Luminous $K$-band selected quasars from UKIDSS

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ABSTRACT

The largest $K$-band flux-limited sample of luminous quasars to date has been constructed from the UKIRT (UK Infrared Telescope) Infrared Deep Sky Survey (UKIDSS) Large Area Survey Early Data Release, covering an effective area of 12.8 deg$^2$. Exploiting the $K$-band excess ($KX$) of all quasars with respect to foreground stars, including quasars experiencing dust reddening and objects with non-standard spectral energy distributions (SEDs), a list of targets suitable for spectroscopic follow-up observations with the AAOmega multi-object spectrograph is constructed, resulting in more than 200 confirmed active galactic nuclei (AGN). $KX$ selection successfully identifies as quasar candidates objects that are excluded from the Sloan Digital Sky Survey (SDSS) quasar selection algorithm due to their colours being consistent with the stellar locus in optical colour space (with the space density of the excluded objects agreeing well with results from existing completeness analyses). Nearly half of the $KX$-selected quasars with $K \leq 17.0$ at $z < 3$ are too faint in the $i$ band to have been targeted by the SDSS quasar selection algorithm, revealing a large population of quasars with red $i-K$ colours. The majority of these objects have significant amounts of host galaxy light contributing to their $K$-band magnitudes, consistent with previous predictions. The remaining objects are morphologically stellar and have colours consistent with quasars experiencing Small Magellanic Cloud (SMC)-type reddening with $0.10 < E(B-V) < 0.25$. The $i-K$ colour distribution indicates that <10 per cent of the quasar population is missing from this $K$-band selected sample due to dust reddening, and comparisons with simulations strongly favour an obscured fraction of <20 per cent. Photometric redshifts and classifications are computed for the candidates that were not observed spectroscopically. For the extended objects whose colours are consistent with those of a reddened quasar, models of galaxy surface brightness profiles appropriate for each object are used to eliminate the possibility of the presence of a nuclear source bright enough for inclusion in a $K \leq 17.0$ quasar sample. The effectiveness of near-infrared colour selection of quasars has been demonstrated by this modest-sized sample, and it will only become more apparent as the amount of available data increases.

Key words: surveys – quasars: general – infrared: general.

1 INTRODUCTION

For many years, the most popular method for selecting quasar candidates has exploited the fact that their spectral energy distribution (SED) produces an excess of flux at short wavelengths compared to the blackbody radiation from stars. This UV-excess (UVX) method has been very efficient at finding ‘typical’ blue quasars at redshifts less than $z = 2$. However, it introduces an unknown bias into the samples, excluding any quasar that has an SED that departs from the assumed standard power law. Multicolour selection with relaxed morphology constraints, as employed by the Sloan Digital Sky Survey (SDSS; Richards et al. 2002), reduces this bias, but does not eliminate it. However, even the multicolour optical selection breaks down at redshifts near $z \sim 2.7$, as the stellar locus intersects the region of colour space occupied by quasars, resulting in low completeness. In addition to excluding some quasars with atypical SEDs, optical selection is incapable of selecting quasars experiencing even a small amount of dust reddening, as passbands at the shorter wavelengths are significantly affected by dust attenuation.

A complete census of quasar activity over cosmic time is essential for understanding galaxy formation and evolution, as evidenced by

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the intimate relation between properties of the central black hole and those of its host galaxy. However, due to the large range in quasar SED properties, no single observational selection encompasses the entire diverse population. Although it is fairly well established that at least some of the differences in SED appearances are due to dust reddening, there is no consensus regarding whether these differences can be explained in the context of a unified model or whether they are a consequence of evolution throughout a quasar’s lifetime.

The existence of heavily dust obscured quasars is not contested, but the debate regarding the fraction of quasars missing from existing samples due to dust extinction is ongoing, with results ranging from ∼15 per cent (Richards et al. 2003) to 60 per cent and higher (see, for example, White et al. 2003; Glikman et al. 2007). A key question is whether the obscured fraction is luminosity dependent, the answer to which would provide important constraints within which any successful scenario would be required to fit.

In order to determine the fraction of optically obscured luminous quasars, a successful experiment must cover large areas to interesting magnitude limits, at wavelengths for which dust extinction is not severe. Deep X-ray studies are capable of detecting all but the most heavily obscured quasars, but their small areas are insufficient for finding the relatively rare, luminous quasars in statistically significant numbers. The Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) essentially covers the entire sky, but the bright magnitude limits restrict the detected population to all but the most luminous quasars, or those very nearby. The new generation of near-infrared (NIR) wide field surveys provides the opportunity to define a sample of quasars, to interesting flux limits, that is sensitive to objects experiencing moderate amounts of dust reddening.

Analogous to the UVX seen at shorter wavelengths, there is an equivalent excess in the $K$-band for quasars compared to stars (Warren, Hewett & Foltz 2000), as illustrated in Fig. 1. Both top and bottom panels of Fig. 1 show quasars overplotted with stars of similar $g-J$ colours, but in each case the quasar exhibits a clear $K$-band excess (KX), even when the quasar is reddened by dust. This illustrates the power of the KX method as it is insensitive to colour changes due to reddening.

There have been two studies to date employing KX selection of quasars: the first by Croom, Warren & Glazebrook (2001) and the second by Sharp et al. (2002). Although pioneering in nature, the limited areal coverage, 48 arcmin$^2$ and 0.7 deg$^2$, respectively, restricts the effectiveness in constraining the fraction of reddened quasars.

The current work combines optical imaging and spectroscopy from the SDSS, new NIR imaging from the UKIRT (UK Infrared Telescope) Infrared Deep Sky Survey (UKIDSS) project and optical multi-object spectroscopy using the new AAOmega spectrograph to create a well-defined sample of luminous quasars, flux-limited in the $K$ band to $K ≤ 17.0$, covering 14 deg$^2$. Close to 100 per cent identification success is required for the entire sample of quasar candidates in order to place meaningful restrictions on the fraction of optically obscured quasars. For the objects observed spectroscopically, secure classifications are generally straightforward to achieve. For the candidates without spectra, a combination of photometric identifications/redshifts, determined using $ugrizYJHK$ photometry, and morphological properties in both the optical and NIR, are employed to provide classifications of high reliability.

The experiment is deliberately set up to undertake as comprehensive a survey as possible with no regard to the question of efficiency. The rationale for such an approach is that it has not been previously demonstrated that an efficient survey that was also highly effective at selecting quasars could be undertaken using this particular combination of optical and NIR data.

The outline of the paper is as follows. Section 2 describes the selection criteria used to create the sample to be observed spectroscopically. The spectroscopic data are presented in Section 3, along with a description of the photometric redshift determination used to classify candidates not observed spectroscopically. Section 4 presents the composition of the new $K$-band selected sample of objects, focusing on the quasars and the few spectra that could not be reliably classified. A comparison of the $K ≤ 17.0$ quasar sample with the $i$-band limited SDSS quasar catalogue is given in Section 5, along with a discussion of the new quasars that possess unusual SEDs. A discussion of the significance of the results and a comparison with previous predictions appears in Section 6, with a summary following in Section 7. Appendix A contains an analysis of the accuracy of the photometric redshifts used, and Appendix B contains a description of the non-quasars identified in the sample. Concordance cosmology with $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ is assumed throughout. Magnitudes on the Vega system are used throughout the paper, with the SDSS $AB$-magnitudes converted to the Vega system using the relations: $u = u_{\text{AB}} - 0.93, g = g_{\text{AB}} + 0.10, r = r_{\text{AB}} - 0.15, i = i_{\text{AB}} - 0.37$ and $z = z_{\text{AB}} - 0.53$, as described in Hewett et al. (2006). Unless otherwise specified, the point spread function (PSF) magnitudes are used for the SDSS $ugriz$ bands, and the aperture corrected aperMag3 magnitudes are used for the Wide Field Camera (WFCAM) $YJHK$ bands.

2 SAMPLE DEFINITION

2.1 UKIDSS

UKIDSS (www.ukidss.org; Lawrence et al. 2007) is a set of five separate surveys with complementary combinations of areal coverage and depth. Observations are carried out on UKIRT with WFCAM (Casali et al. 2007). The Large Area Survey (LAS) is the largest of
the surveys, and will cover 4000 deg$^2$ in $YJHK$ to a 5$\sigma$ limit of $K = 18.2$, i.e. $\simeq$3 mag fainter than 2MASS. There have been three data releases to date, with the Early Data Release (EDR, 2006 February; Dye et al. 2006), Data Release 1 (DR1, 2006 July; Warren et al. 2007a) and Data Release 2 (DR2, 2007 March; Warren et al. 2007b), containing 27.3, 189.6 and 282 deg$^2$, respectively, of coverage in the full set of $YJHK$ bandpasses for the LAS. Data are accessed via the online WFCAM Science Archive (WSA; Hambly et al. 2008). The LAS lies within the SDSS footprint and each detected object will potentially possess $ugrizYJHK$ photometry plus extensive morphological information. With such a wealth of information available, a relatively sophisticated approach to the definition of object samples for further study is possible.

2.2 Initial sample definition

Our study employs the UKIDSS EDR data base and SDSS DR4 to define a flux-limited object sample with $K \leq 17.0$. A list of objects possessing measured $K$-band magnitudes was extracted from the UKIDSS EDR and matched to the DR4 data base using a matching radius of 2.0 arcsec, resulting in two subsamples: one consisting of objects detected in both UKIDSS and SDSS, and one with objects detected only in UKIDSS. The matching objects with both sets of data comprise the main sample to be used for further analysis, but both the matched and UKIDSS-only object lists were retained.

The astrometric consistency between the SDSS and UKIDSS is better than 0.5 arcsec, and virtually no real matches are missed with a 2 arcsec match radius. At matching radi $> 1$ arcsec, false matches dominate, but an empirical determination of the frequency of false positives shows that less than 1 per cent of the matches are coincidental.

2.3 Quality cuts

A magnitude limit of $K \leq 17.0$ was applied to both the matched and unmatched object lists, the point at which the UKIDSS photometric errors begin to increase significantly. For $K \leq 17.0$, the error in the $K$-band magnitude is $\sigma_K \leq 0.1$. A measured magnitude in the $J$ band was also required of each object, effectively imposing a $J$-band magnitude limit of $J \leq 19.6$. Objects detected within 64 pixel of the WFCAM chip edges were also removed as there are a large number of spurious sources in these regions. A particularly effective method of removing false UKIDSS detections is to cut out the regions immediately surrounding bright stars and nearby galaxies. To obtain a list of such objects, the 2MASS Point Source and Extended Source Catalogues were queried for the areas of interest. Circular regions of radius 1 arcmin around stars brighter than $K = 9.5$ were cut out, as were regions around galaxies of $K < 12.0$ with their size determined by the 2MASS-catalogued total radius. The noise morphological classification provided by the UKIDSS pipeline also eliminates a small number of unmatched objects, but was not applied to the matched list.

The local sky variance values, provided in the UKIDSS data base, for each detection is an indicator of photometric quality. A histogram of the measured variances for a given region displays a dominant, near Gaussian, component with an extended tail toward large values. Objects with sky variance values located in the tail lie in regions affected by poor sky subtraction/determination, confirmed by visual inspection of the images. Objects in the tail are excluded from the $K$-band flux-limited sample because their photometry is adversely affected by the sky-background uncertainties, which result in a noticeable broadening of the stellar locus. There remain a few objects whose sky variance values are not extreme but whose WFCAM images indicate poor sky subtraction, such as objects located within the very extended haloes of bright stars. There was no obvious method for removing these objects without excluding significant areas of sky, so no further cuts were imposed.

