

SUBMILLIMETER OBSERVATIONS OF A SAMPLE OF BROAD ABSORPTION LINE QUASARS

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ABSTRACT

The broad absorption line (BAL) features seen in a small fraction of quasar optical/UV spectra are attributed to bulk outflows away from the quasar core. Observations suggest that dust plays a key role in these systems, although whether the inferred dust properties are a signature of orientation effects or whether they are indicative of an evolutionary sequence remains an outstanding issue. Submillimeter detections of BAL quasars (BALQSOs), which would clearly help to resolve this issue, have so far been sparse. This Letter reports on new submillimeter observations of seven BALQSOs. The strongest influence on the observed flux is found to be the redshift, with the two highest redshift sources appearing intrinsically more submillimeter-luminous than the lower redshift ones. Since this trend is also seen in other high-redshift active galactic nuclei (AGNs), including non-BAL quasars, it implies that the dust emission properties of these systems are no different from those of the general AGN population, which is difficult to reconcile with the evolutionary interpretation of the BAL phenomenon.

Subject headings: quasars: general — submillimeter

1. INTRODUCTION

A small fraction (≈ 0.2 ; Hewett & Foltz 2003; Becker et al. 2000) of quasars display broad absorption features in their spectra, with widths of several thousand kilometers per second, blueward of the prominent broad emission lines. Seen only in permitted lines, these absorption troughs are attributed to bulk outflows from the quasar's heart. Typically, the broad absorption lines (BALs) are seen in high-ionization lines, such as Ly α and C iv $\lambda 1549$ (HiBALQSOs), although, more rarely, some systems also display low-ionization lines such as Mg II $\lambda 2800$; these LoBALs comprise $\sim 10\%$ of the BALQSO population. The BAL phenomenon in quasars appears to be part of a much broader manifestation of absorption outflows from active galactic nuclei (AGNs); lower velocity and narrower UV absorption features are detected more readily in Seyfert spectra, and similar spectral features from "associated absorbers" are also detected in some (mainly steep spectrum) radio-loud quasars (see Crenshaw, Kraemer, & George 2002 for a review). Indeed, the recently released catalog of BALQSOs from the Sloan Digital Sky Survey (Reichard et al. 2003) reveals numerous quasars possessing weak absorption features, hinting at the possible ubiquitous nature of intrinsic absorption outflows.

The BAL phenomenon, and in particular its relation to the overall quasar population, has been the subject of debate for a number of years. Two distinct interpretations for the occurrence of BALs are the orientation and evolution hypotheses. According to the orientation interpretation (Weymann et al. 1991; Schmidt & Hines 1999), all quasars possess BAL outflows with a restricted covering factor, so that the frequency of detection simply translates to the rate at which our line of sight intercepts the outflow. According to the evolution hypothesis (Briggs, Turnshek, & Wolfe 1984; Voit, Weymann, & Korista 1993), the incidence rate of the BAL phenomenon is interpreted as the duration of a phase of a quasar's natural life cycle.

Observational evidence supporting the orientation hypoth-

esis comes largely from spectral comparisons of BAL and non-BAL quasars (Weymann et al. 1991) and polarization studies (Hines & Wills 1995; Goodrich & Miller 1995; Cohen et al. 1995; Hutsemekers, Lamy, & Remy 1998; Schmidt & Hines 1999). Evidence in favor of the evolution hypothesis comes largely from *IRAS*-selected BALQSOs (e.g., Boroson & Meyers 1992), particularly those showing evidence of recent mergers or close interactions, consistent with proposed evolutionary scenarios for quasars (e.g., Sanders et al. 1988). Further support for the evolution hypothesis has been provided indirectly by radio observations of BALQSOs, which are inconsistent with simple orientation schemes (Becker et al. 2000).

Both hypotheses also rely on observations indicating that (1) BALQSOs are substantially more reddened than non-BAL quasars (Hall et al. 1997; Reichard et al. 2003); (2) their continua are virtually indistinguishable from those of non-BAL quasars once dust extinction is taken into account (e.g., Yamamoto & Vanssevicius 1999); and (3) LoBALQSOs are much redder than HiBALQSOs (Sprayberry & Foltz 1992). In the orientation scheme, these observations support the idea that BAL outflows become increasingly more dusty as the viewing angle becomes more inclined, with LoBALs seen along sight lines grazing the putative nuclear dusty torus that plays a key role in orientation-based unification schemes for AGNs. In evolutionary scenarios, the merging of two gas-rich systems fuels both vigorous star formation and a central AGN, resulting in the strong dust emission associated with an ultraluminous infrared galaxy (ULIRG) phase (Sanders et al. 1988; Voit et al. 1993; Sanders & Mirabel 1996; Canalizo & Stockton 2001).

