The Optical and Near-Infrared Properties of 2837 Quasars in the \textit{UKIRT} Infrared Deep Sky Survey (UKIDSS)

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ABSTRACT

The UKIRT Infrared Deep Sky Survey (UKIDSS) is the first of a new generation of hemispheric imaging projects to extend the work of the Two Micron All Sky Survey (2MASS) by reaching three magnitudes deeper in \textit{Y JHK} imaging, to $K = 18.2$ (5\,\sigma, Vega) over wide fields. Better complementing existing optical surveys such as the Sloan Digital Sky Survey (SDSS), the resulting public imaging catalogues provide new photometry of rare object samples too faint to be reached previously. The first data release of UKIDSS has already surpassed 2MASS in terms of photons gathered, and using this new dataset we examine the near-infrared properties of 2837 quasars found in the SDSS and newly catalogued by the UKIDSS in $\sim 189 \, \text{deg}^2$. The matched quasars include the RA range 22$^h$ to 4$^h$ on the Southern Equatorial Stripe (SDSS Stripe 82), an area of significant future followup possibilities with deeper surveys and pointed observations. The sample covers the redshift and absolute magnitude ranges $0.08 \leq z \leq 5.03$ and $-29.5 \leq M_i \leq -22.0$, and 98 per cent of SDSS quasars have matching UKIDSS data. We discuss the photometry, astrometry, and various colour properties of the quasars. We also examine the effectiveness of quasar/star separation using the near-infrared passbands. The combination of SDSS \textit{ugriz} photometry with the \textit{Y JHK} near-infrared photometry from UKIDSS over large areas of sky has enormous potential for advancing our understanding of the quasar population.

Key words: surveys – catalogues – quasars: general – quasars: emission lines

1 INTRODUCTION

In the several years since the SDSS (Sloan Digital Sky Survey) and 2MASS (Two Micron All Sky Survey) projects pioneered large uniform digital datasets accessible to the astronomical community, another generation of surveys has been spurred by improvements in imaging technology, software pipelines, and the ability to carry out sophisticated astronomical science on databases. In particular, over the next several years, two large consortia will be exploring deeply into the near-infrared with surveys from 4-metre class telescopes. Using UKIDSS (UKIRT Infrared Deep Sky Survey, Lawrence et al. 2006) and VISTA (Visible and Infrared Survey Telescope for Astronomy, Emerson et al. 2004), they aim to extend the limiting flux of the 2MASS \textit{JHK} bands by three magnitudes or more, as well as into new parameter spaces using the novel \textit{Z} and \textit{Y} optical/near-infrared filters (Hewett et al. 2006).

In part motivated by the search for objects such as the coolest brown dwarfs and highest redshift quasars, deeper surveys in the near-infrared provide valuable information for the practical selection and identification of rare objects from parent catalogues of normal stars and other contaminants. Both high-redshift quasars and brown dwarfs are marked by rising flux towards and beyond 1\,$\mu\text{m}$, but, until recently, were rarely discovered in the near-infrared due to the shallow limiting magnitude of existing surveys. For normal Galactic stars detected in SDSS, for example, 2MASS data has provided sufficient depth for successful characterization, such as in Finlator et al. (2000), but brown dwarfs and high-redshift quasars are typically much fainter than the 2MASS survey limits – only $\sim 17$ per cent of SDSS-discovered quasars are also detected in 2MASS, and these are primarily at low redshifts.

With the first large data release by the UKIDSS, it is now possible to study the near-infrared properties of a large sample of SDSS spectroscopically identified quasars over an extended redshift range. Further, with an eye towards future selection techniques, the addition of deeper near-infrared
photometry has potential for the identification of new classes of rare quasars. Just as importantly, deeper near-infrared data facilitates the rejection of spurious candidates in such surveys. Therefore, combining data from the UKIDSS with existing data from SDSS and other surveys may offer large gains in observing efficiency.

In this work, we match spectroscopically identified quasars from the SDSS DR3 with their newly released UKIDSS DR1 photometry. We discuss the data matching procedures in the following sections, examine the joint properties of the quasars compared with normal stars, the photometric behaviour of the quasars versus redshift, and their relation to synthetically generated model quasars. As in Schneider et al. (2003), all absolute magnitude values in this paper are based on the standard 'concordance' cosmology of $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

## 2 DATA SOURCES

### 2.1 SDSS DR3 Quasar Catalog

The quasars used in this work are drawn from the SDSS DR3 Quasar Catalog, assembled by Schneider et al. (2003). The DR3 quasar catalogue was generated from spectroscopically confirmed quasars discovered and/or reidentified by the SDSS over 3732 deg$^2$, within the main SDSS northern area as well as southern equatorial stripe (SDSS Stripe 82). While further updates to the SDSS quasar catalogue are ongoing, the DR3 version represents the final product in the right ascension (RA) and declination (Dec) regions used in this paper. The SDSS automated spectroscopic quasar program, whose selection criteria and strategy have been discussed in Richards et al. (2002), targets quasars at redshifts up to $z = 5.4$, and down to magnitudes $m_i < 20.2$ (AB), using several magnitude and colour cuts applied to the SDSS ugriz photometry.