After all of these quality cuts, the remaining objects in the matched list have good quality UKIDSS and SDSS photometry covering $ugrizYJHK$, along with morphology classification, and in the case of a few objects, SDSS spectra. Table 1 lists the number of matched and unmatched objects that remain in the sample following the series of cuts for a typical 1.5 deg$^2$ area of sky.

The UKIDSS-only detections arise from several sources. First, there are objects where the form of the SED is such that they are detected in the $K$ band but not in $ugriz$. Reddened quasars, L and T dwarf stars and elliptical galaxies above $z > 1$ are examples of such populations. Alternatively, the UKIDSS-only detection could be spurious, as occurs frequently in the haloes of bright stars or the outer regions of large, nearby galaxies. Another common source of UKIDSS-only detections arises from cross-talk between the detector channels. For bright stars, cross-talk produces spurious images located at integer multiples of 128 pixels from the star in all bands (see Dye et al. 2006 for further explanation and examples). Asteroids also contribute significantly to the UKIDSS-only population, but are easily identified by shifts in position between the $K$- and $H$-band images, which are always taken sequentially. For a small percentage of sources, the SDSS photometric catalogue (PhotoObj) is incomplete, with an object clearly visible in the SDSS imaging at the location of the UKIDSS detection, but no photometry entry exists in the SDSS catalogue. Finally, pairs of objects with very small separations are occasionally segmented differently by the UKIDSS and SDSS photometric pipelines, producing mismatching entries in either the SDSS or UKIDSS photometric catalogues. Objects from these five sources of spurious images dominate the UKIDSS-only population, comprising $\sim$98 per cent of the total. Our primary goal of constraining the number of heavily reddened quasars relies on identifying real UKIDSS-only detections. In order to achieve the goal, both the UKIDSS and SDSS images at the location of the UKIDSS-only detections were extracted from the data bases and inspected visually. The exercise was time consuming but resulted in the elimination of all but the few objects for which the UKIDSS detection is unambiguous and the SDSS image shows no hint of a detection.

### Table 1. Number of objects that remain after each cut for a typical 1.5 deg$^2$ area of sky.

| Cut                        | Matches | Unpaired |
|----------------------------|---------|----------|
| Initial sample             | 13,404  | 1,100    |
| $11.5 < K < 17.0$          | 5,618   | 218      |
| Remove bright stars/galaxies| 5,763   | 99       |
| Large sky variance         | 5,554   | 58       |
| Require $J$ and $K$         | 5,536   | 58       |
| Right of selection line    | 2,335   | 58       |
| Centrally concentrated     | 1,378   | 58       |
| MergedClassStat <35        | 1,214   | 58       |
| Visual inspection          | 1,214   | 1        |
| Stellar                    |         |          |
| Extended                   |         |          |
| Final catalogue            | 33      | 1,182    |

1 http://surveys.roe.ac.uk/WSA/pro/index.html
2.4 Final sample and quasar candidates

The final $K$-band flux-limited sample of objects can be plotted on an optical–NIR colour–colour diagram, exploiting the $KX$ of quasars. Fig. 2 shows a $g-J$ versus $J-K$ (hereinafter $gJK$) diagram for one $\sim 1.5$ deg$^2$ field suitable for follow-up observation with the new dual beam, multi-object AAOmega spectrograph (Saunders et al. 2004) instrument on the Anglo-Australian Telescope (AAT). Stars, which make up the majority of the sample, are confined to a well-defined locus, as indicated by the black dots. The purple dashed line is the selection boundary, described by

$$g - J = \begin{cases} 4(J - K) - 0.6 & \text{for } J - K \leq 0.9, \ g - J \leq 3, \\ 33.3(J - K) - 27 & \text{for } J - K > 0.9, \ g - J > 3. \end{cases}$$

Objects to the left of the line are eliminated, with objects to the right considered to be a quasar candidate. The position of the selection line along the $J - K$ axis varies slightly from field to field (the hinge point changes from $J - K = 0.9$ to $J - K = 1.0$) to account for variation in photometric quality. The stellar locus is broader in fields with poor photometry, forcing the selection line rightward to prevent the quasar sample from being overwhelmed by stars scattered across the selection boundary.

The blue track follows the $gJK$ colours for a parametric quasar model, the components of which have been optimized to reproduce the $ugrizYJHK$ colours of the matched SDSS–UKIDSS spectroscopic quasar sample over $0.0 < z < 4.8$. The model is similar to that described in Maddox & Hewett (2006, section 2.2), with some alterations. The power-law component is now described by $\alpha = -0.54$ for $\lambda < 2750 \, \text{Å}$, and $\alpha = 0.041$ for $\lambda > 2750 \, \text{Å}$, where $F(\nu) \propto \nu^\alpha$. The upturn at NIR wavelengths is provided by a black-body with temperature $1775 \, \text{K}$, similar to the composite spectrum of Glikman, Helfand & White (2006). For the model to match the median colours of matched SDSS–UKIDSS quasars at low redshifts (Chiu et al. 2007), flux from an Sb-type host galaxy is included. The contribution from the host galaxy decreases rapidly at increasing redshift. The red track follows the $gJK$ colours for a model elliptical galaxy as described in Mannucci et al. (2001) for $0 < z < 2.0$. The ‘star’ symbols on both the quasar and galaxy model tracks indicate redshift zero.

Use of the $g$-band in the colour selection restricts the redshifts accessible by this technique to $z < 4$, as there is little flux falling within the $g$-band for higher redshift objects. This effect is evinced in Fig. 2 by the model quasar track rapidly becoming very red in $g - J$. The two-colour selection technique can be easily extended to higher redshifts by using redder optical passbands, for which the diagrams are similar.

The objects in Fig. 2 are segregated by their UKIDSS and SDSS morphological classifications into unresolved and resolved sources. The SDSS morphology is determined by the difference between the PSF and the cmodel magnitudes, whereas morphology classification for UKIDSS data is derived from the flux curve-of-growth of each object. Blue crosses are candidates with point source morphology as determined by both UKIDSS and SDSS, which constitute only a small fraction of the initial sample, and are assigned the highest observing priority value of 9. Quasars included in the SDSS DR3 quasar catalogue (Schneider et al. 2005) were also specifically included as targets for observation. Six objects with secure UKIDSS identifications and no SDSS counterpart were also assigned high observing priority.

In Fig. 2, red dots indicate candidates with extended morphology. As quasars reside in host galaxies, which may contribute significantly to the total flux from the object at longer wavelengths (Maddox & Hewett 2006), extended objects should not be simply excluded. As the goal of this study is to create a quasar sample to $K \leq 17.0$, it is important to differentiate between the nuclear and host galaxy flux. The WFCAM pipeline provides magnitude measurements derived from the flux falling within apertures of different radii. aperMag3 is recommended as the aperture providing the most accurate and stable measure of magnitude for a variety of objects, and includes flux to a 1.0-arcsec radius. aperMag1 is based on flux falling within the innermost 0.5-arcsec radius and provides a bright limit to the flux from any unresolved nuclear source present in resolved objects. A more sophisticated estimate of the nuclear $K$-band flux present in each resolved object is provided in Section 3.4. However, for the purposes of defining the sample for spectroscopic observation, only resolved objects with $K_{\text{aperMag3}} < 17.0$ were included (listed as ‘Centrally concentrated’ in Table 1). Very extended, nearby galaxies, with UKIDSS MergedClassStat (a measure of stellarness) >35 were also excluded.

Even after applying the restriction on nuclear flux, there are still far more extended objects than can be observed with the $\sim 300$ fibres.

\footnote{See http://www.sdss.org/dr5/algorithms/ for definitions of PSF and cmodel magnitudes.}

\footnote{Recall that aperMag3 is used to define the base $K \leq 17.0$ flux-limited sample.}
3 NEW SPECTROSCOPIC DATA

3.1 Observations

Spectroscopic observations were performed on 2006 April 30, May 1–3, at the AAT. A summary of the fields observed is provided in Table 2. The last three fields listed in Table 2 were observed in poor conditions. Spectra were obtained using the 2dF fibre positioning robot and the AAOmega spectrograph. The 580V and 385R volume phase holographic (VPH) gratings were used, providing spectral coverage 3700–5800 and 5600–8800 Å in each arm, with the two segments spliced together. The 5800 Å wide spectral coverage at resolution 1300 from 3700–8800 Å. Of the 400 fibres, eight are allocated for guide stars. 35–40 are used as sky fibres and approximately 50 fibres were broken, leaving just over 300 fibres available for science targets. 11 fields were observed in total, resulting in 3154 usable spectra spanning approximately 14.2 deg², making this study the largest K-band selected quasar survey to date by a factor of more than 20. Accounting for the area lost due to the quality cuts described in Section 2.3, and the damaged fibres outlined in Section 3.3.1, the effective area of the survey is 12.8 deg².

A subset of the fibres exhibit a fringing pattern, caused by a gap between the front end of the fibres and their retractors. The fringing is not stable, resulting in unusable spectra in some cases. In the less severe cases, object identification is still possible, but measurements of linewidths or continuum values are not. In order to reduce the impact of these fibres on the experiment, the highest priority targets (i.e. point sources) were first assigned to fibres known not to suffer from fringing. Lower priority objects were assigned randomly to the remaining fibres, which include both fringing and non-fringing fibres. Unfortunately, the available list of fibres experiencing fringing was not complete and occasionally a high priority target was assigned to a fringing fibre. The (small) number of fibres affected by fringing is listed in the last row of Table 4.

3.2 Data reduction

All spectra were reduced with the custom reduction package 2dF Data Reduction (2dFDR; Bailey et al. 2003), upgraded to handle the separate blue and red AAOmega spectrograph arms and splice the reduced spectra together. The classification routine RUNZ (Colless et al. 2001) was used in manual mode to identify the quasars, star-forming and absorption line galaxies, and stars. The classifications and redshifts for each object were determined by eye.

3.2.1 Spectra quality

The new AAOmega spectra of confirmed quasars from the SDSS DR3 quasar catalogue allow an assessment of the effectiveness of our quasar identification and provide a direct empirical determination of the AAOmega wavelength-dependent sensitivity. There does not appear to be any significant variation in wavelength response dependent on fibre location within the field, although some fields have a more consistent response than others. The last two fields listed in Table 2 had no SDSS spectral coverage at the time of observation, but the area has since been observed and included in the newly released SDSS DR5 quasar catalogue (Schneider et al. 2007). Confirmed KX-selected quasars were matched to the SDSS quasars with a matching radius of 1.0 arcsec.

As these observations were some of the first performed with AAOmega, the 2dFDR splicing routine employed to join the red and blue arms was still under development. The splicing routine was performing poorly in some cases, particularly for objects with low signal, or when an emission line was present in the joining region. The red and blue arms for each spectrum are reduced independently, and are thus available for additional manipulation in order to improve poor joins.

The SDSS spectra and the new observations can be used to determine the AAOmega spectral response and correct poor splicing. 89 such spectra exist, with 78 below $z < 2.1$. High redshift objects were excluded as the Lyα forest means there is very little flux in the blue arm. After median filtering each spectrum with a 15-pixel window to remove noise spikes but retain spectral features, the SDSS and blue arm AAOmega spectra were normalized between 4000 and 5000 Å then divided, and the SDSS and red arm AAOmega spectra were normalized between 6000 and 7000 Å then divided, to provide the red and blue response curves for each AAOmega spectrum. The median red and blue response curves for each field were then computed.

