Red quasars not so dusty

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Abstract

Webster et al (1995) claimed that up to 80% of QSOs may be obscured by dust. They inferred the presence of this dust from the remarkably broad range of $B−K$ optical-infrared colours of a sample of flat-spectrum PKS radio QSOs. If such dust is typical of QSOs, it will have rendered invisible most of those which would otherwise been have detected by optical surveys. We used the William Herschel Telescope on La Palma to obtain $K$ infrared images of 54 B3 radio quasars selected at low frequency (mainly steep-spectrum), and we find that although several have very red optical-infrared colours, most of these can be attributed to an excess of light in $K$ rather than a dust-induced deficit in $B$. We present evidence that some of the infrared excess comes from the light of stars in the host galaxy (some, as previously suggested, comes from synchrotron radiation associated with flat-spectrum radio sources). The $B−K$ colours of the B3 QSOs provide no evidence for a large reddened population. Either the Webster et al QSOs are atypical in having such large extinctions, or their reddening is not due to dust; either way, the broad range of their $B−K$ colours does not provide evidence that a large fraction of QSOs has been missed from optical surveys.
1 Introduction

Internal and line-of-sight dust absorbs some of the light that would otherwise reach us from extragalactic objects. We can deduce the relative amounts absorbed by comparing the optical colours of objects selected at a wavelength unaffected by dust absorption (e.g. in the radio). Recently, Webster et al (1995) (hereinafter W95) found a broad range of $B - K$ colours ($1 < B - K < 8$) for flat-spectrum QSOs selected from the Parkes radio survey. They interpreted this scatter in colour in terms of dust-reddening, implying an extinction in the blue of several magnitudes for a substantial fraction of the QSOs. W95 suggested that if this extinction is typical of QSOs, it will have led to 80% of them being missed by optical surveys (and these might contribute that part of the X-ray background not yet accounted for). This has profound cosmological implications, e.g. for the space density of QSOs and its evolution with redshift (Boyle et al 1988).

However, several effects might redden the observed $B - K$ colours of QSOs. Contamination by starlight from the host galaxy, and by optical/infrared synchrotron radiation associated with flat radio spectra; variability between the epochs at which the $B$ and $K$ magnitudes were measured; and photometric errors, all need to be excluded before concluding that dust is responsible for any observed reddening. In particular, it has long been known that the optical-infrared colours of flat-radio-spectrum QSOs can be unusually red (Rieke et al 1979). The redness is in many cases due to a sharp spectral break in the optical/infrared, consistent with a high-frequency cutoff in a synchrotron spectrum (which dominates at radio wavelengths); and is in many cases not consistent with reddening due to extinction by dust (Bregman et al 1981, Rieke et al
1982). Serjeant & Rawlings (1995) have already noted that such non-thermal emission may explain the red colours measured by W95.

At low redshift, $z < 2$, a few red QSOs do exist, and dust is probably responsible for the reddening in some cases (Rawlings et al 1995). The location of the dust is unknown, but it may lie in the obscuring torus popularly invoked when explaining the diversity of appearance of active galaxies as a dependence on viewing angle (Wills et al 1992, Urry & Padovani 1995). If the torus does not have a sharp edge, some QSOs will be seen reddened rather than extinguished. Some of these reddened objects satisfy the conventional definition of a QSO, with broad emission lines in the optical (e.g. Smith & Spinrad 1980, Kollgaard et al 1995). Others have only narrow lines in the optical, but have been classified as obscured QSOs after broad $H_\alpha$ emission was discovered in the infrared (e.g. 3C22: Economou et al 1995, Rawlings et al 1995); after broad emission lines were detected in polarised light (e.g. Goodrich et al 1996, Hines et al 1995); or on the basis of X-ray properties (Stocke et al 1982, Ohta et al 1996, Almaini et al 1995). Our main interest here is in the cause of reddening of objects conventionally classified as QSOs (broad lines in the optical), since only these would have been included in W95’s sample.

