ISO observations of the radio-loud BALQSO 1556+3517[*]

J. Clavel

ISO Science Operations Center, Astrophysics Division, ESA Space Science Department, P.O. Box 50727, E-28080 Madrid, Spain

Abstract. To date, the quasar 1556+3517 is the only radio loud Broad Absorption Line QSO (BALQSO; Becker et al. 1997). This prompted narrow band filter imaging observations in the range 4–15 μ with the ISO satellite. The source is clearly detected in all filters and appears point-like and isolated at the resolution of ISO. The overall Spectral Energy Distribution (SED) in erg s^{-1} peaks at a rest wavelength $\geq$ 6 μ and is reddened by 1.6 visual magnitudes. Correction for reddening brings 1556+3517 within 1.3 sigma from the log R = 1 dividing line between radio-loud and radio-quiet sources. The mid-IR luminosity integrated over the 1.8–6 μ rest wavelength range is $\sim 2\,10^{46}$ erg s^{-1} (H$_0$ = 75 km s^{-1} Mpc^{-1}, q$_0$ = 0), which requires at least 4 M$_\odot$ of dust and 800 M$_\odot$ of associated gas. It is unlikely that such a large mass stems from the BAL wind itself.

Key words: quasars: absorption lines – quasars: individual: 1556+3517 – infrared: galaxies

1. Introduction

Broad Absorption Lines (BAL) quasars constitute about $\sim$ 10 % of the overall quasar population. Observationally, they are characterized by very broad (0.1 c at zero intensity) and blue shifted absorption lines mostly from highly ionized species such as NVλ1240, CIVλ1550, ... Approximately 10 % of the BALQSO display in addition absorption lines from low ionisation species such as SiII, MgII and AlIII (Weymann et al. 1991). These are the so-called low ionisation BALQSO, or Lo-BAL. BALQSO in general are also heavily absorbed in the X-rays (Green & Mathur 1996) though it is not clear that the hot and highly ionized gas needed to produce the ionization edges seen in the keV range is the same as that which produces the UV and optical absorption troughs.

The BALQSO phenomenon is poorly understood theoretically. In particular, its relation to the general QSO phenomenon is unclear. There are basically two classes of models: in the first class, BALQSO represent a transitory "cocoon" phase in an evolutionary process whereby a temporary excess of accretion fuel is expelled by radiation pressure from the central engine through a wind (Voit, Weymann & Korista 1993). This model predicts that eventually BALQSOs will evolve into "normal" quasars once the excess gas has been removed. In the second class of models, BALQSO are normal quasars but viewed at a particular inclination such that our line-of-sight intercept a wind of material blown-off the surface of the accretion disk or the top of the molecular torus (e.g. Murray et al. 1995). Spectropolarimetric observations tend to support this second hypothesis in that they often reveal significantly polarized emission which is best explained by the scattering of a partially obscured but otherwise normal quasar spectrum (e.g. Wills et al. 1992, Cohen et al. 1995, Hines & Wills 1995, Goodrich & Miller 1995 . . .). The fact that the emission lines and continuum properties of BALQSOs are indistinguishable from that of non BAL QSOs (Weymann et al. 1991) also lend credit to the viewing direction hypothesis.

An intriguing and important property of BALQSOs is that, up to now, there were no known radio-loud broad absorption line quasars (Stocke et al. 1992). The criterion commonly used for radio-loudness is $\log R \geq 1$, where R is the K–corrected ratio of 5 GHz to 4400 Å (B Band) flux (Stocke et al. 1992). There is some intriguing suggestion that BALQSOs show an excess of radio emission over non-BALQSOs such that there is an apparent accumulation of BALQSOs close-to but slightly below the log R = 1 dividing line (Francis, Hooper and Impey 1993).

The quasar 1556+3517 (z = 1.48) was recently discovered in the course of the FIRST VLA radio survey (Becker White and Helfand 1995). 1556+3517 belongs to the Lo-BAL class, and, with $\log R$ = 3.1, unambiguously qualifies as the first and so far only radio-loud BALQSO (Becker et al. 1997). Because it holds the promise of shedding light on the radio-loudness/BALQSO dichotomy and, by extension, on the difference between radio–loud and radio–quiet quasars, I initiated a program to observe 1556+3517 in the mid-IR with the ISO satellite (Kessler et al. 1996). One particular aim was to obtain a better estimate of the amount of dust on the line of sight to the QSO and check that 1556+3517 remains radio-loud even

after reddening correction. Another was to verify the prediction that Lo-BAL QSO in general are heavily obscured. More generally, it is important to measure the spectral energy distribution (SED) of BALQSO over as wide a frequency range as possible in order to compare it to that of non-BAL QSO in the hope of finding differences that hold clues to the origin of the BAL phenomenon.