After applying the median response curves to the separate red and blue spectral arm data, the arms can be spliced together. As a test, the median response curves were applied to the original individual AAOmega spectra that have corresponding SDSS spectra. The procedure produces a significant improvement in both overall shape and in continuity across the splice region; an example is shown in Fig. 3. The median response curves were then applied to all spectra containing emission lines.

The response correction was applied after the spectroscopic classifications were performed, to provide an approximate relative flux
spectra have been median filtered using a 15-pixel window, as described in the text. Note that the telluric A and B absorption bands visible in the original spectrum more closely matches the fluxed SDSS spectrum of the quasar (bottom). The AAOmega spectra have been median filtered using a 15-pixel window, as described in the text.

Figure 3. Illustration of the effectiveness of the wavelength-dependent response correction. Top: the raw AAOmega spectrum of a quasar at \( z = 1.44 \), as produced by the 2dFDR pipeline. Middle: corrected spectrum, derived using the procedures described in the text. The continuity of the corrected spectrum in the region where the red and blue arms are spliced together (5600–5800 Å) improves significantly, and the shape of the corrected spectrum more closely matches the fluxed SDSS spectrum of the quasar (bottom). The telluric A and B absorption bands visible in the original spectrum have been removed by the response-correction process. The AAOmega spectra have been median filtered using a 15-pixel window, as described in the text.

3.3 Classification

Although many spectra allowed high confidence identifications to be made, a number of spectra were not easily identifiable due to low SNR or a lack of obvious spectral features. For the eight fields with the best observing conditions, <10 per cent of the spectra remained unclassified. When the three poorest quality fields are included, the number of unclassified spectra increases to 14 per cent. Of the 3154 new AAOmega spectra, 2728 resulted in classifications. The other 426 objects for which spectra exist but did not result in a classification are referred to as `Damaged' in Table 4. Fibres that exhibit the severe fringing, making an identification impossible. These spectra are referred to as ‘Damaged’ in Table 4. Fibres that exhibit the severe fringing, making an identification impossible. These spectra are referred to as ‘Damaged’ in Table 4.

3.3.1 Spectroscopically unclassified objects

Spectra that did not produce an identification fall into three classes. First, there are objects with anomalously low SNR spectra, given their SDSS magnitudes, due to some instrument-related problem unrelated to the intrinsic nature of the objects. These objects are distributed essentially randomly in \( gJK \) colour space, as shown by the red crosses in Fig. 4. Secondly, the fibre may be suffering from severe fringing, making an identification impossible. These spectra are referred to as ‘Damaged’ in Table 4. Fibres that exhibit the large fringing pattern were preferentially assigned to extended objects as they were considered to have lower observing priority than point sources. In a number of cases, an identification was still possible, due to strong emission lines or only mild fringing. These spectra are marked as having an identification, but they are not included in the ‘Best’ category in Table 4. The 43 low SNR spectra and 56 fringing spectra decrease the effective area of the survey by 0.4 deg\(^2\), leaving 12.8 deg\(^2\) total effective area, and are not included in subsequent analysis of unclassified spectra.

The remaining unclassified objects possess spectra of reasonable SNR but do not show any identifiable features. The location of these objects on the \( gJK \) diagram is shown by the black dots in Fig. 4. In addition to quasar and elliptical galaxy model tracks, the model track for an Sc-type galaxy from Mannucci et al. (2001) is overlaid on the \( gJK \) diagram. The unidentified objects are primarily located between the elliptical and Sc-type galaxy tracks. The redder objects cluster around the elliptical galaxy track at \( z \simeq 0.4 \). It is difficult to identify with confidence an absorption line galaxy at this redshift, as the 4000-Å break falls in the region of the spectrum where the AAOmega red and blue spectral arms are spliced together. The cluster of objects slightly bluer in \( g − J \) occupy the region of colour space dominated by star-forming galaxies at a range of redshifts. Emission lines of only moderate strength can be difficult to identify given the modest SNR of the spectra of some of the fainter objects. The few objects located at \( g − J \simeq 6.5 \) are probably faint M-type stars, whose red SEDs are difficult to identify unambiguously given the poor sky subtraction at \( >7500 \) Å in the AAOmega spectra. There are very few unclassified objects located near the quasar track for \( z < 3 \) on the \( gJK \) diagram, indicating that the identification success rate for unobscured quasars is very high.
The distribution of unidentified spectra in the $gJK$ diagram accords well with expectations. For $g - J < 3$, where the majority of objects are quasars or AGN with prominent emission lines, 823 objects were observed, 797 have classifications, nine were affected by damaged/fringing fibres, leaving only 17 objects with reasonable SNR and no classifications. For $g - J > 3$, where the majority of galaxies lie, including many with no readily identifiable emission lines, 2331 objects were observed, 1931 have classifications, 90 were affected by damaged/fringing fibres, leaving 310 with no classifications. The difference in classification success, 97 per cent ($g - J < 3$) compared to 83 per cent ($g - J > 3$) is primarily attributable to different object populations present in each colour interval. The photometric classification statistics presented in Section 3.3.2 confirm such a conclusion.

The location of an object on the $gJK$ diagram provides a clue to the classification of the object. However, there is an overlap between the location of the many galaxies and the few highly reddened [with $E(B-V) > 0.5$] quasars, at $g - J \approx 4$ and $J - K \approx 1.8$. As a consequence, we employ photometric redshift techniques, using the full $ugrizYJHK$ photometry, and the morphological information available for each object to provide high-confidence identifications for the objects without spectroscopic classifications.

### 3.3.2 Photometric redshifts

Although nearly all (93 per cent) of the stellar candidates possess spectra, thousands of extended objects with $K \leq 17.0$ could not be observed due to the finite number of spectroscopic fibres available. An additional 516 spectra obtained as part of the SDSS spectroscopic programme, consisting mostly of galaxies, are added to the 2728 of 3154 AAOmega spectra which resulted in classifications to increase the number of spectroscopically classified objects to 3244. For objects with no spectroscopic information, the $ugrizYJHK$ photometry, plus the morphological information, available for each object is used instead to provide classifications. At this stage we are interested in establishing whether the SEDs of the candidates without spectroscopic classifications are consistent with those of ordinary stars or galaxies. We return to the more ambitious goal of establishing that each of the candidates is not consistent with harbouring a reddened quasar with $K \leq 17.0$ in Section 3.4.

The SDSS has determined photometric redshifts and type classifications for every object contained within the DR5 catalogue by fitting template galaxy SEDs to the observed objects’ $ugriz$ photometry (for detailed information regarding the Phototz algorithm, see Csabai et al. 2003). The SDSS Phototz is optimized for use with galaxies, therefore, quasars and stars generally result in unreliable fits, as determined by their large $\chi^2$ and redshift error values. The results for each object identified as a potential observation candidate (objects lying to the right of the selection line in a $gJK$ diagram) were extracted from the SDSS Phototz table. An object with a good Phototz template fit, as determined by a value of $\chi^2 < 20$ or a quality flag of either four or five, can be considered to have an SED consistent with that of a normal galaxy, and not a quasar.

For the small percentage of objects which result in a poor photometric redshift fit and have no spectroscopic classification, further investigation into their possible identification is required. In a manner similar to the SDSS Phototz algorithm which uses only the optical magnitudes and galaxy SEDs, model SEDs extended to the NIR can be fit to the full suite of $ugrizYJHK$ photometry, with the expectation that the additional passbands will provide extra discriminatory power. In addition to the $YJHK$ photometry, model templates of an unreddened quasar, five reddened quasars with $0.1 < E(B-V) < 1.0$, several galaxy types and galactic stars are included in the fitting, with the aim of distinguishing between the various types of objects that may be present in the whole population, not just identifying the galaxies. For clarity, the photometric redshift results provided by the SDSS will be referred to as SDSS Phototz, and the photometric redshift results using the additional NIR photometry and quasar templates will be referred to as the NIR-extended Phototz. As a consistency check, both photometric redshift schemes were performed on the set of objects with spectroscopic identifications and redshifts to ensure reliable results are computed. The results from both schemes, when applied to the entire population of extended candidates, are also highly consistent. Plots displaying the quality of the photometric redshifts and spectral types are provided in Appendix A.

Combining the SDSS Phototz and the NIR-extended Phototz results with the new and existing spectroscopic data greatly increases the number of objects for which a confident classification exists, as for the objects with spectra, or whose colours are consistent with those of ordinary galaxies. Table 3 lists the order in which objects were identified and subsequently removed from the initial population of 11 895 objects located to the right of the selection line in the $gJK$ diagram for the 13.8 deg$^2$ area. Objects with spectroscopic identifications are considered to be the most secure, and are thus removed first. Next, objects that are classified as morphologically stellar and are classified by the NIR-extended Phototz as stars are removed. Objects with high confidence SDSS Phototz results are then removed, which includes the bulk of the remaining population. The NIR-extended Phototz removes a further five objects, leaving only 11 objects remaining without classification of any kind. The SED of one of the five objects removed is consistent with that of an unreddened quasar, and is flagged as ‘TargetQSOFaint’ by the SDSS, but was not observed spectroscopically. Inspection of the 11 remaining images reveals six of these objects to be apparent close pairs of objects for which there is only one entry in the SDSS photometric data base, one object is a saturated star and the remaining four objects are the UKIDSS-only detections, discussed further in Section 5.2.3.

Focusing on the subset of 327 objects observed with AAOmega that did not result in spectroscopic identifications outlined in Section 3.3.1, only five objects did not result in a good fit from the SDSS Phototz or the NIR-extended Phototz and are a subset of the 11 unclassified objects described above. The computed redshift distributions for the 322 classified objects span $0 < z < 1.0$, and peak at $z \approx 0.4$, consistent with the conclusions drawn from the $gJK$ plot. The type distributions, available from SDSS Phototz and the NIR-extended Phototz, contain a majority of early type galaxies, with a significant population of galaxies with a range of star formation activity. The SDSS Phototz results for these 322 objects are shown in Fig. A3 of Appendix A.

Applying the NIR-extended photometric redshift scheme to the entire population of candidates results in a significant number of unidentified objects left after each identification routine is applied.

### Table 3. Number of unidentified objects left after each identification routine is applied.

| Identification          | Removed | Remaining |
|-------------------------|---------|-----------|
| Initial sample size     | 0       | 11 895    |
| Spectral ID             | 3244    | 8 651     |
| Stellar                 | 10      | 8 641     |
| SDSS Photoz             | 8625    | 16        |
| NIR-extended Phototz     | 5       | 11        |
objects that are classified as ordinary galaxies with high confidence, but whose colours are also consistent with the reddened quasar models. The redshift distribution from the galaxy classifications is very similar to the redshift distribution of the spectroscopically confirmed galaxy population, whereas the redshift distribution from the reddened quasar classifications shows a sawtooth pattern with peaks at $z = 0.3$, 1.3 and 2.3. Based on these redshift distributions, it was assumed that in each case, the ‘galaxy’ classification was correct. However, as described in Section 3.4, the possibility of these objects harbouring reddened quasars bright enough for inclusion in a $K \leq 17.0$ sample is investigated and ruled out.

3.4 Excess nuclear flux in extended objects

As seen in Section 3.3.2, all but 11 objects of the initial 11 895 candidates possess either spectroscopic or confident photometric classifications. However, for 2249 of the objects, the photometric information is not sufficient to exclude the possibility that the object may be a reddened quasar. In this section we use a more sophisticated approach, based on the radial light profile information available in SDSS and UKIDSS for extended objects, to eliminate objects as candidate reddened quasars. Specifically, for all but a handful of objects, we show that any unresolved nuclear component present in the $K$ band is fainter than the $K = 17.0$ flux limit of our quasar sample.