There exist a number of observations which place limits on the amount of dust in such QSOs. One expects for example that significant amounts of dust would markedly affect their $U - B$ and $B - V$ colours. Schmidt (1968) found the variation with redshift of the $U - B$ and $B - V$ colours of (mainly steep-spectrum) 3CR QSOs to be consistent with that expected for a composite (power-law $S_\nu \propto \nu^\alpha$ plus emission lines) QSO spectrum, out to $z = 2$. The scatter on the relations is $< 0.2$ mag, implying rest-frame $A_V < 0.8$ mag. Smith & Spinrad
(1980) obtained optical spectra for 8 unusually red 3CR QSOs (15% of the 3CR QSOs then known) and found 7/8 to have steep straight spectra whose indices are consistent with reddening $A_V \sim 1.5$ mag. The eighth QSO (representing 2% of the 3CR QSOs) has a spectrum which steepens dramatically in the UV, consistent with considerably higher extinction. Reddening can also be estimated on the basis of the observed ratios of flux in certain emission lines of given elements. Netzer et al (1995), on the basis of Ly$\alpha$/H$\beta$ line ratios, estimated extinctions up to rest-frame $A_V = 1.2$ for a sample of 3CR and other radio-loud QSOs. Larger extinctions have been inferred on the basis of line ratios for quasars selected from the Molonglo 408-MHz survey (Baker J.C. & Hunstead 1995, 1996), but interpretation of the ratios is not straightforward (e.g. Binette et al 1993, Baker A.C. et al 1994) and considerably less extinction is implied by the small reddening of the continua; the change in slope from $\alpha = -0.5$ to $\alpha = -1$ corresponding to $A_V \approx 0.5$ mag. Boyle & di Matteo (1995), selecting QSOs in the X-ray rather than the radio, inferred from the range of optical/X-ray flux ratios a rest-frame dust extinction $A_V < 1$ mag. These limits are consistent with the small amounts of dust extinction $\sim 0.3$ mag inferred from the range of optical-UV colours of the optically-selected PG QSOs (Tripp et al 1994, Rowan-Robinson 1995). Recently, Drinkwater et al (1996) observed 11 of the redder W95 QSOs at mm-wavelengths, but failed to detect CO absorption at a level two orders of magnitude below that implied if the reddening were due to extinction. This suggests that the red colours are not due to absorption within the galaxy, although they could still be due to external line-of-sight absorption. In summary, a few red QSOs do exist at low redshift, $z < 2$ (Smith & Spinrad 1980; Kollgaard et al 1995), but the above results, particularly those of Schmidt, and of Boyle & di Matteo, suggest that
only a small fraction of QSOs is obscured by dust with rest-frame extinction $A_V > 1$ mag, and that the large dust extinctions deduced by W95 are not typical of QSOs.

Dust obscuration is likely to be more important at high redshift ($z > 3$) (Fall & Pei 1993; Mazzei & de Zotti 1996; Chini & Krügel 1994), and is probably needed to account for the form of the faint galaxy counts (Wang 1991; Gronwall et al 1995; Campos & Shanks 1997). Direct evidence for such dust comes from sub-mm spectra of high-redshift QSOs (Omont et al 1996).

Dust-obscured QSOs have also been considered as a possible source of that part of the cosmic X-ray background radiation not already attributed to known populations (Madau et al 1994, W95, Comastri et al 1995). However, this no longer appears necessary; after identification of many of the faintest ROSAT X-ray sources with low-redshift galaxies, the amplitude and spectrum of the X-ray background are adequately accounted for (Boyle et al 1995, Carballo et al 1995, Roche et al 1995, Almaini et al 1996, Griffiths et al 1996).

We have obtained $B - K$ colours and $K$ imaging of a sample of (mainly steep-spectrum) B3 QSOs, in order (a) to test the hypothesis that the red colours are associated mainly with flat radio spectra, and (b) to investigate the origin of any reddening.