2. Observations and data reduction

The quasar 1556+3517 was observed with the 32×32 px long wavelength (LW) array of the ISOCAM instrument (Cesarsky et al. 1996) on board the ISO satellite (Kessler et al. 1996). The observation was executed nominally with the C01 observing mode (AOT) on 14 March 1997 (revolution 484), starting at 06:17:10 (UT) and lasting 46 minutes and 26 second. It consisted of a series of 3×3 raster maps centered on the optical position of the QSO (R.A. = 15h 56m 33.8s, Dec = 35° 17′ 58″, epoch = J2000), with one map per filter. The magnification selected was 3″ per pixel and the distance between two raster points was 6″. The axis of the rasters were oriented parallel to the celestial North and East. The number of exposures per raster dwell point was 19, with a unit integration time of 2.1 s per exposure and an amplifier gain of 2. The 6 filters used were, in sequential order: LW3 [12–18 μ], LW2 [5–8.5 μ], LW9 [14–16 μ], LW8 [10.7–12 μ], LW7 [8.5–10.7 μ] and LW1 [4–5 μ], where the numbers in brackets refer to the wavelength range covered by each of the filter. This sequence corresponds to decreasing pixel illuminations such that it minimizes the detector stabilization time.

The six monochromatic maps were processed with the CAM Interactive Analysis (CIA) Software [1] starting from the Edited Raw Data (ERD). The first few ($\sim$ 4) exposures of each frame were discarded so as to retain only those data for which the detector throughput had reached 90 % of its stabilisation level. The remainder of the processing was standard and involved the usual steps, i.e. dark current subtraction, flat-fielding, removal of particle hits ("de-glitching") and flux calibration. The source is clearly detected in all six maps at a very high significance level (e.g. 63 sigma for the LW3 map). The 12–18 μ map is shown in Fig. 1 as an example.

The monochromatic intensities were computed by integration of the flux in a 6 px radius (18″) circle centered on the source and subtraction of the normalized background integrated in an annulus of 8 and 13 px internal and external external radii, respectively. The results are displayed in Table 1. The errors quoted derive mainly from the uncertainty in the calibration and background, the latter being induced by residual flat-fielding errors. The full widths at half maximum (FWHM) of the source images were computed by fitting a two dimensional gaussian to the flux spatial distribution. The results are listed in column 5 of Table 1. For comparison, the theoretical value of the full
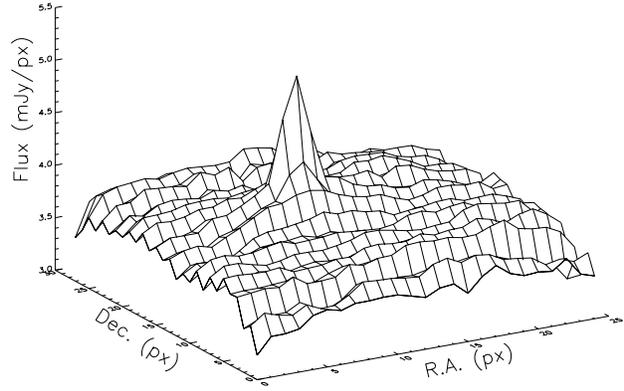
---

[1]　CIA is a joint development by the ESA Astrophysics Division and the ISOCAM Consortium led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matiere, C.E.A., France.
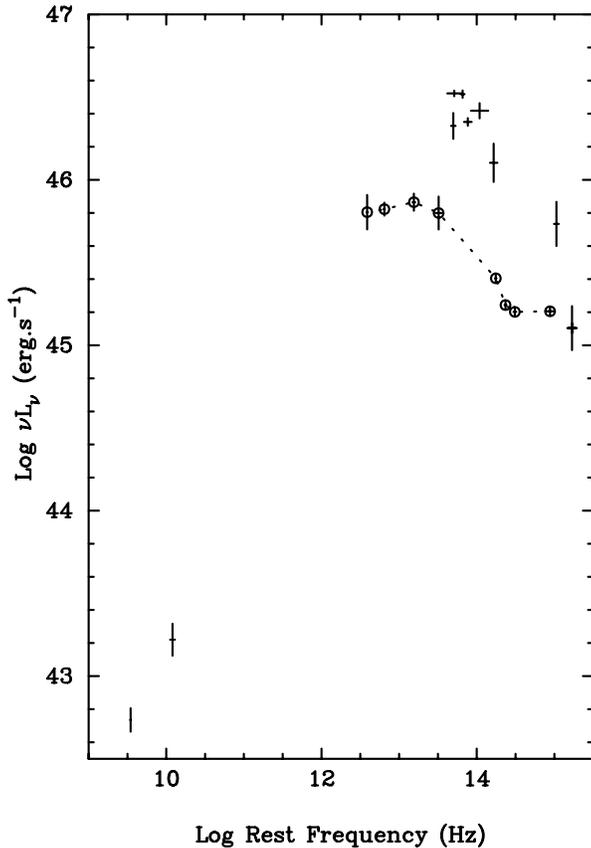