We have already applied a morphological restriction to eliminate very low surface brightness galaxies from the sample targeted for spectroscopy. The selection (Section 2.4) required that the $K$-band flux from the innermost 0.5-arcsec radius satisfied $K \leq 17.0$. However, this measure includes both flux from the inner regions of the host galaxy in addition to any nuclear source that may be present. A more robust method of measuring flux from a nuclear point source that accounts for flux from the host galaxy is possible using the radial surface brightness profile information provided for each object by the SDSS and the UKIDSS data bases. For the procedure described below, the SDSS $i$-band data are chosen because the $i$-band is the reddest passband for which the SDSS imaging is of high SNR and the galaxy radial profiles in the $i$- and $K$-bands are not expected to be significantly different. Galaxy profile fits are not provided as part of UKIDSS but we use the $K$-band flux in two different apertures to constrain the nuclear flux.

For each object, the SDSS data processing pipeline fits both a deVaucouleurs and an exponential radial surface brightness profile in each photometric band, and provides the likelihood of the object being a star or a galaxy, of either profile, based on which fit best matches the data. Objects for which none of the profiles is good fit, such as merging galaxies, have very small likelihoods for all three fits. Using the SDSS $i$-band profiles, the candidate list of 11 895 objects is split into four categories: stellar, deVaucouleurs, exponential or no adequate fit. For each extended object with a good profile fit, the SDSS model profiles are blurred, using the UKIDSS $K$-band seeing, to predict the ratio of fluxes in two apertures of radii 1.0 and 2.83 arcsec, corresponding to the UKIDSS aperFlux3 and aperFlux6. In other words, based on the SDSS-provided model profile fits and the $K$-band seeing, it is straightforward to predict the aperture flux ratio of a galaxy with no additional central point source. Then, using the measured $K$-band values of aperFlux3 and aperFlux6, a central flux excess with respect to the predicted value can be computed. The excess flux, if present, may be converted to an excess magnitude (including appropriate aperture and zero-point corrections), and if this excess magnitude is brighter than $K = 17.0$, the galaxy hosts a nuclear source bright enough to be included in a $K \leq 17.0$ survey.

The model predictions showed good agreement with the observed $K$-band flux ratios for the galaxy population. However, as the number of objects available is large, the reference flux ratio for galaxies (without any additional nuclear component) was derived as follows. For each profile type (deVaucouleurs or exponential), the median flux ratio as a function of profile scalelength, either the half-light radius or exponential scalelength, was determined for all resolved objects observed in similar seeing conditions in the $K$-band. Seeing intervals of $< 0.7, 0.7–0.8, 0.8–0.9, \ldots, 1.1–1.2, > 1.2$ arcsec were used. The behaviour of the aperture flux ratios was systematic and well defined over the full range of profiles observed in each seeing interval. The excess nuclear flux for each object was then calculated from the observed flux excess over and above the empirical median flux ratio for the object’s profile scalelength.

Focusing on the 2249 objects whose SEDs are consistent with both ordinary galaxies and reddened quasars, only two are computed to have nuclear magnitudes brighter than $K = 17.0$. The first, ULAS J125949.08+001344.9, is the smaller of a close pair of possibly interacting galaxies, and thus the radial light profile is most likely affected by the neighbour. Although the NIR-extended Photoz initially classified this object as a reddened quasar at redshift $z = 2.7$, the SDSS Photoz classifies it with very high confidence as an ordinary galaxy at $z = 0.14$. The SDSS spectrum of the companion galaxy shows evidence of star formation, and lies at $z = 0.13$, lending further confidence to the SDSS Photoz result.

The second object, ULAS J131101.23+000310.8, is a resolved galaxy. The NIR-extended Photoz classified this object as a highly reddened quasar at $z = 0.1$, but the SED is also consistent with an Sbc-type galaxy at $z = 0.15$. The SDSS Photoz results agree with the classification of a star-forming galaxy. The existing SDSS spectrum shows narrow emission lines with type 2 ratios at $z = 0.096$, indicating the possible presence of an obscured active nucleus. However, its low redshift ensures that the object would not satisfy the absolute magnitude criterion of $M_r < -22.4$ required for inclusion in the quasar sample.

Objects classified as stellar are not included in this analysis, as virtually every stellar candidate was observed spectroscopically. The galaxy profile-based procedure is not expected to work for low redshift, extended objects with a quasar visible in the $i$-band, as their SDSS surface brightness profiles should not be well fit by either a deVaucouleurs or an exponential model. However, the targets of our investigation are galaxies hosting optically obscured quasars, where the obscured quasar is not evident in the SDSS $i$-band. Thus, the SDSS galaxy surface brightness profiles should be largely unaffected by the hidden quasar and provide a good estimate of the expected $K$-band aperFlux3/apertureFlux6 ratio. Then, due to the much reduced extinction in the $K$-band, a central flux excess should be apparent if a bright nuclear source is present.

In summary, although not every object located to the right of the selection line on a $gK$ plot was observed spectroscopically, we have used all of the available photometric and morphological information from both the SDSS and UKIDSS data bases to assign a high confidence classification to each object. The cases for which the photometry is consistent with that of a reddened quasar, the radial light profile information is used to exclude the possibility of the objects harbouring nuclear point sources bright enough to be included in our $K$-band $K \leq 17.0$ sample. Only 11 objects remain without such classifications, and in each case the reason is readily understood.
Table 4. Spectroscopic classification of objects. The second column includes data from all 11 observed fields with confident and very confident identifications, while the third column only includes data from the eight fields with the best observing conditions and initial photometry, and only very confident identifications.

| Category                        | All     | Best    |
|---------------------------------|---------|---------|
| Broad-line quasars/AGN          | 196/15  | 137/6   |
| Narrow-line type 2              | 96      | 74      |
| Star-forming galaxies           | 944     | 676     |
| Absorption line galaxies        | 1206    | 718     |
| Stars                           | 270     | 172     |
| Spectroscopically unclassified  | 327     | 159     |
| Damaged                         | 99      | 45      |

4 K-BAND SELECTED SAMPLE

4.1 Sample composition

Each of the 3154 AAOmega spectra were classified as either broad-line quasars/AGN, narrow-line type 2 Seyfert galaxies, star-forming galaxies with obvious emission lines, absorption line galaxies, stars or remained spectroscopically unclassified. The number of objects in each category is listed in Table 4. The first column lists the type classification, the second column includes every object of each type, while the third column only includes objects with very high confidence identification and whose spectra are of high enough quality for further study, i.e. excluding fields observed under poor conditions, for example. One BL Lac object was identified and excluded from the quasar sample. Details for the broad-line objects follow in Section 4.2, whereas the unclassified objects were examined in Section 3.3.2. Information for the other object classes may be found in Appendix B.

Table 5 shows a subset of the object catalogue. The complete catalogue appears in the online version of this paper, along with a description of each column. Descriptions of only the columns appearing in the table subset are given here. Column 1 is the IAU (International Astronomical Union) name of each object. Column 2 contains the UKIDSS morphology class, with 1 = extended, 0 = noise, −1 = stellar, −2 = marginally stellar, −3 = marginally extended, −9 = saturated. Columns 3–4 contain the SDSS PSF g-band magnitude and error, while Columns 5–8 contain the UKIDSS apermag3 J- and K-band magnitudes and errors.

Column 9 lists the E(B − V) values provided in the WFCAM Science Archive, derived from the galactic dust extinction value measured from the Schlegel, Finkbeiner & Davis (1998) maps. The identifying type name in Column 10 is derived from the spectroscopic identifications, with ‘QSO’ (quasi-stellar object) for broad-line quasars and AGN, ‘Abs’ representing all absorption line galaxies, ‘Em’ for star-forming galaxies and ‘Type2’ for emission-line galaxies showing type 2 emission line ratios. ‘NoID’ denotes objects with flux in their spectra but no identifiable features, ‘Fringing’ is for objects in which the fringing within the fibre prohibited an identification and ‘NoFlux’ identifies spectra with particularly low SNR. The stars are divided into three broad classes of ‘Astar’, ‘Kstar’ and ‘Mstar’, and ‘BL Lac’ denotes the one object whose spectrum was entirely featureless. Column 11 provides the spectroscopic redshifts, which is set to be 0.000 for stars and −99.999 for objects with no identification. Column 12 contains an approximate measure of the SNR of each spectrum, computed from the mean and standard deviation of the spectra between 6000 and 7000 Å.

Of the six objects that were observed specifically because they had detections in UKIDSS but not in any of the SDSS bands, two were classified as absorption line galaxies, one has some flux in its spectrum but has no identifiable features and three do not have sufficient flux in their spectra to make identifications. These will be discussed further in Section 5.2.3.

4.2 Quasars and AGN

Quasars and AGN are separated from other objects by requiring the presence of one emission line of full width at half-maximum (FWHM) of at least 1500 km s⁻¹, with the distinction between quasars and AGN based purely on an absolute magnitude cut of M<sub>K</sub> < −22.4. In practice, it does not make a significant difference if the broad-line cut-off is reduced to 1000 km s⁻¹, as only a handful of objects are added, some of which exhibit type 2 high ionization emission line ratios. One object is added to the broad-line sample by hand, due to the presence of very broad wings at the base of strong narrow lines. Line characteristics for the quasars and all of the emission line objects are measured using the IDL program lineequiv.pro from the FUSE IDL TOOL package. The measurements are approximations only, as values such as FWHM are estimated assuming the emission line follows a Gaussian profile.

The absolute magnitude limit is taken directly from the SDSS quasar selection algorithm (Richards et al. 2002), converted to the Vega system. After correcting the apparent magnitude measurements for Galactic extinction using the maps of Schlegel et al. (1998), absolute magnitudes for the broad-line objects are calculated employing K-corrections computed from the quasar–galaxy composite model described in Section 2.4. As the model quasar is representative of a typical, unreddened quasar, the calculated absolute magnitudes are upper limits (i.e. lower limits on the luminosities). Using models that include dust reddening or more host galaxy flux will serve to increase the K-correction, thus decreasing (i.e. brightening) the computed absolute magnitudes. 15 of the 211 broad-line objects fail to meet the M<sub>K</sub> < −22.4 restriction when using the unreddened quasar model K-correction, and are confined to z < 0.6. These 15 objects will hereinafter be referred to as AGN, not quasars.

Fig. 5 shows the location of the confirmed broad-line quasars and AGN on the $gJK$ plane, divided by UKIDSS morphological classification. Blue crosses indicate quasars classified as point sources, and red circles are extended. As can be seen, the extended quasars are located between the low-redshift end of the model quasar track and the corresponding low-redshift end of the elliptical galaxy model track, indicating a significant amount of host galaxy flux is being included in the SDSS PSF and UKIDSS apermag3 magnitude measurements. The unresolved quasars tend to cluster close to the model quasar track at higher redshifts. However, there are a significant number of unresolved quasars located away from the quasar track, in the region of colour space that is expected to be populated by red or reddened quasars, as indicated by the black arrow in Fig. 2. These objects will be discussed further in Section 5.2.