2 Sample and observations

The B3 survey (Ficarra et al. 1985) catalogues sources to a radio flux-density limit $S_{408MHz} = 0.1$ Jy. 1050 of the sources (the B3VLA sample, Vigotti et al 1989) have been mapped at the VLA in A and C configurations at 1.46 GHz. Candidate QSO identifications (objects of any colour, appearing starlike
to the eye) were sought on the Palomar Observatory Sky Survey (POSS-I) red plates ($R \leq 20$). CCD images were obtained of any objects of uncertain classification, or falling within 1 mag of the POSS limit, in order to distinguish reliably between extended and starlike images. This yielded a sample of 172 QSOs, the B3-VLA QSO sample, described in detail by Vigotti et al (1997). Optical spectra were obtained for all 172. 125 were confirmed as QSOs, the remainder being stars, galaxies or BL Lac objects. The fraction of quasars fainter than the POSS-I limit depends strongly on the frequency of selection and the limiting flux of the sample; at low frequency this fraction decreases with increasing flux density (in 3CR, $S_{408\,\text{MHz}} > 5$ Jy, there are no QSOs fainter than POSS-I). Current optical investigations of the empty fields ($R > 20$) in the B3 VLA sample provide a direct constraint on the number of QSOs missed: out of 202 POSS-I empty fields with $S_{408} \geq 0.8$ Jy, 95 have been optically identified to $R \approx 23 - 24$ using various telescopes, and of these, 66 have been spectroscopically classified as radio galaxies $0.5 < z < 3.2$, and only 1 as a QSO (Djorgovski, private communication 1996). From the histogram of the magnitudes of our 125 confirmed QSOs, which starts to decline well before the POSS-I limit, we deduce that at least 90% of QSOs with $S_{408\,\text{MHz}} > 0.6$ Jy are brighter than the POSS-I limit (fig. 11 of Vigotti et al 1989). We therefore selected for study all 47 QSOs with $S_{408\,\text{MHz}} > 0.6$ Jy, and 7 with $0.5 < S_{408\,\text{MHz}} < 0.6$ Jy, in right ascension range $7 - 14^h$.

We imaged the sample of 54 B3 QSOs in $K$ (2.2 µm), with the WHIRCAM IR camera of the William Herschel Telescope on La Palma, on 5 and 6 February 1996 (Carballo et al 1997). 52 of the QSOs were detected; the other two were probably detected, but unambiguous identification with the radio source was
not possible. The error in measured $K$ is typically 0.1 mag. The observations, including QSO-subtracted photometry of the host galaxies, are reported in detail by Carballo et al (1997).

3 Results

The distribution of $B - K$ colours for the B3 QSOs is shown in Fig. 1a (that for optically-selected QSOs is shown for comparison in Fig. 1b). The $B$ magnitudes (accuracy 0.3 mag rms) were taken from the catalogue of objects on the POSS-I plates generated by the Automated Plate-measuring Machine (APM) in Cambridge (Irwin et al 1994). The distribution of $B - K$ colours for B3 QSOs is similar in breadth to that found by W95 for flat-spectrum ($S_\nu \propto \nu^{\alpha}, \alpha > -0.5$) radio-selected QSOs (their fig 1b), except for a lack of extreme red colours $B - K > 6$. As noted in the introduction, unusually-red optical-infrared colours are often associated with flat-spectrum QSOs and are probably due to non-thermal (synchrotron) emission. There are only 11 flat-spectrum sources in the B3 sample. The distribution of their colours is not significantly different from that of the steep-spectrum QSOs in the sample, although of the 6 with the flattest spectra ($\alpha > -0.3$), only one has $B - K < 3.5$.

Most of the red B3 QSOs do not have flat radio spectra. We believe that many appear red because the $K$ light includes a contribution from stars in the host galaxy. Radio-selected QSOs are usually hosted by giant elliptical galaxies, and such galaxies have current-epoch $M_v \approx -23$ ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) (Lehnert et al 1992, Dunlop et al 1993). At the redshifts of the B3 QSOs ($z > 0.4$), none would be detectable in $B$ at the POSS limit. In $K$ however, as shown in Fig.
2 (the $K - z$ Hubble diagram), such galaxies are nearly as bright as many of the QSOs are measured to be. One therefore expects significant contamination of the $K$ magnitudes by starlight. For example, for the 10 QSOs lying within 1 mag of the mean $K - z$ relation for radio galaxies, the starlight from an underlying giant elliptical with $M_V = -23$ will redden $B - K$ by a median of $\approx 1$ mag. For $z < 1$, excluding flat-spectrum objects from the comparison, the mean $B - K$ colour for this group is 3.6, compared with 2.9 for the remaining QSOs, supporting this interpretation. Further support for substantial starlight contamination in $K$ comes from the non-stellar radial profiles of many of the $K$ images of the QSOs, and from the correlation between image extension and red $B - K$ evident in Fig. 1. Image extensions were determined on the basis of deconvolution of 30 images taken on the first night, and our estimates are conservative; as well as the 14/30 noted in Fig. 1, several images show weaker evidence for non-stellar profiles (Carballo et al 1997). Images taken on the second night had poorer seeing/focus, and have not been analysed for extension.