Since evolutionary models implicitly predict that BALQSOs should exhibit enhanced dust emission with respect to non-BAL quasars, one method of distinguishing between the two competing hypotheses is to measure submillimeter luminosities. To date, only a handful of BALQSOs have been observed at submillimeter wavelengths (e.g., Hughes, Dunlop, & Rawlings 1997; Lewis et al. 1998; Page et al. 2001). In this Letter, we present submillimeter photometry observations of seven BALQSOs in order to determine how their dust emission properties compare with that of the general quasar and AGN population.

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TABLE 1
PROPERTIES OF THE SAMPLE OF BALQSOs

Name	z	$S_{450\ \mu\text{m}}$ (mJy)	$S_{850\ \mu\text{m}}$ (mJy)	M_d ($10^8 h_{50}^{-2} M_\odot$)	L_{FIR} ($10^{12} h_{50}^{-2} L_\odot$)	SFR ($\alpha \times h_{50}^{-2} M_\odot \text{ yr}^{-1}$)
PSS 1537+1227	1.20	-10.1 ± 32.2	-0.4 ± 1.0	<2.1	<7.2	<713
0840+3633	1.22	-4.8 ± 9.2	1.1 ± 1.0	<2.1	<7.2	<713
1104-0004	1.35	7.8 ± 13.2	0.7 ± 1.8	<3.9	<12.8	<1276
1556+3517	1.50	31.0 ± 28.7	1.6 ± 1.2	<1.1	<3.7	<371
1053-0058	1.55	6.6 ± 15.3	0.9 ± 1.2	<0.7	<2.5	<248
LBQS 0059-2735	1.59	19.2 ± 56.3	10.3 ± 3.3	7.1 ± 2.4	23.6 ± 6.9	2369 ± 764
Hawaii 167	2.35	66.0 ± 20.7	6.0 ± 1.7	3.7 ± 1.0	12.2 ± 3.3	1219 ± 333

NOTE.—From left to right, the source name, redshift, flux at 450 and 850 μm , the inferred dust mass, far-infrared luminosity, and star formation rate, as determined via the recipe of McMahon et al. 1999. The upper limits represent 3σ values for the nondetections.

2. OBSERVATIONS

Our target sample was drawn from the literature⁴ and consisted of a range of BAL systems. Given weather constraints, seven BALQSOs from our sample were observed. These were PSS 1537+1227,⁵ 0840+3633 (Becker et al. 1997), 1104-0004 (Brotherton et al. 1998), 1556+3517 (Najita, Dey, & Brotherton 2000), 1053-0058 (Brotherton et al. 1998), and LBQS 0059-2735 (Hazard et al. 1987; Weymann et al. 1991), whose submillimeter fluxes are presented in this Letter. The details of our observations of Hawaii 167 (Cowie et al. 1994; Egami et al. 1996) are presented elsewhere (Lewis & Chapman 2000).

Observations were made in 2000 May with the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT)⁶ on Mauna Kea, Hawaii. We used the “photometry” three-bolometer chopping mode described in Chapman et al. (2000) and Scott et al. (2000) to keep the source in a bolometer throughout the observation. This mode has the additional advantage of allowing a check on the apparent detection of a source over three independent bolometers. While the 450 and 850 μm arrays are illuminated simultaneously, the bolometer alignment is not perfect, and we did not include the 450 μm off-beams in our final flux estimate, except to check that the source had off-beam flux consistent with the detection in the primary bolometer.

The observations incorporate chopping (7.8125 Hz) and nodding (every 9 s), and the final flux density in an individual bolometer is a *double-difference* with $N = 3$ beams. The central beam has an efficiency of unity, and the two off-beams have

$$\epsilon = -0.5 \exp\left(-\frac{d^2}{2\sigma_b^2}\right), \quad (1)$$

where d is the angular distance of the off-beam center from the source and σ_b is the Gaussian half-width of the beam. For the secondary bolometer, the beam efficiency is simply 0.5. Distortion in the field results in our chosen third bolometer being slightly offset from the source position, resulting in a beam efficiency of 0.44. Our 2- and 3-beam measured fluxes agree within less than 1σ of the primary-beam measurement

⁴ This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

⁵ Currently unpublished, the position of this quasar was deduced from images available in the press as R.A. = $15^{\text{h}}37^{\text{m}}42^{\text{s}}$, decl. = $12^{\circ}27'44''$ (J2000).