Fig. 6 shows the redshift distribution of confirmed quasars and AGN. The solid grey histogram shows all of the broad-line objects identified in this study, whereas the hatched histogram shows the SDSS-confirmed quasars recovered. Objects targeted for spectroscopic observation by the SDSS quasar selection algorithm but have not yet been observed are not included in the hatched histogram. The
Table 5. Photometric and spectroscopic information for each observed object.

| Name               | UKIDSS class | $g$     | $σ_g$    | $J$      | $σ_J$    | $K$      | $σ_K$    | $E(B-V)$ | Type | Redshift | SNR |
|--------------------|--------------|---------|----------|----------|----------|----------|----------|----------|------|----------|-----|
| ULAS J121737.39−001212.2 | 1            | 21.600  | 0.049    | 17.736   | 0.051    | 16.555   | 0.050    | 0.022    | Abs  | 0.207    | 6.0 |
| ULAS J121738.61+002016.6  | −2           | 22.212  | 0.075    | 18.365   | 0.104    | 16.715   | 0.065    | 0.027    | Abs  | 0.383    | 4.2 |
| ULAS J121739.55−000124.5   | 1            | 19.328  | 0.020    | 16.334   | 0.015    | 15.210   | 0.015    | 0.026    | Abs  | 0.117    | 11.7|
| ULAS J121741.65+002310.2   | 1            | 21.417  | 0.043    | 17.383   | 0.043    | 16.037   | 0.035    | 0.027    | Abs  | 0.257    | 5.5 |
| ULAS J121744.02+000234.8   | 1            | 21.415  | 0.042    | 18.152   | 0.086    | 16.621   | 0.060    | 0.027    | Em   | 0.373    | 7.6 |
| ULAS J121745.21+001600.5   | −2           | 20.197  | 0.025    | 17.579   | 0.051    | 16.564   | 0.057    | 0.027    | Kstar | 0.000    | 11.0|
| ULAS J121749.22−000143.3   | −2           | 20.780  | 0.030    | 18.260   | 0.082    | 16.657   | 0.055    | 0.027    | Em   | 0.303    | 9.4 |
| ULAS J121749.26−001129.5   | −3           | 24.263  | 0.407    | 18.678   | 0.120    | 16.922   | 0.070    | 0.023    | Abs  | 0.786    | 1.9 |
| ULAS J121749.58−000514.4   | 1            | 21.635  | 0.050    | 18.060   | 0.069    | 16.463   | 0.046    | 0.025    | Type2 | 0.326    | 7.6 |
| ULAS J121749.87+001721.8   | 1            | 22.340  | 0.083    | 17.771   | 0.061    | 16.106   | 0.037    | 0.027    | Abs  | 0.349    | 7.1 |

Note: the full table of 3154 objects is published in the electronic version of the paper. A portion is shown here for guidance regarding its form and content.

Figure 6. Redshift histogram for confirmed quasars and AGN. The light grey histogram contains all broad-line objects identified in this study, and the hatched histogram shows recovered SDSS quasars. The blue histogram shows quasars that satisfy the SDSS magnitude selection criteria but were not targeted for observation by the SDSS quasar selection algorithm.

5 ANALYSIS

We begin by comparing our quasar sample to the SDSS quasar sample in the same area of sky, dividing the comparison into two redshift regimes. We address the completeness and the effectiveness of the SDSS quasar selection algorithm, as well as commenting on the detection of broad absorption line (BAL) quasars. Next, we consider three different populations of red objects, contained within our large number of low-redshift KX-selected objects highlight the contribution of host galaxy light in the $K$-band. Most of these objects have extended morphological classification, and many of the objects at $z < 0.5$ are fainter than the $M_i < −22.4$ mag restriction. The 11 quasars shown in blue are bright enough to have been selected as SDSS quasar targets but in fact were not included. These objects are discussed further in Section 5.1.

5.1 Completeness of the SDSS quasar catalogue

With more than 77 000 quasars, the SDSS DR5 quasar catalogue (Schneider et al. 2007) is the largest collection of quasars selected from a single photometric data set to date. However, the DR3 quasar catalogue (Schneider et al. 2005) has been much more thoroughly studied (Vanden Berk et al. 2005; Richards et al. 2006). Our results provide an independent test of the completeness of the SDSS quasar selection. As the SDSS target algorithm differs for $z < 3.0$ and $z > 3.0$, the two redshift intervals should be treated separately. For $z < 3.0$, an object must have $i < 18.7$ to be selected. If the $ugriz$ colours indicate that the object is probably at $z > 3.0$, the magnitude limit changes to $i < 19.8$.

5 Recall that all magnitudes quoted in this work are based on the Vega system.
There are 13 KX-selected, spectroscopically confirmed quasars that have $z < 3.0, i < 18.7, M_i < -22.4$, and do not have SDSS spectra. Six of these objects were targeted by the SDSS selection algorithm but have not been observed. The remaining seven objects, three of which are at $z \leq 2.6$, where the quasar locus comes very close to the stellar main sequence in optical colour space, eluded the selection algorithm. The other four objects have redshifts $0.8 < z < 1.5$. These seven untargeted objects result in a density of $0.5\, \text{deg}^{-2}$ quasars which evade the SDSS selection algorithm, consistent with the 0.44 $\text{deg}^{-2}$ found by Vanden Berk et al. (2005). However, as Vanden Berk et al. (2005) considered only point sources, 0.44 $\text{deg}^{-2}$ is a lower limit. The properties of the seven untargeted objects found in this sample are very similar to the population of quasars uncovered by Vanden Berk et al. (2005). KX selection successfully identifies as quasar targets objects that are excluded from the SDSS selection algorithm.

Focusing on the high-redshift regime, there are seven KX quasars at $z > 3.0$, two of which have SDSS spectra, and one of which was targeted for observation by SDSS. The remaining four quasars include two objects that have strong BAL troughs. The density on the sky of KX-selected quasars at $3.0 < z < 3.7$ of $0.5\, \text{deg}^{-2}$ (seven quasars in 12.8 $\text{deg}^2$) compares very well with the SDSS DR3 quasar catalogue density of 0.48 $\text{deg}^{-2}$ (2011 quasars in 4188 $\text{deg}^2$). Therefore, although there are significantly more $z > 3.0$ quasars found in this study (seven KX-selected compared to three SDSS-selected), the difference may well be attributed to small number statistics. It should be noted that the KX selection is extremely effective in recovering confirmed quasars from the SDSS catalogue. There are 153 SDSS quasars included in our $K < 17.0$ photometric catalogue and all but one satisfy the KX-selection criteria.

5.1.1 Broad absorption line quasars

At least nine objects displaying strong, deep BAL troughs are included in our KX-selected quasar catalogue. There are three additional objects that show signs of associated absorption, but the SNR of the spectra is too low for a definitive BAL identification to be made. Estimates of the fraction of BAL quasars among the quasar population range from 10 to 30 per cent (Chartas 2000; Hewett & Foltz 2003; Trump et al. 2006), the difference arising, at least in part, from difficulties in quantifying the selection of BALs accurately.

The BAL fraction within the SDSS DR3 quasar catalogue has been computed by Trump et al. (2006). The ‘classical’ BAL population (objects with balnicity index $>0$) is $10.4 \pm 0.2$ per cent of quasars at $1.7 < z < 4.38$. This same fraction holds true for the more restricted redshift range of $1.7 < z < 3.8$. For the KX-selected sample, the percentage of BAL quasars within the entire population over $1.7 < z < 3.8$ is $\sim 15$ per cent (eight BALs and 44 non-BAL quasars). A recent study from Dai, Shankar & Sivakoff (2008) matches the SDSS DR3 quasar catalogue to 2MASS, and notes an increasing fraction of BAL quasars with increasingly redder passbands. Although the Dai et al. (2008) study uses the much brighter 2MASS photometry, the result of the BAL fraction increasing at longer wavelengths appears to be consistent with this small KX-selected sample. A much larger sample flux limited in the K-band can be created by matching the SDSS DR3 quasar catalogue to the UKIDSS LAS DR2+. The fraction of classical BAL quasars at $K < 17.0$ and $1.7 < z < 3.8$ is computed to be 17.5 per cent, confirming both the Dai et al. (2008) result and the result from the present study. We return to the colour distribution of the BAL quasars in Section 6.1.

Figure 7. Example spectra of BAL quasars included in the sample. The objects’ names and redshifts are (a) ULAS J142034.43+000451.2, $z = 2.65$; (b) ULAS J154258.19+054016.7, $z = 3.12$; (c) ULAS J130348.94+020104.3, $z = 3.62$; (d) ULAS J130409.48−000833.9, $z = 3.72$. Only spectrum (c) is included in the SDSS quasar catalogue. The absorption feature seen at 7600 Å is the atmospheric $A$ band.

The BAL quasars lie close to the quasar locus in a $gJ$ diagram, with the higher redshift objects following the quasar track redward in $g − J$. The quasar locus comes very close to the selection boundary at high redshifts. At $z > 3$, absorption associated with Mg II enters into the $J$ band, which could alter their $J − K$ colours such that they would be moved leftward across the selection boundary. For the regions where the DR3 quasar catalogue overlaps the UKIDSS LAS DR2+ area, a cross-match of the BAL catalogue from Trump et al. (2006) with the DR2+ results in 350 matches, of which 158 possess both measured $J$ and $K$ magnitudes. Only two of the 158 objects lie to the left of our KX-selection line, confirming that the KX selection is highly effective at identifying BAL quasars. Fig. 7 shows spectra of four of the BAL quasars identified in our study. Only one of the objects shown (spectrum c) is included in the SDSS quasar catalogue.

5.2 Red quasars

As anticipated, the $K$-band flux-limited sample includes a number of quasars with non-standard SEDs and quasars that are not identified by the SDSS quasar selection algorithm. Three populations of objects are discussed here, starting with quasars that are red in $g − J$. Secondly, we consider objects whose $i − K$ colours are such that their $i$-band magnitudes are too faint for inclusion in the SDSS quasar catalogue. Finally, there is a small population of objects with $K < 17.0$, which are so red that they do not appear in the SDSS photometric catalogue at all.

5.2.1 Red in $gJK$

There are 20 broad-lined objects with $g − J > 2.5, J − K > 1.2$ and $M_i < -22.0$ in our sample. The spectra for two of the
red objects, corrected for the AAOmega response function, are shown in Fig. 8. Object ULAS J130548+000735, at $z = 0.47$ and $g - J = 2.81$, was selected for spectroscopic follow-up as a high-redshift candidate by the SDSS. It is classified as extended by the WFCAM pipeline and the red colours are at least partially due to host galaxy light. The absolute magnitude in the $i$-band, computed using a K-correction based on a blue, unobscured, quasar SED, is too faint for it to be included in the SDSS quasar catalogue, and the host galaxy flux almost certainly boosted the object into the $K \leq 17.0$ sample. ULAS J125438+001447 at $z = 1.16$ and $g - J = 3.0$ was not targeted, as it is fainter than the SDSS quasar catalogue $i$-band limit. Its stellar morphological classification indicates that the red colour of this object is most likely due to extinction by dust. This pair of objects highlights the need for a distinction between objects that have intrinsically red continua, objects with significant host galaxy contribution and objects that are reddened due to the effects of dust.

As mentioned in Section 4.2, the dust reddening vector tends to move objects from the model, unreddened, quasar track into the region of the $g/K$ diagram populated by galaxies at low redshifts. While there are 20 objects with $g - J > 2.5$, the majority are at redshift $z \approx 0.5$, and significant host galaxy contribution produces their red colours.

