LIMITS ON DUST EXTINCTION IN B3 QSOS

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Abstract. The broad range of optical–infrared colours of radio QSOs, $1 < B - K < 6$, has been cited as evidence for several mag of dust extinction (Webster *et al.*, 1995). If such large extinctions are typical, the implications for our understanding of the space density of optically selected QSOs are profound. We have previously found that the host galaxies of several of the reddest B3 QSOs are readily detectable in K-band images. This suggests contamination of the K apparent magnitudes by starlight, i.e. the redness in $B - K$ may be due to excess light in K, rather than to dust extinction of the B light. We have now imaged the B3 QSOs in $UBVR$, and we use the range of observed optical and optical–IR colours to place an upper limit on the amount of dust extinction present, rest-frame $A_V < 1.5$ mag.

1. Introduction

The fraction of QSOs significantly extinguished by internal or line-of-sight dust is unknown. Optical selection discriminates against such QSOs. Selection in the radio should avoid this bias. Webster *et al.* (1995) found the colours of Parkes radio-selected QSOs to range between $1 < B - K < 8$, and they interpreted this in terms of dust extinction A_V of up to several mag. Benn *et al.* (1998) measured the $B - K$ colours of a sample of B3 QSOs and found these also to range widely, $1 < B - K < 6$, but showed that some of the reddening is due to an excess of light in K, from host-galaxy starlight, rather than a dust-induced deficit in B. Here we investigate the shapes and slopes of the optical–IR spectra, in order to place a limit on the range of extinctions which may be present.

2. The B3 QSO Sample

The B3 survey (Ficarra, Grueff and Tomassetti, 1985) catalogues sources with radio flux-density $S_{408\ MHz} > 0.1$ Jy. 1050 of the sources (the B3VLA sample, Vigotti *et al.*, 1989) have been mapped with the VLA in A and C configurations at

Astrophysics and Space Science **276:** 1037–1040, 2001.

1.46 GHz. Candidate QSO identifications were sought on the Palomar Observatory Sky Survey (POSS-I) red plates ($R \leq 20$). CCD images were obtained of any object of uncertain classification, or falling within 1 mag of the POSS-I limit, in order to distinguish reliably between extended and starlike images. This yielded 172 QSO candidates, described in detail by Vigotti *et al.* (1997). Optical spectra were obtained for all except 35, whose redshifts were available from the literature. 125 of the 172 were confirmed as QSOs, the remainder being stars, galaxies or BL Lac objects. These 125 constitute the B3 QSO sample.

The fraction of quasars fainter than the POSS-I limit depends strongly on the frequency of selection and on the limiting flux of the sample; at low frequency this fraction decreases with increasing flux density (in 3CR, $S_{408\ MHz} > 5$ Jy, there are *no* QSOs fainter than POSS-I). Our subsample of 52 QSOs with $S_{408\ MHz} > 0.3$ Jy is believed to be 84% optically complete (Vigotti *et al.*, 1997).

3. Observations

Images of the 52 QSOs in the K band were obtained at the William Herschel Telescope (Benn *et al.*, 1998; Carballo *et al.*, 1998). The QSOs were imaged through U, B, V and R filters at the 1 m Jacobus Kapteyn Telescope on La Palma and at the 2.2 m Telescope on Calar Alto (Carballo *et al.*, 1999). Nearly all images were obtained in photometric conditions.

4. Limit on Extinction from *U-R, R-K* Colours

Figure 1 shows the distribution of optical ($U - R$) and optical–infrared ($R - K$) spectral indices for the B3 QSOs. Most of the QSOs have optical and optical–infrared spectral indices which are similar within the errors, i.e. the spectra are approximately straight with a range of slopes which may be intrinsic or which may be caused by dust reddening.

As noted by Benn *et al.*, there is a correlation between red $R - K$ spectral index and detection of host galaxies in the K images, suggesting that some of the K emission is starlight. The arrows indicate the effect on the $R - K$ colours of subtracting the estimated contribution from the galaxy.

The effect of typical dust-extinction laws (e.g., Calzetti, Kinney and Storchi-Bergmann, 1994) is to steepen the slope of a power-law spectrum, with negligible curvature being induced redward of 1500 Å rest-frame. The lack of curvature in the observed B3 QSO spectra therefore does not place a limit on the amount of dust present. The range of slopes, however, does place a limit.