⁶ The JCMT is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.

in all nondetection cases. For the two sources that we claim as detections, H167 and LBQS 0059, the detection significance increases after folding in the negative flux density from the 2 off-beam pixels.

The effective integration time on-source varied from 1200 to 4800 s for the seven objects in our sample. The secondary was chopped with a throw of $52''$ to keep the source on the bolometer at all times. Pointing was checked before and after the observation on blazars, and a sky dip was performed to measure the atmospheric opacity directly. The rms pointing errors were $1''.4$, while the average atmospheric zenith opacities at 450 and 850 μm were 1.7 and 0.21, respectively. The data were reduced using the Starlink package SURF (Scuba User Reduction Facility; Jenness & Lightfoot 1998) and our own reduction routines to implement the three-bolometer chopping mode. Spikes were first carefully rejected from the data, followed by correction for atmospheric opacity and sky subtraction using the median of all the array pixels, except for obviously bad pixels and the source pixels. The data were then calibrated against standard planetary and compact H II region sources, observed during the same night.

3. RESULTS

Table 1 summarizes the submillimeter photometry and dust properties of our sample. There is a strong redshift dependence on the submillimeter properties of these BAL systems, with only upper limits for all systems below $z \sim 1.59$, despite deep and uniform noise limits achieved for this sample. The inferred dust masses, far-infrared (FIR) fluxes, and star formation rates are substantially higher for the two highest z sources compared with the values calculated from the upper limits for the lower z sources. While our sample is small, these results nevertheless support the notion that the high-redshift universe is considerably more dusty than the local universe. Our results also corroborate other separate submillimeter observations of three different BALQSOs, all with $S_{850\ \mu\text{m}} > 5$ mJy and all lying at $z > 1.6$ (Hughes et al. 1997; Lewis et al. 1998; Page et al. 2001).

How do the submillimeter properties of our BALQSO sample compare with those of other AGNs at high redshift? Priddey et al. (2003) obtained 850 μm fluxes for a sample of 57 optically bright quasars in the range $1.5 < z < 3.0$, overlapping with the redshift range of our sample. With slightly worse noise limits, their study detected nine targets at greater than 3σ significance, a similar detection rate to this sample. The BALQSOs presented here have 850 μm properties very similar to the Priddey et al. (2003) bright quasar sample, although only a slight trend with redshift is found in their sample, and this trend is consistent with negative K -correction effects.

At higher redshifts, the dependence of FIR luminosity on

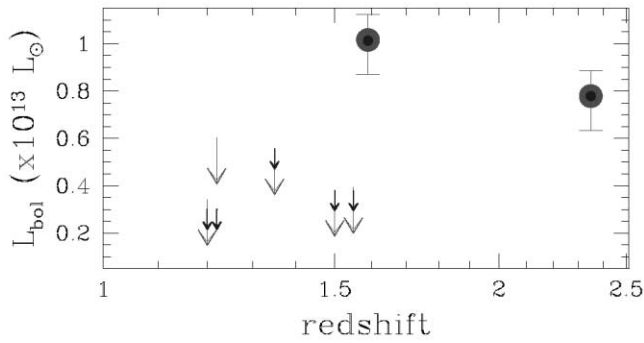


FIG. 1.—Filled circles: Bolometric luminosities of the BAL systems presented in this study (appropriate K -corrections have been applied). Error bars: Submillimeter measurements only.

redshift becomes more evident in samples of quasars (e.g., McMahon et al. 1999; Isaak et al. 2002) and even more so for radio galaxies (e.g., Archibald et al. 2001). In the Archibald et al. (2001) study of 47 radio galaxies in the range $1 < z < 5$, 20 of the sources lie in the redshift range $1.2 < z < 2.35$, overlapping with our BALQSO sample, and four are detected at 3σ , a level similar to both our BALQSO sample and the Priddey et al. (2003) bright quasar survey. The FIR fluxes of the detected radio galaxies are broadly similar to those in both quasar samples. Archibald et al. (2001) also found a dramatic increase of FIR flux with redshift [$L_{\text{FIR}} \propto (1+z)^3$], a much stronger evolution than that seen in the quasar samples. This trend is interpreted as increasingly younger stellar populations associated with the radio galaxies at earlier epochs. Finally, $850\ \mu\text{m}$ fluxes for a sample of X-ray-absorbed AGNs (Page et al. 2001) reveal a very similar trend to that of our BALQSO sample, with four significant detections above $z = 1.7$ and only upper limits at lower redshifts, with similar detected levels of $850\ \mu\text{m}$ fluxes.