5.2.2 $K \leq 17.0, i > 18.7$

There is a significant population of quasars in the KX sample which are too faint in the $i$-band for inclusion in the SDSS quasar catalogue. Fig. 9 shows the population: the black crosses are all KX-selected quasars with $K \leq 17.0, M_i \leq -22.4$ and $z \leq 3.0$, of which there are 189. Of the 189, 93 are fainter than the SDSS $i$-band limit of $i = 18.7$, identified by the open circle and open square plot symbols. The blue circles mark 33 quasars which have been classified as stellar in both the UKIDSS and SDSS catalogues, whereas the red squares are the 60 quasars classified as non-stellar in the UKIDSS catalogue. The solid black line indicates the $i - K$ versus $z$ colour for the model unobscured quasar, whereas the blue long dashed line, the green short dashed line and red dotted line show the $i - K$ colour of the model quasar after being subjected to Small Magellanic Cloud (SMC)-like dust reddening, with $E(B - V) = 0.10$, $E(B - V) = 0.25$ and the model quasar reddened with $E(B - V) = 0.50$.

As can be seen, the objects that are too faint in the $i$-band are preferentially redder in $i - K$ than the model quasar, sometimes by more than a magnitude. There are three circled objects in Fig. 9 that are bluer in $i - K$ than the model quasar at $z \approx 2.4$. These can be understood by noting that fixed magnitude limits in the $i$- and $K$-bands ($i < 18.7$ and $K \leq 17.0$) results in a constant colour value of $i - K = 1.7$. Because of the presence of the Hz emission line in the $K$ band at $z \approx 2.4$, most quasars will be redder than $i - K = 1.7$, even objects that happen to be bluer than the model quasar.

The majority of the low redshift objects are classified in the UKIDSS catalogue as having extended morphology. Host galaxy flux is important at longer wavelengths and the red colours are in part due to host galaxy contamination. This effect decreases with increasing redshift as the quasars become much brighter than the hosts, and thus the red colours of unresolved objects at $z \gtrsim 1$ are most likely due to dust reddening.

There are still a significant number of objects redder than the model quasar locus that are classified as stellar in both the UKIDSS and SDSS catalogues, indicating that host galaxy light is not the cause of their red colours. If dust reddening is responsible, their $i$-band magnitudes have been underestimated, and are thus excluded from flux-limited samples defined at optical wavelengths.

Assuming that the redder $i - K$ colours are due to dust reddening, the amount of extinction these objects are suffering can be estimated from their location on the $i - K$ versus redshift diagram. There are 91 stellar, non-BAL quasars with $M_i < -22.4$ in Fig. 9 for which the following calculations will be performed. Because of
the apparent intrinsic spread of $i-K$ colours, as displayed by the distribution of objects with colours both redder and bluer than the unreddened model quasar seen in Fig. 9, objects lying bluer than the $E(B-V) = 0.10$ track are assigned $E(B-V) = 0.0$. For the 14 stellar, non-BAL quasars redder than $E(B-V) = 0.10$, SMC-like dust reddening is assumed, and the amount of extinction in the $K$-band, $A(K)$, is calculated. The values range from $0.06 < A(K) < 0.41$. A histogram of the estimated $E(B-V)$ distribution derived from Fig. 9 is shown in Fig. 10. Note that there are 77 objects in the $E(B-V) = 0.0$ bin.

Following a very similar calculation as outlined in Hewett & Foltz (2003), for BALs the true number of quasars that would appear in a $K \leq 17.0$ sample, correcting for the effects of dust obscuration, can be estimated. For a population unaffected by dust, the number of objects in a flux-limited sample is simply the sum of the observed objects, corrected for any selection effects that may have been introduced. For a population that is affected by dust, an extra factor is introduced, which accounts for the fact that the corrected magnitudes are brighter than the nominal magnitude limit, as

$$N_{\text{corr}} = \sum_{j=1}^{n} \frac{N_{\text{QSO}}(K \leq 17.0)}{N_{\text{QSO}}(K \leq 17.0 - A(K))}. \tag{1}$$

$N_{\text{corr}}$ is the corrected number of objects that should be observed in a flux-limited sample, and $n = 91$ for this KX-selected sample. For all but 14 of the objects in the sum, the fraction will be unity, as their corresponding $A(K)$ values are zero. The corrected number of quasars that should be observed to $K \leq 17.0$, accounting for the dust reddening derived from Fig. 9, is $N_{\text{corr}} = 97$. This implies that only 6 per cent ($97 - 91/97$) of the total population is missing from this sample due to obscuration. In an effort to determine how sensitive this result is to small changes in the $E(B-V)$ distribution, the same calculations are performed with the quasar with $E(B-V) > 0.5$ at $z \geq 0.7$ excluded. The resulting changes in the computed missing fractions are of the order of 1 per cent.

A similar calculation can be performed for the SDSS DR3 quasar catalogue, flux limited in the $i$-band and restricted to $z \leq 3.0$, using the $A(i)$ values derived from the $E(B-V)$ distribution of the KX-selected sample. Estimates of the fraction of the total population that is missing from the observed $i$-band selected sample reach the much larger value of $\sim 30$ per cent.

If any of the four UKIDSS-only detections turn out to be quasars, the fraction of obscured objects increases significantly for both $K$-band and $i$-band samples. We consider the identification of the four objects next.

5.2.3 UKIDSS-only detections

Six objects that were detected in the UKIDSS bands and not in SDSS were observed spectroscopically, which resulted in two identifications. Objects listed as ULAS J125254−000947 and ULAS J131049−001514 were both classified as absorption line galaxies. The other four spectra did not have sufficient flux for identifications to be made. Image cutouts of one of the four unclassified objects are shown in Fig. 11. The $ugrizYJHK$ magnitudes and magnitude limits are listed in Table 6, along with their $i-K$ colours. The calculated $E(B-V)$ required in order for each object to have $i-K$ colours consistent with that of the unreddened model quasar are also listed, assuming the objects are at $z = 1$ or 2.

The NIR-extended Photoz can be used to determine which object SEDs are consistent with the colours of the UKIDSS-only objects. For the two spectroscopically classified UKIDSS-only objects, the NIR-extended Photoz produces consistent fits to galaxy SEDs at redshifts similar to the spectroscopically determined redshifts,
lending support to the spectroscopic classifications. The photometry of ULAS J125946−001135 is consistent with both an emission line galaxy at \( z \approx 2.15 \) and a highly reddened quasar at \( z \approx 0.7 \). Using the measured \( i \)-band magnitude and a K-correction for an Sc-type galaxy, an emission line galaxy at \( z \approx 2.15 \) would be unfeasibly bright at \( M_i \approx -27 \), reducing the confidence in the galaxy classification. ULAS J131910+000956 is similarly consistent with an emission line galaxy at \( z \approx 1.65 \) and also a highly reddened quasar at \( z \approx 2.1 \), but also an L dwarf star of spectral class L3. Again, an emission line galaxy at \( z \approx 1.65 \) would be unphysically bright, making the galaxy classification the least likely of the three. ULAS J154727+052451 is somewhat consistent with an absorption line galaxy at \( z \approx 1.7 \), but a much better fit to a class L4.5 L dwarf. The best fit to ULAS J154827+054821 is an SB-type galaxy at \( z \approx 2.6 \), with the very red \( jHk \) colours difficult to fit with any of the models. Further observations, preferably NIR spectra, are required in order to identify these four objects unambiguously. ULAS J131910+000956 has a NIR spectrum, but no features have been identified (R. G. McMahon, private communication). The implications for these four objects in the context of a putative population of highly obscured quasars are discussed in Section 6.1.

6 DISCUSSION

The population of quasars selected in the KX sample that do not appear in the SDSS catalogue is briefly discussed here, along with the implications for uncovering a population of highly reddened quasars. The observations are compared to simulations based on a quasar luminosity function (QLF) defined in the \( b_j \)-band, and then compared to results from recent studies.

6.1 A population of red quasars

6.1.1 Mild reddening

Selecting quasars in the \( K \)-band has been shown to be very effective at finding not only standard, blue quasars, but also quasars with red SEDs, either due to red intrinsic SEDs, host galaxy light, dust reddening or the presence of BALs.

The distribution of \( i - K \) colours as a function of redshift is shown in Fig. 9. The SDSS quasar catalogue can be used to provide a comparison sample. Cross-matching the DR3 quasar catalogue to the UKIDSS DR2+ catalogue results in 3401 matches, 969 of which are stellar, have measured \( K \)-band magnitudes \( K \leq 17.0 \) and are at \( z \leq 3.0 \). Extended objects are excluded from this comparison as it is understood that the \( K \)-band selected sample is more sensitive to host galaxy flux than the optically selected sample. The comparison is also restricted to \( z \leq 3.0 \) as the SDSS \( i \)-band faint magnitude limit changes at this redshift.

Another population to be considered separately are the BAL quasars. Extracting the matched SDSS DR3–UKIDSS DR2+ quasars at \( 1.7 < z < 3.8 \), and dividing the sample into BAL (144) and non-BAL (249) quasars, a two-sided Kolmogorov–Smirnov (KS) test comparing the \( i - K \) distributions of each subpopulation returns the probability that the two subpopulations are drawn from the same parent population as \( 5 \times 10^{-10} \). The BAL quasars are preferentially redder in \( i - K \). The cause of the reddening is not known definitely but the presence of an additional average value of \( E(B - V) = 0.02 - 0.03 \) affecting the BAL quasars, consistent with the findings of Reichard et al. (2003) and Dai et al. (2008), can explain the colour difference.

After removing the extended objects and BAL quasars, the \( i - K \) distributions for the remaining stellar objects can be compared. A KS test comparing the SDSS DR3 stellar quasars and the KX-selected stellar quasars for \( 0.0 < z < 3.0 \), excluding the BAL quasars, returns a probability of 0.45 that they are from the same underlying distribution. Although there is no evidence for a difference in the \( i - K \) distributions for the samples as a whole, there is an indication of the presence of a red ‘tail’ in the KX-selected sample. Specifically, of 830 stellar SDSS quasars between \( 0.0 < z < 3.0 \), 65 (8 per cent) are redder than the model quasar reddened by \( E(B - V) = 0.10 \), compared to 14 of 87 (16 per cent) within the KX-selected sample. Eight of 830 (1 per cent) SDSS quasars are redder than the model reddened by \( E(B - V) = 0.25 \), compared to three of 87 (3 per cent) of the KX-selected sample. Using a binomial statistic, the probability of finding 14 of 87 BALs at \( E(B - V) > 0.1 \) if they share the same \( i - K \) distribution as the non-BALs is only 0.7 per cent. Similarly, there is a 5 per cent chance of finding three of 87 BALs at \( E(B - V) > 0.25 \) if the BALs and non-BALs have the same \( i - K \) distribution.

Note that although we have identified a number of quasars with red \( i - K \) colours, there does seem to be an upper limit to the distribution. From Fig. 9, it is apparent that there are no confirmed quasars with \( i - K > 4.3 \), even though the experiment is sensitive to objects with redder colours, as demonstrated by the fact that galaxies with \( i - K > 4 \) are successfully identified.

6.1.2 Severe reddening

It is very important to secure identifications for the four unclassified objects in Section 5.2.3. As seen in Table 6, three of the four have \( i - K > 6 \). If these objects are quasars, they will lie 2 mag redder in \( i - K \) than the reddest quasars in Fig. 9, leaving a large gap in \( i - K \) that is seemingly unpopulated. Physical models consistent with such a distribution would include a bimodal distribution of \( E(B - V) \), or a very strong dependence of severe reddening on the intrinsic luminosity of the quasars.