In summary, of the 13 B3 QSOs with measured $B - K > 4$, five have extended $K$ images, two have flat radio spectra ($\alpha > -0.5$) and one has both. At least these eight, and maybe all of the $B - K > 4$ colours, may thus be attributed to starlight and/or synchrotron contamination in $K$. The sources with $B - K = 5.58$ (flat-spectrum) and 4.39 (both $K < 14$) clearly have a large excess of $K$ emission relative to other B3 QSOs at similar redshift and with comparable radio emission. The red colours of these sources lend additional support to the hypothesis that the reddening is due to an excess of $K$ light rather than a deficit of $B$ light.
Even if a few of the red colours are not due to starlight or synchrotron contamination, other causes must be explored before attributing the red colours to dust extinction. For example, a change in the QSO brightness between 1950 (B) and 1996 (K) would introduce a random error into the B – K colours. The size of this error will typically be a few tenths of a magnitude (Neugebauer et al 1979, Meusinger et al 1994, di Clemente et al 1996, Cristiani et al 1996), but variability by 1 - 2 mags on timescales of years is not uncommon (Elvis et al 1994), particularly for low-luminosity QSOs (Veron & Hawkins 1995) and both extreme blue and extreme red measured B-K colours could result. Emission lines probably have only a small effect ∼ 0.05 mag on the broad-band colours. The UV/optical lines in QSOs typically have equivalent widths ∼ 50Å (Francis et al 1991, Miller et al 1992). The Hα line might be included in the K band, but even with an equivalent width of 1000Å (e.g. Hawaii 167, Egami et al 1996), the change in K would only be 0.3 mag. Only two of the B3 QSOs observed here lie in the affected redshift range 2.05 < z < 2.50; neither has unusual B – K colour.

POSS/APM R apparent magnitudes are also available for the B3 QSOs. The B – R, R – K colours are consistent (within the errors, 0.3 mag rms each in B, R) with power-law colours -2 < α < 0. Unfortunately, the B – R and R – K colours do not allow discrimination between the effects of reddening and of different power-law slopes, because at all redshifts of interest, the reddening vectors are almost parallel to the locus of power-law colours in B – R and R – K.

There is no correlation between B – K colour and redshift, which argues against any reddening being due to line-of-sight dust outside the host galaxy. This is
consistent with the finding of Shaver et al (1991) that the observed decrease with redshift of the space density of QSOs is real and not due to intervening obscuration.

The small incompleteness of the optical identifications for B3 imposes a slight colour bias. As noted above, 10% (5) of the QSOs at this flux-density level are likely to be fainter than the POSS-I limit $R=20$, and since there is a weak positive correlation between B-K and $R$, these are likely to be red. However, there is no reason to suppose that the colours of these missed objects are due to effects other than those discussed above.

We therefore find no evidence that the redder $B-K$ colours need be attributed to dust, and the range of observed colours for the remainder, $2 < B-K < 4$, limits the amount of dust reddening in $B-K$ to $< 2$ mag, corresponding, for the extinction law of Calzetti et al (1994) to rest-frame dust extinction $A_V < 1.0$ mag ($z = 2.0$) or $A_V < 1.6$ mag ($z = 0.5$). This is a conservative limit; one would expect some of the spread in $B-K$ colours to be intrinsic. This figure is comparable to the limits on dust extinction implied by other observations discussed in the introduction.

4 Conclusions

W95 argued that the broad observed range of $B-K$ colours for flat-spectrum PKS radio QSOs was evidence for dust extinction of up to several magnitudes, and they argued that if this extinction is typical of QSOs (i.e. not confined to flat-spectrum radio QSOs), it implies that a large fraction of QSOs will have been missed by optical surveys.