In Figure 1, bolometric luminosities (total FIR luminosity plus total UV/optical luminosity) are plotted against redshift for our BAL sample. Both the optical and submillimeter luminosities have been K -corrected, assuming $f_\nu \propto \nu^{-\alpha}$, with $\alpha = 0.5$ for the optical correction and gray-body emission with $\beta = 1.5$ and $T = 40\ \text{K}$ for the submillimeter correction. Infrared luminosity is integrated over the gray body from a 1100 to $60\ \mu\text{m}$ rest frame, while optical luminosity is integrated over the power-law continuum from 2000 to $5000\ \text{\AA}$. The plot also shows only the FIR luminosities overlaid (*smaller symbols*), illustrating that the bulk of the bolometric luminosity is generated through dust reprocessing, generating ULIRG-class luminosities for both submillimeter detections. Note that the deep SCUBA limits are insufficient to exclude the lower redshift BALQSOs from being ULIRG-class sources also. The mean submillimeter signal from the five nondetections (calculated by weighting each measurement by its inverse variance) is $0.7 \pm 0.5\ \text{mJy}$, which translates into an FIR luminosity of $8.6 \times 10^{11}\ L_\odot$. Note also that the negative K -correction in the observed $850\ \mu\text{m}$ flux results in a quasi-linear flux-luminosity relation, varying less than 20% over the redshift range $1 \rightarrow 3$ (e.g., Blain, Barnard, & Chapman 2003). Thus, while the negative K -correction eases the detection of distant submillimeter sources, its small variation over the redshift range of interest here implies that the detections/upper limits would have been similar if the redshifts were interchanged.

Figure 2 presents a comparison of $S_{850\ \mu\text{m}}$ -to- R -band flux ratios for our BALQSO sample (*filled circles*) with those for a subsample of the Archibald et al. (2001) radio galaxies for

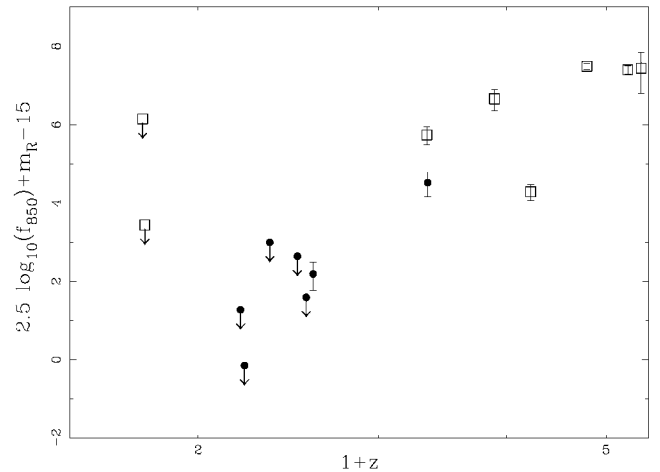


FIG. 2.—Filled circles: f_{850} -optical colors for the BAL systems presented in this study. Appropriate K -corrections have been applied, so the values reflect the rest-frame ratio, whereas error bars reflect the uncertainty in the submillimeter measurements only. Open squares: Subsample of the submillimeter observations of radio galaxies by Archibald et al. (2001). See text for more details.