Using the observed \( i - K \) values listed in Table 6 as well as the model quasar colours, estimates of each object’s unreddened \( i \)- and

| Object name       | \( u \) | \( g \) | \( r \) | \( i \) | \( z \) | \( Y \) | \( J \) | \( H \) | \( K \) | \( i - K \) | \( E(B - V) \) \((z = 1)\) | \( E(B - V) \) \((z = 2)\) |
|-------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|----------------|----------------|
| ULAS J125254.31−000947.1 | >21.9 | >23.9 | >23.4 | 21.1 | 20.0 | 19.8 | 18.9 | 18.1 | 16.8 | 4.3 | – | – |
| ULAS J125946.54−001135.8 | >21.8 | >23.8 | >23.1 | 21.1 | 20.6 | 19.9 | 19.3 | 18.1 | 16.6 | 4.5 | 1.12 | 0.81 |
| ULAS J131049.36−001514.5 | >21.9 | >23.6 | >23.8 | 21.3 | 20.0 | 19.1 | 18.6 | 18.1 | 17.0 | 4.3 | – | – |
| ULAS J131910.65+000956.1 | >21.8 | >23.3 | >23.4 | >22.2 | >20.5 | 20.2 | 18.7 | 17.2 | 16.0 | >6.2 | 1.34 | 0.94 |
| ULAS J154727.37+052451.9 | >21.6 | >24.0 | >23.4 | >22.8 | >20.7 | 20.0 | 18.5 | 17.6 | 16.8 | >6.1 | 1.30 | 0.92 |
| ULAS J154827.70+054821.5 | >21.8 | >24.1 | >23.4 | >22.4 | >20.4 | >20.8 | 20.2 | 17.7 | 16.4 | >6.0 | 1.26 | 0.89 |

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K-band magnitudes can be made. If the four objects are quasars at $z = 1$ they would have intrinsic colours of $i - K \simeq 1.93$ and would be experiencing $0.7 < E(B - V) < 1.2$ of reddening. Corresponding unreddened magnitudes fall in the range $14.9 < K < 15.9$, putting them at the bright end of the quasar magnitude distribution. Adopting a redshift of $z = 2$ instead, their unreddened magnitudes fall in the range $14.2 < K < 15.4$, with the brightest of the four brighter than all the quasars included in this study.

### 6.2 Comparison with previous predictions

In an effort to put new NIR observations in context with the existing optical data, simulated surveys in a variety of passbands, including the UKIDSS K-band, were performed by Maddox & Hewett (2006). Briefly, the simulations were based on a QLF derived from observations spanning $16 < b_J < 20.85$ by Croom et al. (2004), and a quasar SED that matched the median colours of bright SDSS DR3 quasars for $0.1 < z < 3.6$. Host galaxy brightnesses were estimated from the $g - r$ colours of low redshift SDSS quasars and were added to that of the quasars according to three different relationships between the luminosity of the quasar and the luminosity of its host galaxy. The additional host galaxy flux serves to boost the magnitude of the combined quasar–host galaxy system, and alters the shape of the combined SED. The combined quasar–host galaxy SED is used to convert the QLF from the $b_J$ passband to the passband of choice, resulting in number–magnitude and number–redshift relations for the chosen passband.

Fig. 12 shows a comparison of the results from the simulations, using the updated quasar SED described in Section 2.4, with the results of the $12.8 \text{deg}^2$ of observations presented here. The solid line in the top panel considers the results for a simulated survey for $14.0 < K < 17.0$ and $12.8 \text{deg}^2$ including only flux received from the quasars, while the dashed line includes light from both the quasars and their host galaxies. As can be seen, host galaxy light at long wavelengths makes a significant contribution to the total light, and affects the results to $z \simeq 2$. The solid line in the bottom panel is the actual redshift distribution of the observed quasars brighter than $M_K < -22.4$ in this study. The agreement in overall shape and normalization is very good, except at very high redshifts, as the simulations were limited to $z \leq 3.6$.

From this comparison, it becomes apparent that the importance of the additional light contributed by the quasar host galaxies at longer wavelengths has been successfully accounted for, as indicated by the large population of morphologically extended objects selected in the K-band that do not appear in the $b_J$-band selected sample, and the good agreement between the observed and simulated number–redshift relations. In converting the QLF defined in the $b_J$-band to the K-band, only additional host galaxy flux was added, with no corrections or additions made based on a population of dust-reddened objects that would be visible in the K-band but not in the $b_J$-band. A large, moderately obscured population would be apparent in the comparison as a large excess in the K-band selected sample not present in the simulated results, which is not seen in Fig 12. This contribution from the quasar hosts at longer wavelengths and low redshifts complicates the construction of luminosity functions and magnitude distributions, for example, due to the difficulty of accurately separating the quasar from the host galaxy light.

### 6.3 Comparison with recent studies

Work has recently been published by Glikman et al. (2007) studying radio-selected quasars with very red $(R - K > 4)$ colours over a large area of sky. Unfortunately, as their NIR photometry is taken from the 2MASS survey, the magnitude range for which their survey is complete ($K < 14$) is too bright to overlap with this study. However, the simulations described above can be used to supplement the present study at brighter magnitudes.

Glikman et al. (2007) conclude that, based on their observations, red quasars add an extra 25–60 per cent to the unreddened quasar population at $K \leq 14.0$. This claim can be tested by using a combination of the spectroscopic results and the simulations. From the simulations, we expect 0.081 unreddened quasars deg$^{-2}$ for $K \leq 14.0$. If a further 60 per cent of the total population are red, one expects an additional 0.122 red quasars deg$^{-2}$ to appear at fainter K-band magnitudes. Because of our small survey area, this density of red quasars would add only an additional one or two objects to our sample, and we cannot make a strong statement regarding their fraction with respect to the unreddened population; ~150 deg$^2$ of area would be required in order to find 10 unreddened quasars with $K < 14.0$.

However, assuming the 60 per cent fraction does not depend on magnitude, the same procedure can be followed for fainter magnitudes. For $14 < K < 15$, the simulations predict 0.46 unreddened quasars deg$^{-2}$, or six quasars for our effective area of 12.8 deg$^2$. If an additional 60 per cent of the entire population is red, then we expect an extra 0.69 red quasars deg$^{-2}$, or nine red quasars to appear at fainter magnitudes. Even if all four of the UKIDSS-only detected objects are heavily reddened quasars, they would only account for half of the predicted number.

The number of red quasars increases at even fainter magnitudes, as the unreddened population increases significantly. For $15 < K < 16$, one expects an extra 49 quasars to appear at $K > 16$. As seen from columns 2 and 3 of Table 7, the discrepancy between the simulated and observed numbers of quasars in each magnitude interval is too small to harbour such large numbers of excess quasars, as listed in column 4.

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**Figure 12.** Comparison of simulated (top panel) and observed (bottom panel) number–redshift histograms for the 12.8 deg$^2$, 14.0 < $K$ < 17.0 survey. The solid black line in the top panel considers light from the quasars only, while the red dashed line considers light from both the quasar and the host galaxy. The simulations are described in detail by Maddox & Hewett (2006).
Table 7. Simulated, observed and proposed numbers of missing quasars for different magnitude ranges within 12.8 deg$^{-2}$. The numbers in the second column are derived from the simulations described in the text, while the numbers in the third column are directly from the spectroscopic observations. The fourth and fifth columns contain the number of red quasars that would be missing due to dust obscuration if the obscured fraction is 60 and 20 per cent, respectively. The small difference between the simulated and observed numbers of quasars does not favour a large fraction of obscured objects.

| Magnitude range | 12.8 deg$^{-2}$ sim | 12.8 deg$^{-2}$ obs | Red Q 60 per cent | Red Q 20 per cent |
|-----------------|---------------------|---------------------|-------------------|-------------------|
| $13 < K < 14$   | 1.037               | –                   | 1                 | –                 |
| $14 < K < 15$   | 5.850               | 3                   | 9                 | 1                 |
| $15 < K < 16$   | 32.99               | 33                  | 49                | 8                 |
| $16 < K < 17$   | 149.06              | 160                 | 224               | 37                |

If, instead, we adopt the obscured fraction to be their quoted lower limit of 20 per cent, one expects fewer extra red quasars, as listed in column 5 of Table 7. Based on the small differences between the simulated and observed numbers of quasars in each magnitude range, our results strongly favour an obscured quasar fraction of $<20$ per cent.

A similar study searching for rare, highly reddened objects is being undertaken by Hawthorn et al. (in preparation), using 100 deg$^{-2}$ of UKIDSS LAS data. 22 candidates with $K \leq 17.0$ and $J - K > 2.5$ are selected for further NIR spectroscopic observation. Of 11 candidates observed, seven are clearly identified as broad-lined quasars, while the other four did not produce a definitive identification. One of the four unidentified objects is ULAS J131910+000956, listed in Table 6. The seven identifications result in a lower limit on the surface density of 0.14 deg$^{-2}$. Thus one or two red objects are expected in the 12.8 deg$^{-2}$ of the current study, consistent with one or two of the objects listed in Table 6 being quasars.

A recent study by Jurek et al. (2008), employing a complete spectroscopic sample derived from the Fornax Cluster Spectroscopic Survey, tests the effectiveness of a variation of KX selection at detecting quasars. Instead of using $g - J$ and $J - K$, the combination of colours $by = R$ and $R - K$ is shown to be at least as effective as optical two colour selection, with less bias against dust reddened objects. Although this combination of an optical and optical–NIR colour shows the same property that dust reddened quasars remain separate from the stellar locus, there is significant overlap of the blue quasars and stars in colour space, which is not present when using an optical–NIR and a NIR colour. As seen in Fig. 2, the NIR $J - K$ colour provides the separation of quasars from stars, highlighting the importance of having high-quality NIR data in at least two different passbands.

6.4 Implications for future near-infrared surveys

As this was the first large-area KX-selected quasar survey performed to date, the goal of the study was to undertake a comprehensive survey without regard to efficiency. The single cut in $gJK$ colour space succeeded in selecting more than 99 per cent of the SDSS quasars with $K \leq 17.0$ within the survey area, and has thus been shown to be highly effective in recovering known quasars. The analysis in Section 5.1 also demonstrates the ability of the optical–NIR colour selection to include quasars missed by the SDSS optical colour selection algorithm.

The results from this initial sample may now be used as input for future observations to improve the observing efficiency. The use of photometric redshifts to identify low redshift ($z \leq 0.8$) inactive galaxies, together with the radial light profile information described in Section 3.4, will greatly improve the efficiency of the KX selection by reducing the number of contaminants included as quasar candidates. Particular subclasses of objects can also be more efficiently targeted with the extra information provided by their location on the $gJK$ diagram. High redshift BALs tend to be confined to $J - K = 1, g - J > 2.5$, and highly reddened quasars at $z > 1$ will be point sources located amongst the cloud of morphologically extended galaxies.

7 SUMMARY

With nearly 200 quasars over an effective area of 12.8 deg$^{-2}$, this is the largest $K$-band selected quasar sample to date by a factor of 20, utilizing the high quality, large area NIR data provided by UKIDSS. The KX selection, exploiting the KX of quasars with respect to stars, is equally sensitive to both standard blue quasars and dust-reddened objects over the entire redshift range available. A number of genuine quasars at $z < 3$ not initially selected by the multicolour technique employed by the SDSS are included, consistent with the completeness calculations performed by Vanden Berk et al. (2005).

More than twice as many high-redshift quasars are found with this selection than are targeted by the SDSS, however, the difference can be attributed to small number statistics. The selection is also sensitive to quasars with unusual SED shapes, such as BAL quasars.