Nobody knows what extinction law is appropriate for QSOs. The nature of the dust is unknown, and the wavelength dependence of the extinction depends on the relative distribution of light sources and dust. For example, the extinction curve

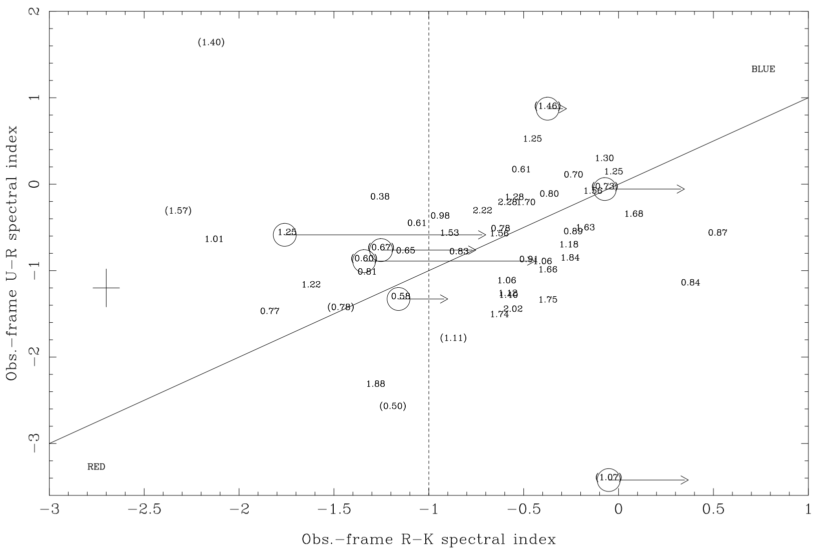

Figure 1. Optical ($U - R$) vs. optical-infrared ($R - K$) spectral indices for the 52 B3 QSOs. The numbers indicate the measured redshifts of the QSOs. *Circles* indicate the seven QSOs for which there is strongest evidence of extended K-band emission on images taken with the WHT and with the Calar Alto 3.5 m. The errors in the colours are mostly < 0.1 mag, indicated by the sample error bars (*left*). Parentheses indicate inaccurate photometry (errors > 0.3 mag rms). The *solid line* indicates $\alpha_{U-R} = \alpha_{R-K}$, as expected for power-law spectra before *or* after reddening by typical dust-extinction laws. The 16 QSOs redward of the *dashed line* indicating $\alpha_{R-K} = -1$ include the 13 noted by Benn *et al.*, as having $B - K > 4$. The arrows indicate the effect on the $R - K$ colours of subtracting estimated host-galaxy light.

derived by Calzetti *et al.* (1994) for starburst galaxies, which have light sources and dust mixed, rises more slowly in the UV than the corresponding law for our own Galaxy, whose sources of light effectively lie behind a screen of dust. A screen model is plausible for the extinction suffered by QSO light grazing a galactocentric obscuring torus or during passage through galaxies lying along the line of sight (including the host galaxy). We have assumed here that any dust extinguishing the light of QSOs will steepen the optical spectral index, α, by at least as much as the Calzetti *et al.*, law ($\Delta\alpha = 1.1\ A_V$).

The $U - K$ spectral indices (Figure 1) range between $-1.6 < \alpha_{U-K} < 0$. Therefore, if all the dispersion is due to reddening caused by different amounts of dust, the *range* of dust extinctions present is $\Delta A_V = 1.5$ mag. If some of the range in colours is due to contaminating starlight or other mechanisms or the true extinction law is steeper, then $\Delta A_V < 1.5$ mag.

The intrinsic shape of the QSO spectrum is unknown, so no limit can be placed on any extinction which is common to all the QSOs in the sample, although the small upper limit on the range of extinctions implies that the amount of common extinction is small.

5. Conclusions

We have placed a limit on the amount of dust extinction in a sample of 52 B3 radio QSOs. From the range of slopes of the rest-frame spectra, we infer a range of dust extinctions $\Delta A_V < 1.6$ mag. We also confirm a correlation between red $R - K$ colour and evidence for extension on K-band images, suggesting contamination of the K-band magnitudes by host-galaxy starlight. On correcting for the estimated starlight contamination, the $B - K$ colours deredden by ~ 1.0 mag. We conclude that the large dispersion in the $B - K$ colours of radio QSOs is unlikely to be due to several mag of dust reddening.

These conclusions relate to dust extinction of the continuum emission in radio QSOs with redshifts $z = 0.5 - 2.8$. At high redshift ($z > 3$) larger amounts of dust have been inferred from the observed sharp cut-off in the number density of QSOs (Ostriker and Heisler, 1984; Fall and Pei, 1993), and from submm spectra of high-redshift QSOs (Omont *et al.*, 1996). Larger dust extinctions than measured here may also affect the *line* radiation of low-redshift QSOs, if there is dust associated with the regions emitting the line radiation (e.g. Baker, 1997).

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