Fig. 1. The 12–18 μ map of the field around the quasar 1556+3517; the size of the map is 75×84 ″ and the scale 3 ″ px^{-1}.

Table 1. Monochromatic mid IR fluxes of 1556+3517

LW	$\Delta\lambda$ (μ)	$\bar{\lambda}_{rest}$ (μ)	Flux (mJy)	FWHM (″)	Limit (μJy/□)
1	4.00–5.00	1.81	1.5 ± 0.4	3.5 ± 1.0	14
2	5.00–8.50	2.75	4.7 ± 0.5	3.0 ± 0.4	8
7	8.50–10.7	3.90	5.7 ± 0.3	2.9 ± 0.5	11
8	10.7–12.0	4.56	9.8 ± 0.5	3.2 ± 0.6	20
3	12.0–18.0	5.85	12.7 ± 0.5	4.3 ± 0.5	8
9	14.0–16.0	6.01	8.3 ± 1.5	3.9 ± 1.0	18

width at 41 % of the maximum intensity of a diffraction limited telescope of diameter D is $\frac{\lambda}{D}$, i.e. 0.343 λ (μ) in the case of ISO. This yields e.g. 5.0 ″ for the LW3 image, consistent with the value in Table 1. As a sanity check, the LW3 images of point sources obtained with the same pixel magnification were retrieved from the set of ISO calibration files and analysed in the same fashion, yielding FHWM = 4.4 ″, in good agreement with the FWHM of 1556+3517. For all six filters, the source width is consistent with that of a point source. Neither of the six maps show extended structures nor close-by objects at least down to the detection limits quoted in column 6 of Table 1. These limits were obtained by computing the standard deviation of the background in areas of the map well outside the image of the source.

3. Discussion and conclusions

The overall rest frame Spectral Energy Distribution (SED) of 1556+3517, from 1.5 GHz to the B band, is plotted in Fig. 2, where the optical and radio data are taken from Becker et al. (1997). All observed fluxes have been converted to rest frame luminosities $\nu L_{\nu e}$ (in erg s^{-1}) assuming H$_o$ = 75 km s^{-1} Mpc^{-1}, q$_o$ = 0 and using the standard equations (e.g. Weedman 1986):

$$L_{\nu e} = 4 \pi d^2 (1 + z) f_{\nu o} \tag{1}$$

$$d = \frac{c z (1 + z/2)}{H_o (1 + z)} \tag{2}$$

Fig. 2. The overall spectral energy distribution (SED) of 1556+3517 in the QSO rest frame from radio to ultraviolet. The SED of the IR selected BALQSO IRAS 14026+4341 is also plotted (circled symbols connected by a dotted line) for comparison.

where $L_{\nu\,e}$ is the monochromatic luminosity per unit frequency in the rest frame of the QSO, $f_{\nu\,o}$ is the monochromatic flux per unit frequency in the observer's frame, d is the distance to the QSO and the other symbols have their usual meanings.

The SED of the quasar IRAS 14026+4341 is also shown in Fig. 2 for comparison, the data being taken from Low et al. (1989). The comparison is illustrative since IRAS 14026+4341 is an IRAS discovered BALQSO with a large IR-to-optical luminosity ratio (Low et al. 1989). It is immediately apparent that, despite similar ultraviolet luminosities, 1556+3517 is almost an order of magnitude more luminous in the near to mid-IR than 14026+4341.

This presumably indicates the presence of a large amount of warm dust in 1556+3517 which causes a depression of the optical-UV continuum by reddening and an enhancement of the near and mid-IR flux because of grain thermal emission.