which R -band magnitudes were obtained (*open squares*). Both the optical and submillimeter fluxes have been K -corrected and hence represent rest-frame quantities. The errors reflect only uncertainties in the submillimeter flux. The strong evolution of submillimeter luminosities exhibited by these radio galaxies may be a key signature of the star formation history of massive elliptical galaxies that are believed to arise from gas-rich mergers. Thus, they may offer clues to test the evolution hypothesis for the BAL phenomenon. The most striking aspect of the submillimeter-to-optical flux ratios in Figure 2 is that the BALQSOs are substantially less submillimeter-luminous than the radio galaxies (relative to their R -band flux). This is most likely due to the increased obscuration of the radio galaxy optical nucleus, since the Archibald et al. (2001) radio galaxies are steep-spectrum sources and thus, according to AGN unification schemes, are probably being viewed at large inclinations with respect to their radio axes. Note also that BALQSOs appear to fall into a distribution that is similar to that of radio galaxies, with higher redshift objects possessing more firm submillimeter detections than the lower redshift objects, for which only upper limits could be obtained. Indeed, this trend prevails in this entire sample of radio galaxies (Archibald et al. 2001). One final and important point is that there does not appear to be a correlation between the submillimeter and optical fluxes of our BALQSOs (or of the radio galaxies), and the high values of $S_{850\ \mu\text{m}}$ relative to R -band flux is indicative of dust heating by starbursts rather than by the BALQSO nucleus. This is also found to be the case in several other large quasar samples (e.g., McMahon et al. 1999; Isaak et al. 2002; see also the discussion and references in Bertoldi & Cox 2002).

It is important to examine whether there are any selection biases in our BALQSO sample. The BALQSOs were drawn from many inhomogeneous surveys; e.g., LBQS 0059–2735 was selected from objective prism plates (Hazard et al. 1987; Weymann et al. 1991), while Hawaii 167 was found in a spectroscopic follow-up of K -band sources (Cowie et al. 1994). Hence, there is no well-defined selection function. One possible concern is that the highest redshift sources are intrinsically the most luminous, and thus a correlation between total luminosity and submillimeter luminosity could be responsible for our bimodal detections between high and low redshifts. However, as

Figure 2 demonstrates, there is no evidence of a correlation between the submillimeter and optical luminosities of our BALQSOs. Although dust obscuration may be affecting the submillimeter-to-optical flux ratios, this lack of correlation is also readily seen in larger samples of optically bright quasars (e.g., Isaak et al. 2002; see also references in Bertoldi & Cox 2002).

4. DISCUSSION AND CONCLUSIONS

This study suggests that the FIR luminosities, inferred dust masses, and star formation rates of BALQSOs are comparable with those of ULIRG-class sources. While this may at first seem consistent with evolutionary models for BALQSOs, two key aspects of these submillimeter properties, namely, the trend of submillimeter flux with redshift and the lack of correlation between the submillimeter and optical fluxes, are also seen in samples of non-BAL quasars and radio galaxies (McMahon et al. 1999; Archibald et al. 2001; Isaak et al. 2002). If, as is proposed in evolutionary scenarios, BAL outflows are a rapid mass-loss phase triggered by a recent gas-rich merger or close interaction event involving vigorous star formation and associated enhanced dust emission, then it is difficult to understand why the submillimeter properties of BALQSOs are similar to those of other AGNs. While these dust properties are consistent with qualitative ideas about the role of star formation in the early universe and the evolution of the overall AGN population, they do not suggest that there is anything remarkable about the dust properties of BALQSOs that would be indicative of a connection between the BAL phenomenon and the presence of dust.

If the submillimeter properties of our (albeit small) BALQSO sample are verified by larger samples, how do we then interpret the BAL phenomenon? It is now clear that standard orientation-based models are unable to account for all properties of BALQSOs; radio spectral index and radio axis measurements indicate that many BALQSOs simply cannot be viewed at large inclination angles (Becker et al. 2000). A possible model that can explain the radio properties of BALQSOs is one in which the BAL material resides in a poorly collimated, weak radio jet (Kuncic 1999). Such a model can also further explain weak, low-velocity absorption outflows in Seyfert galaxies; these outflows are clearly low-luminosity counterparts to the BAL features in quasars. Again, such outflows are difficult to explain with evolution models in which the outflow is triggered by a merger; this is simply not the case for Seyfert galaxies with BAL-like outflows.

Owing to the small number of BALQSOs in our sample, our conclusions are tentative, and, clearly, larger samples are needed in order to verify our results. Ongoing intensive surveys, such as the Sloan Digital Sky Survey, are proving to be very successful in discovering quasars in a relatively unbiased fashion, with the 2dF Quasar Survey now cataloging almost 17,000 quasars (Boyle et al. 2000), providing an ideal basis for such studies.

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Note added in proof.—Recently, C. J. Willott, S. Rawlings, & J. A. Grimes (*ApJ*, in press [2003; astro-ph/0308192]) presented a submillimeter study of BALQSOs that agrees with the conclusions presented in this Letter.