Using the ugriz$Y$JHK photometry as well as morphological information, virtually all of the candidates that were not observed spectroscopically have been classified using the SDSS Photoz algorithm and a new NIR-extended photometric redshift scheme. The population of objects consistent with both galaxy and optically obscured quasar SEDs harbouring nuclear components bright enough for inclusion in this $K$-band flux-limited sample has been ruled by using the $i$-band radial light profile information along with $K$-band flux ratios.

The distribution of $i - K$ colours as a function of redshift is compared to that from the optically selected SDSS DR5 quasar catalogue, and is found to include more objects with redder $i - K$. The observed BAL quasars are preferentially redder than the bulk of the quasar population, the BALs possessing colours consistent with an additional average of $E(B - V) = 0.02$–0.03 of SMC-type dust reddening.

The fraction of quasars missing from this $K$-band selected sample due to dust reddening is computed to be $<10$ per cent, whereas the fraction missing from a sample selected in the $i$-band is considerably larger at $>30$ per cent. Four objects, detected in the NIR but not in the SDSS optical bands, remain unclassified. Their identification is essential, as if all four are quasars, the heavily dust-reddened fraction of the most luminous quasars would be very large.

With ugriz$Y$JHK photometry, morphology classification, and spectra for more than 3000 objects, this data set contains a wealth of information which is yet to be fully exploited. The results from this initial sample can be used as input for future observations, improving the observing efficiency by reducing the number of contaminants. Particular subclasses of quasars can also be more efficiently targeted using their location in the $g/K$ diagram, with high-redshift BALs confined to $J - K = 1, g - J > 2.5$, and highly reddened quasars at $z > 1$ will be point sources located amongst the cloud of morphologically extended galaxies. This modest sized sample has already placed improved constraints on the fraction of obscured quasars missing from optically selected samples, and as larger areas are surveyed, this fraction can be constrained even further.
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APPENDIX A: PHOTOMETRIC REDSHIFTS

Two photometric redshift routines were employed to classify the many thousands of extended objects within the survey area that were not observed spectroscopically, and the few objects with spectra that remained unclassified. The SDSS Photoz routine is optimized for use with galaxies, whereas the NIR-extended Photoz is capable of identifying unresolved objects as well. The top panel of Fig. A1 shows the difference between the SDSS Photoz redshift and the spectroscopic redshift for spectroscopically classified galaxies that possess confident Photoz results. The bottom panel of Fig. A1 compares the SDSS Photoz redshift to the NIR-extended Photoz redshift, for extended candidates that possess confident results from both routines. The two sets of photometric redshifts are highly consistent with spectroscopic redshifts and with each other.

Fig. A2 displays the ability of the SDSS Photoz routine to classify the spectral type of an extended object as well as fitting the redshift. The top panel shows the resulting spectral type distribution for objects spectroscopically classified as absorption line galaxies, with values near zero indicating old, passively evolving stellar populations. The bottom panel of Fig. A2 shows the resulting spectral types for spectroscopically classified emission line galaxies, with values greater than zero indicating increasing amounts of star formation.

From the results shown in Figs A1 and A2, confidence in the SDSS Photoz output is gained. Fig. A3 shows the SDSS Photoz results for the 322 objects with spectra but no classification, and confident Photoz results. The top panel shows that this population is dominated by absorption line galaxies (spectral type near zero), with a small population of objects with moderate star formation, consistent with the conclusions drawn from Fig. 4. The bottom panel of Fig. A3 puts the bulk of the population of objects at $z \lesssim 0.4$.

APPENDIX B: SAMPLE COMPOSITION: GALAXIES AND STARS

As objects with extended morphology were not discriminated against during selection of candidates for follow-up spectroscopy,
there are a significant number of galaxies included in the spectroscopic sample. Type 2 Seyfert galaxies are classified by the presence of narrow high-ionization emission lines, as described in Section B1, with regular star-forming galaxies identified by having at least one narrow emission line. Absorption line galaxies are objects with no emission lines, and visible stellar absorption features such as the Ca II H&K lines. Stars are separated into two subgroups, M-type stars and stars of earlier types, ranging from A to K.

**B1 Type 2 Seyfert galaxies**

Objects with narrow emission lines and high-ionization line ratios are classified as type 2 Seyfert galaxies. The criteria used to identify candidates are taken directly from Zakamska et al. (2003), who studied a large number of objects extracted from SDSS DR1, except that the only emission lines used in this work are Hβ, [O III]λ5008, Hα and [N II]λ6583. As the presence of the [O III]λ5008 line in the spectra is critical for this analysis, the sample is restricted to $z < 0.76$. The selection criteria require the rest-frame equivalent width (EW) of the [O III]λ5008 to be less than $-4$ Å, the FWHM of the ([O III]) to be greater than 400 km s$^{-1}$ and the FWHM for all emission lines present in each spectrum to be less than 2000 km s$^{-1}$. For spectra with all four lines present, the following must be true for selection:

\[
\log \left( \frac{[\text{O III}]\lambda5008}{\text{H} \beta} \right) > 0.61 \log([\text{N II}]/\text{H} \alpha) - 0.47 + 1.19.
\]  

(B1)

For spectra at redshifts $z > 0.33$, both Hα and [N II]λ6583 have redshifted outside the usable spectral range, leaving only Hβ and [O III]λ5008. For these cases, the following is applied:

\[
\log \left( \frac{[\text{O III}]\lambda5008}{\text{H} \beta} \right) > 0.3.
\]  

(B2)

Measurements were made on the flux-calibrated spectra. There are 96 objects that satisfy either equation (B1) or equation (B2), and 43 at $z < 0.33$. For objects with Hβ emission lines that are too weak to be measured, a flux limit is imposed so that the spectra may still be used in the analysis. The flux limit is set to be 2.5 times the standard deviation calculated from a small section of continuum at the wavelength of the absent line.
Luminous K-band selected quasars from UKIDSS

Figure B1. A BPT diagram containing all galaxies for which each of the four emission lines was present, excluding objects with emission lines broader than 1500 km s$^{-1}$. Arrows represent objects for which only an upper limit to the H$\beta$ emission line flux exists. The dashed line is the theoretical demarcation between star-forming galaxies and AGN, while the solid lines divide the plot into regions dominated by Seyfert galaxies in the top right-hand corner, and LINERs in the bottom right-hand corner.

Figure B2. Location of spectroscopically confirmed galaxies on the gJK diagram. Blue crosses show emission line galaxies, with red dots marking absorption line galaxies. The purple selection line, blue model quasar and red elliptical galaxy tracks are as in Fig. 2, with the green track following the colours for a model Sc-type galaxy.

Fig. B1 shows a standard diagnostic tool used in AGN studies, first demonstrated by Baldwin et al. (1981, hereinafter BPT). The BPT diagram separates normal star-forming galaxies from AGN by considering emission line ratios. The dashed demarcation line is from Kewley et al. (2001), defined by equation (B1), with objects above this line having line ratios that cannot be produced by normal star formation. Red crosses indicate objects that have measured emission line properties consistent with the selection criteria described above. Red arrows are objects with only upper limits on their H$\beta$ flux. The few black dots located above the dashed line have emission line ratios consistent with the AGN criteria, but the measured values of the $\text{[OIII]}\lambda 5008$ line EW and FWHM do not meet the specified criteria.

As the cut-off specifying broad emission lines is set to be FWHM $> 1500$ km s$^{-1}$ (which is slightly larger than the SDSS limit of $>1000$ km s$^{-1}$) and the narrow line selection requirement is FWHM $< 2000$ km s$^{-1}$, consistent with the analysis from Zakamska et al. (2003), there is the possibility for some objects to be classified as both broad and narrow lined with linewidths $1500 < $ FWHM $< 2000$ km s$^{-1}$. To remedy this situation, the broad-line selection was done first, followed by the narrow line selection, with the stipulation that an object classified as broad lined cannot be reclassified as narrow lined.

The objects identified as type 2 Seyferts lie in the same region of the gJK plot as ordinary emission line galaxies, separate from the model quasar locus. Additional information, such as a measure of central concentration, as described in Section B2, would be required for an experiment aimed specifically at their selection. However, as type 2 objects were not the primary target of this study, no attempt was made to select them specifically.

Much information regarding the type 2 population may be gleaned from this sample. For the 43 objects at $z < 0.33$, both H$\alpha$ and H$\beta$ are visible in the spectra, and a measure of the dust reddening can be estimated using the ratio of the attenuated to observed Balmer line ratio. The distribution of E$(B - V)$ values can then be determined, and applied to all 96 objects to estimate their unreddened
magnitudes. However, due to the fact that these spectra are not of high enough quality to accurately subtract the stellar continuum to fully reveal the emission lines, and the PSF magnitudes show signs of host galaxy light contamination, further analysis on this type 2 population is deferred to a later date.

B2 Star-forming galaxies

Star-forming galaxies are selected as having at least one visible emission line, but do not satisfy the criteria for type 2 AGN as described in the previous section. Fig. B1 shows their location on the BPT plot as black dots below the dashed demarcation curve. Fig. B2 indicates where they lie in the gJK diagram, marked as blue crosses. They are generally bluer than the absorption line galaxies in \( g - J \), but still significantly redder than quasars at the same low redshifts. The model track for an Sc-type galaxy is overlaid on the gJK diagram as well, as in Fig. 4. The star-forming galaxies cluster around the model track as expected.

Star-forming galaxies are a significant contaminant in the gJK selection of quasars, as they can be morphologically compact and lie in the region of colour space occupied by reddened quasars at \( 1 < z < 3 \). However, their images tend to be much less centrally concentrated than quasars and AGN, so imposing a restriction on a measurement of concentration (such as the difference between the PSF and Petrosian magnitudes from SDSS photometry, or between the aperMag1 and aperMag3 measures from WFCAM photometry) could significantly reduce the number of star-forming galaxies considered as candidates. This additional information could also assist in selection of type 2 Seyfert galaxies, as they tend to be more concentrated than star-forming galaxies as well, albeit to a lesser degree than the quasars.

B3 Absorption line galaxies

Aside from the stellar locus, the most densely populated region of the gJK two-colour diagram is occupied by low redshift absorption line galaxies, shown as red dots in Fig. B2. As we did not want to completely eliminate morphologically extended objects, but did not have enough spectroscopic fibres available to observe them all, the galaxy region was sparsely sampled, resulting in the hole seen in Fig. B2 at \( g - J = 4, J - K = 1.5 \). Most of the objects with peculiar colours, such as the absorption line galaxies at \( g - J \sim 1 \), have close neighbours, or have poor SDSS photometry.

B4 Stars

Stars account for nearly 10 per cent of the total number of objects observed. Fig. B3 indicates where they lie in gJK colour space, with the majority clustered near the selection line. As can be seen, there are two distinct populations, with M-type stars redder in \( g - J \) than the other types, which includes K through A-type stars.

Stars with particularly red colours in \( J - K \) are predominantly close pairs of stars. Occasionally the objects that are red in \( J - K \) are located in the haloes of bright stars, and were not excluded by the sky variance cut described in Section 2.3. Some objects clearly exhibit spectral features of two stellar types, with the final designation being determined by the type contributing most to the flux in the AAOmega spectra. These account for most of the objects that are classified as one type but appear in the colour space occupied by the other type.

If reduction of stellar contamination is a priority when designing future observations based on the gJK colours, the selection line could be moved redward in \( J - K \), at the expense of rare, high-redshift objects seen in Fig. 5. The number of pairs of stars observed spectroscopically that have anomalously red \( J - K \) colours could be significantly reduced by visual inspection of their images.

SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article:

**Table 5.** Photometric and spectroscopic information for each observed object.

This material is available as part of the online article from: http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-2966.2007.13138.x (this link will take you to the article abstract).

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