The 1556+3517 spectral index ($F_\nu \propto \nu^\alpha$) from the B band ($\lambda_{rest} = 0.1774\,\mu$) to the LW1 filter ($\lambda_{rest} = 1.81\,\mu$) is $\alpha = -1.99 \pm 0.25$. Using the R band ($\lambda_{rest} = 0.2826\,\mu$) flux instead yields $\alpha = -1.46 \pm 0.31$. Both indices are significantly steeper than those of "normal" non-BAL quasars. Note that only the hottest dust grains at ~ 1600 K yield a significant contri-

bution to the 1.81 μ flux. Since such a temperature is higher or equal to the grain sublimation temperature, relatively little dust thermal emission is expected at this wavelength. Hence, to a first approximation, the steep UV-to-near-IR spectral index of 1556+3517 is mostly a consequence of dust extinction.

There are two reasons why the $\alpha = -1.99 \pm 0.25$ index value should be preferred:

1. The 1774.2 Å band lies in a region relatively free of any strong emission or absorption lines. This is not the case of the 2823 Å band which is contaminated by the MgIIλ 2798 emission and absorption.
2. More importantly, the 2823 Å band is definitely enhanced by Balmer continuum (BaC) emission and blended low-contrast FeII emission lines which create a pseudo-continuum in quasar spectra often referred to as the "small–bump".

The extinction internal to 1556+3517 was therefore computed under the following assumptions:

1. The "intrinsic", i.e. un-reddened, optical-UV spectral index of 1556+3517 is -0.5. Within the uncertainty, this is equal to the mean UV spectral index $\alpha = -0.46 \pm 0.05$ of the sample of 33 high redshift ($z \geq 1$) QSOs of O'Brien, Gondhalekar and Wilson (1988) as well as to the mean optical spectral index $\alpha = -0.5 \pm 0.1$ of the large 227 QSO sample of Cheney and Rowan-Robinson (1981) or that obtained by Neugebauer et al. (1987) from their sample of 104 quasars ($\alpha = -0.4 \pm 0.04$).
2. The reddening law is as parametrized by Seaton (1979) in the optical-ultraviolet range and as tabulated by Rieke and Lebofsky (1985) from 1 to 13 μ.

Under these conditions, the amount of visual extinction internal to 1556+3517 required to steepen the power-law index from -0.5 to $\alpha = -1.99$ is given by:

$$A_v = \frac{(\alpha + 0.5)\,ln(\frac{\lambda_1}{\lambda_2})}{ln(10^{0.4\,(R_{\lambda_1} - R_{\lambda_2})})} \qquad (3)$$

where $[\lambda_1 - \lambda_2]$ is the (rest) wavelength range over which the spectral index is measured (0.177–1.810 μ in the present case) and the function $R(\lambda) = \frac{A_\lambda}{A_V}$ is the reddening law at wavelength λ. This yields a visual extinction $A_v = 1.64 \pm 0.27$ magnitudes which implies that the continuum is reddened by 4.01 magnitudes at a rest wavelength of 1774 Å but only 0.256 magnitudes at 1.81 μ. Note that the foreground galactic extinction in the direction of 1556+3517 ($l_{II} = 56.48°$, $b_{II} = 49.95°$) is only 0.05 V magnitudes and can be neglected.

After correction for extinction, the radio–to–optical flux ratio becomes $\log R = 1.50 \pm 0.23$ if the B band data are used to derive the flux at $\lambda_{rest} = 4400$ Å (K correction) and $\log R = 1.15 \pm 0.25$ if one uses the R flux instead. The two estimates differ at the 1.1 sigma level only. I therefore adopt the mean of the two $\log R \simeq 1.32 \pm 0.25$. Such a ratio is less than 1.3 sigma away from the $\log R = 1$ dividing line between radio-loud and radio-quiet quasars. One therefore concludes that the case for 1556+3517 being radio-loud is marginal, at best. It

is also worth pointing-out that de-reddening brings 1556+3517 close to the $\log R = 1$ line where data suggests that there is an apparent excess of BALQSOs over non-BALQSOs (Francis, Hooper and Impey 1993).

The near to mid-IR luminosity L_{MIR} of 1556+3517 was computed by integrating all the de-reddened rest-frame emission over the range $\lambda_{rest} = 1.81\,\mu$ to $\lambda_{rest} = 6.01\,\mu$ after subtraction of an -0.5 index power-law matching the de-reddened B band and LW1 band luminosities: $L_{MIR} = 1.9\,10^{46}\,erg\,s^{-1}$.

