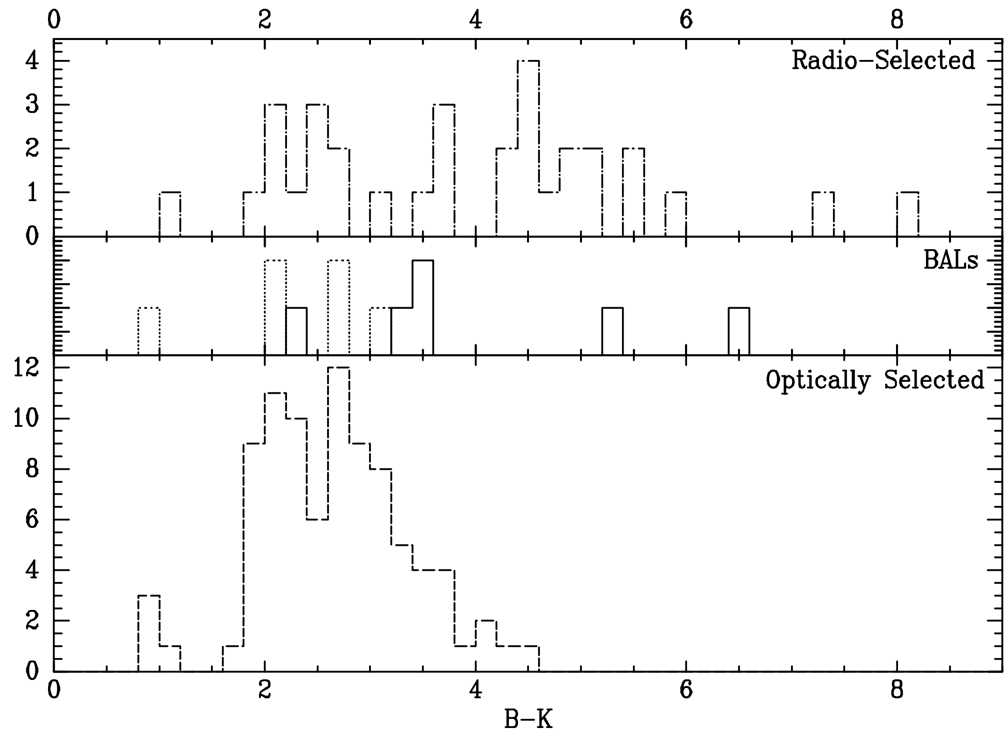

Fig. 1.— Histogram of quasar $B-K$ colors. Bottom (Dashed): $z>1$ quasars, primarily optically selected, from Francis (1996) and Srianand & Kembhavi (1997). Middle: Data from this paper. Solid: our BALs (see Table 1). 1556+3517 is the reddest of our objects, and Hawaii 167 the next reddest. Dotted: BALs from the literature. BALs were taken from Table 2 of Junkkarinen, Hewitt, & Burbidge 1991, and colors from the above two references. In order of increasing $B-K$, these objects are 2225−05, 1254+047, 0946+301, 2241+0016, 0004+147, and 1309−056. Top (Dot-Dash): Radio-selected Parkes quasars from Webster et al. (1995), including 23 objects with $z>1$ and 11 objects of unknown redshift.

Table 1. BAL Quasar Optical-Infrared Properties

ID	z	Galactic E(B-V)	B	J	H	K	B-K	J-K	H-K	M_B
0059−2735	1.62	0.0203	18.2	15.8	14.9	14.7	3.4	1.1	0.2	-27.03
Hawaii 167	2.36	0.1443	23.0	18.8	17.8	17.2	5.25	1.5	0.6	-25.89[b]
0840+3633	1.22	0.0253	17.3	14.87(0.07)	14.10(0.10)	13.92(0.06)	3.29	0.94	0.18	-27.22
1212+1445	1.627	0.0312	17.94	16.29(0.07)	15.74(0.07)	15.53(0.08)	2.29	0.75	0.20	-27.29
1246−0542	2.236	0.0102	17.09	14.96(0.06)	14.34(0.04)	13.61(0.05)	3.44	1.34	0.72	-29.23
1246−0542[a]				15.20(0.04)	14.43(0.02)	13.71(0.02)	3.34	1.48	0.71	
1556+3517	1.48	0.0143	21.2	15.87(0.06)	14.94(0.04)	14.57(0.05)	6.57	1.29	0.36	-28.18[b]

Note. — H_0=50, q_0=0.1, and $\alpha_{\rm opt}$=−1.0. 0059−2735 and Hawaii 167 magnitudes from Cowie et al. (1994), except 0059−2735 B magnitude from Warren, Hewett, & Osmer (1991), and 0059−2735 R magnitude from Becker et al. (1997). 1212+1445 *B* magnitude from Hooper et al. (1995). 1246−0542 *B* magnitude from Hewitt & Burbidge (1993). 0840+3633 and 1556+3517 optical magnitudes from Becker et al. (1997).

[a] Literature data from Hyland & Allen 1982

[b] Calculated using dereddened *B* magnitudes of 16.79 for 1556+3517 and 20.24 for Hawaii 167. See text.

Table 2. BAL Quasar Radio Properties

ID	S_{1400}	S_{5000} (mJy)	S_{8400}	Log(L_{1400})	Log(L_{5000}) (ergs s^{-1} Hz^{-1})	Log(L_{8400})	Log(R^*)	Log($R_{8.4}$)
0059−2735	···	$< 0.36^{c}$	···	$< 31.71^{f}$	< 31.66	$< 31.64^{f}$	< 0.06	< 0.12
Hawaii 167	$< 2.5^{a}$	···	···	< 32.85	$< 32.79^{h}$	$< 32.77^{h}$	< 1.58	< 1.71
0840+3633	1.6^{b}	···	···	32.05	32.00^{h}	31.97^{h}	0.38	0.37
1212+1445	< 0.60	0.45(0.06)	$0.38(0.04)^{e}$	< 31.95	31.82	31.75	0.12	0.13^{i}
1246−0542	< 1.89	0.52(0.05)	0.53(0.06)	32.00^{g}	32.05	32.06	−0.49	−0.34
1556+3517	30.6^{b}	27.0^{d}	···	33.50	33.45	33.43^{h}	1.41	1.45

Note. — H_0=50, q_0=0.1, and $\alpha_{\rm rad}$=−0.1 except 1212+1445 (−0.259±0.009) and 1246−0542 (+0.097±0.021). S values are monochromatic fluxes at the subscripted *observed* frequency in MHz. L values are monochromatic luminosities at the subscripted *rest − frame* frequency in MHz. R values are ratios of radio to optical luminosities as described in the text. Fluxes for 1212+1445 and 1246−0542 from Barvainis & Lonsdale 1997. All upper limits are 3σ.

[a] Upper limit from the NVSS survey, Condon et al. 1996

[b] FIRST Survey, Becker, White, & Helfand 1995

[c] Stocke et al. 1992

[d] GB 5GHz survey, Becker et al. 1991

[e] Hooper et al. (1995) give 0.45±0.07 mJy

[f] Estimated from S_{5000} upper limit

[g] Estimated not from S_{1400} upper limit but from higher frequency data in Barvainis & Lonsdale 1997

[h] Estimated from S_{1400} detection or upper limit

[i] Hooper et al. (1995) give 0.31±0.32, calculated assuming $\alpha_{\rm rad}$=−0.3