We have studied a sample of 54 B3 QSOs, which are representative of QSOs
with $S_{408MHz} > 0.5$ Jy, and we find a broad range of colours $1 < B - K < 6$, similar to that found by W95. We provide evidence that for both samples of QSOs the reason for the range of colours is a variable excess of light in $K$ rather than a variable deficit in $B$. Many of the reddest QSOs in our sample have non-stellar images in $K$, consistent with underlying giant-elliptical galaxies, and indeed most of the B3 and W95 QSOs are not much brighter than one would expect giant-elliptical galaxies at similar redshift to be (Fig. 2). This suggests that contamination by starlight accounts for much of the reddening of the measured $B - K$ colours of the QSOs. In addition, our data are consistent with some of the red colours of the W95 QSOs being associated with flat radio spectra, probably due to a steep optical-infrared cutoff in the non-thermal synchrotron spectrum (Rieke et al. 1979, Rieke et al. 1982, Serjeant & Rawlings 1995); we detect no QSOs with $B - K > 6$, whereas W95 detected several. Finally, two objects which stand out as being particularly luminous in $K$ are also very red. We conclude from these results that the red colours of at least the B3 QSOs are due to additional light in $K$ (starlight or synchrotron radiation) rather than a deficit in $B$ due to dust extinction. Either the red colours of the W95 QSOs are due to the same effects and dust extinction is not important (we incline to this view), or the W95 flat-spectrum QSOs are not typical in this respect. The spread of $B - K$ colours of radio QSOs does not provide evidence for a large ‘missing’ population of extinguished QSOs.

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**Figure captions**

Fig. 1 - Distributions of $B - K$ colours for:

(a) Radio-selected B3 QSOs, this paper. ‘Extended’ indicates that the K image is significantly extended. ‘Flat-spectrum’ indicates radio (0.4 - 1.5 GHz) $\alpha > - 0.5$. Two of the objects marked ‘extended’, with $B - K = 3.5$ and 4.5, are also flat-spectrum. The two objects for which the K identification is ambiguous have been omitted from this diagram (and from Fig. 2). This distribution is consistent with that found for a smaller sample of (mainly steep-spectrum) Parkes QSOs by Dunlop *et al* (1989).

(b) Optically-selected LBQS QSOs, from W95. This distribution is similar to that found for other optically-selected samples of QSOs e.g. that of Elvis *et al* (1994).
The difference in the $B - K$ distributions of radio-selected and optically-selected samples is due mainly to the effects of apparent-magnitude and colour selection on the latter. The dashed line superimposed on Fig 1b indicates the colour distribution of the B3 QSOs after imposing a cutoff $B < 19$ (similar to the limiting magnitude of the LBQS sample). Optical quasar samples are typically selected on the basis of colour as well, which imposes a further bias. For example, LBQS QSOs, with which W95 compared their data, are selected on the basis of blue optical colour (Hewett et al 1995).

(The $B$ passbands used for the samples of Fig 1a and 1b are slightly different, but the effect on the measured B-K colour is small, < 0.1 mag for most of the QSOs.)

Fig. 2 - $K$ apparent magnitude vs redshift for the B3 QSOs. The number marking the location on the plot of each QSO is its $B - K$ colour. Circles indicate B3 QSOs with extended $K$-band images. Underlining indicates B3 QSOs with flat ($\alpha > -0.5$) radio spectra. The curves ‘B2/6C’ and ‘3CR’ show the mean $K - z$ relations for B2/6C and 3CR radio galaxies (Eales & Rawlings 1996). The former is similar to that for non-evolving giant elliptical galaxies. The dashed curve is the mean of those for B2/6C and 3CR; the dotted line indicates the apparent mag of radio galaxies 2 standard deviations (1.0 mag) brighter than this mean. The median 408-MHz flux density of the B3 QSO sample is 2 Jy, close to that of the B2/6C sample. The curve ‘Sbc’ shows the locus for typical Sbc spiral galaxies (spectra from Pence 1976 and Aaronson 1978). Crosses represent measurements for QSOs from Elvis et al (1994).
(a) B3 radio-selected quasars

(b) LBQS optically-selected QSOs.