One can use L_{MIR} to estimate the mass of dust responsible for near to mid-IR emission in 1556+3517. The mean rest wavelength of the MIR emission corresponds to a black-body temperature of ~ 740 K. Under the assumptions that the dust grains have a mean size of $0.1\,\mu$ and radiate like black-bodies and following Rudy and Puetter (1982), I obtain a dust mass $M_d \sim 4\,M_\odot$. This should in fact be seen as a lower limit since actual grains are likely to emit less efficiently than black-body thereby requiring an even larger mass to produce the observed MIR luminosity. For a normal galactic dust–to–gas mass ratio of 200, this implies a total mass of gas of about $800\,M_\odot$.

The color temperature of the dust is higher than that of typical HII regions which suggests that it is closely associated to the active nucleus. It is therefore legitimate to ask whether the dusty gas responsible for the MIR emission could be the BAL wind itself. In the disk wind model of Murray et al. (1995), the BAL region covering factor is about 10 %, its column density $N_H \sim 10^{23.5}\,cm^{-2}$ and its inner radius is of the order of 10^{16} cm. This yields a BAL mass $M_{BAL} \simeq 3\,10^{-2}\,M_\odot$, more than 4 orders of magnitude smaller than the above estimate. Of course, there is more mass available as the wind will accumulate material over the years. For an axially symmetrical wind, the mass flow rate is given by:

$$\dot{M} = 3.33\,10^{-2}(\frac{\Omega}{4\pi})N_{23}R_{16}v_8 \quad (M_\odot\,yr^{-1}) \qquad (4)$$

where, $\frac{\Omega}{4\pi}$ is the solid angle sustained by the wind as seen from the central source, N_{23} its column density in units of $10^{23}\,cm^{-2}$, R_{16} its radius in units of 10^{16} cm, and v_8 its velocity in units of $10^8\,cm\,s^{-1}$. Assuming parameters value as in Murray et al's model yields $\dot{M} \simeq 3.3\,10^{-3}\,M_\odot\,yr^{-1}$. This implies that the BAL phenomenon should have lasted at least $\sim 250,000$ years to accumulate the MIR emitting gas. While such a value in itself is not unreasonable, there are problems with this scenario:

- On the one hand, the dust must somehow "see" the central UV source in order to retain a temperature of ~ 700 K for such a long time. However, given the mass involved and the geometry of the wind, the opacity will be extremely high and the bulk of the dust and gas will be (self-)shielded from the central source.
- This gas would presumably be at least partially ionized. Since the total column would far exceed $10^{24}cm^{-2}$, the gas would be opaque to free-free absorption and the continuum totally suppressed, contrary to what is observed.

It therefore seems unlikely that the observed MIR emission originates from the wind itself. A more plausible origin would be e.g., the molecular torus, the Narrow Line Region, or a recent burst of star formation.

References

Becker, R.H., White, R.L., Helfand, D.J. 1995, ApJ, 450, 559
Becker, R.H. et al. 1997, ApJ, 479, L33
Cesarsky, C.J. et al. 1996, A&A, 315, L32
Cheney, J.E., Rowan-Robinson, M. 1981, MNRAS, 195, 831
Cohen, M.H. et al. 1995, ApJ, 448, L77
Francis, P.J., Hooper, E.J. & Impey, C.D. 1993, AJ, 106, 417
Goodrich, R.W., Miller, J.S. 1995, ApJ, 448, L73
Green, P.J., Mathur, S. 1996, ApJ, 462, 637
Hines, D.C., Wills, B.J. 1995, ApJ, 448, L69
Kessler, M.F. et al. 1996, A&A, 315, L27
Low, F.J. et al. 1989, ApJ, 340, L1
Murray, N. et al. 1995, ApJ, 451, 498
Neugebauer, G. et al. 1987, ApJS, 63, 615
O'Brien, P., Gondhalekar, P.M., Wilson, R. 1988, MNRAS, 235, 801
Rieke, G.H., Lebofski, M.J. 1985 ApJ, 288, 618
Rudy, R.J., Puetter, R.C. 1982, ApJ, 263, 43
Seaton, M. 1979, MNRAS, 187, 73P
Stocke, J.T. et al. 1992, ApJ, 396, 487
Voit, G.M., Weymann, R.J., Korista,K.T. 1993, ApJ, 95, 109
Weedman, D.W. 1986, Quasar Astronomy, Cambridge University Press
Weymann,R.J. et al. 1991, ApJ, 373, 23
Wills, B.J. et al. 1992, ApJ, 400, 96