Following inspection of the individual spectra and compilation with attributes such as radio, near-infrared, and X-ray emission properties, Schneider et al. retained 46,420 objects, ranging in redshifts from $z = 0.08$ to 5.41, and absolute magnitudes $M_i = -22$ to $-30.2$ (including some serendipitously discovered quasars down to a spectroscopic survey limit of $i < 21.0$). Typically, the photometric accuracy of the SDSS is 0.03 mag and systematic astrometric errors are less than 0.2′. These photometric and astrometric properties reflect the high quality of SDSS data. Further details of the SDSS hardware and software can be found in: York et al. (2000), Fukugita et al. (1996), Gunn et al. (1998), Hogg et al. (2001), Lupton et al. (1999), Stoughton et al. (2002), Smith et al. (2002), Pier et al. (2003), Abazajian et al. (2004).
Figure 3. The redshift and absolute $M_i$ magnitude distribution of UKIDSS-SDSS matched quasars is shown, and compared against the parent SDSS DR3 quasar catalogue. In the central panel are plotted the 2837 quasars from the successfully matched UKIDSS-SDSS subsample. The slight density edge perceptible within the sample results from the magnitude limits of the SDSS main quasar spectroscopic survey (Richards et al. 2002). The side panels are histograms of the distributions in redshift and absolute magnitude, with the parent DR3 quasar catalog shown as a dotted line, and matched quasars as a solid line. The parent sample histograms have been scaled by a factor of 0.14 for comparison.

Figure 4. Differences between SDSS and UKIDSS measured positions in arcseconds. The dotted line shows results for a bright stellar reference population of 34,000 sources in the matched area. The solid line shows the sample of 2837 matched quasars. The modeled profiles have Gaussian FWHM of 0\'\'3 for the quasar sample, and 0\'\'35 for the stellar reference sample. The stellar population histograms have been scaled by a factor of 0.14 for comparison.

2.2 UKIDSS

UKIDSS represents the first wide and deep ground-based survey in the near-infrared regime since 2MASS operations concluded in 2001. The UKIDSS \cite{cam} is composed of several sub-surveys targeting different parameter spaces of both Galactic and extragalactic observations, planned in a typical ‘wedding cake’ strategy which balances wide-field versus deep coverage. The five sub-surveys include deep/narrow target fields such as the UDS (Ultra Deep Survey), and wide/shallow fields such as the GPS (Galactic Plane Survey). Of relevance to this work is the UKIDSS Large Area Survey (LAS), which aims to cover an area of 4,000 $deg^2$ matching the SDSS over seven years.

During the $\sim 130$ nights per year in which the WFCAM instrument \cite{wfcam} is mounted on UKIRT and devoted to UKIDSS, the project observes the sky under tolerable seeing conditions (\lq 1\'\'2), and photometric or mildly non-photometric skies. Each pointing of the telescope covers an effective area of 0.21 $deg^2$, but due to the sparse-filled arrangement of the four 2K$\times$2K infrared detectors, four pointings are necessary to fill in a full sky patch of $\sim 0.77$ $deg^2$. Because of the large pixel scale of the detectors (0\'\'4/pixel) and the large field of view, survey progress is quick, covering this filled tile area in the four LAS $YJHK$ filters to a depth of $K = 18.2$ (5$\sigma$, Vega) in approximately 20 minutes, with a total of 40 s effective exposure time per band. Survey progress under good conditions can thus produce approximately $25$ $deg^2$ of complete LAS imaging data per night. Dye et al. \cite{dye}, Lawrence et al. \cite{lawrence}, and Warren et al. \cite{warren} provide comprehensive descriptions of the survey hardware, software strategy and data product characteristics.

Following observation, pipeline processing, and catalogue generation, the typical limiting magnitude of the LAS is $YJHK = [20.16, 19.56, 18.81, 18.19]$ (Vega, 5$\sigma$) or [20.79, 20.49, 20.19, 20.09] (AB, 5$\sigma$), with photometry having been bootstrap-calibrated to the 2MASS system. These limits represent an approximately three magnitude depth gain compared to the 2MASS $YJHK$ imagery. Astrometric accuracy in the LAS is typically $< 0\'\'1$, and photometric accuracy is $\sim 0.04$ mag, measured in the $J$-band. Imaging in the four filters is taken in pairs, $YJ$ and $HK$, for any particular field. The imaging catalogues present essentially an instantaneous single epoch measurement for each filter-pair but significant time intervals can exist between the two filter-pairs.

3 CATALOGUE MATCHED DATA

3.1 Matching Procedure

The UKIDSS DR1 release overlaps a subset of the SDSS northern and southern areas and achieves a limiting magnitude nearer to the SDSS for a typical quasar spectral energy distribution (SED) than did 2MASS. At the same time, the photometric and astrometric performance of the UKIDSS is similar to the SDSS.

The areal extent of the newly released UKIDSS imaging is much smaller than the available SDSS DR3 coverage and we first trimmed the Schneider et al. (2005) quasar catalogue to dimensions similar to the UKIDSS DR1 imaging areas. Among the total UKIDSS DR1 imaging area released, a significant portion is located in the southern equatorial stripe, which is also a special SDSS region where many repeated scans have been taken over the lifetime of the survey. In the future, this area may become a target of deeper survey programs at various wavelengths. The SDSS and UKIDSS have a common southern equatorial stripe area with an RA-range of approximately 22$^h$ to 4$^h$, and a declination-range of $\pm 1.265^\circ$, centered on 0$^\circ$.

\footnote{\url{http://www.ukidss.org}}
Figure 5. Photometry differences between UKIDSS and 2MASS measurements. Left panel: for a sample of reliable stellar sources detected by both UKIDSS and 2MASS with $J > 14$, the photometry differences between the two surveys are shown versus UKIDSS magnitude, in the three 2MASS bands, $JHK$. Dotted vertical lines in both panels indicate the 2MASS 5σ limiting point-source magnitude in each band ($JHK = 16.55, 15.85, 15.05$, Vega). Right panel: the photometry of 474 (out of 2837 matched) SDSS DR3 quasars found in both UKIDSS and 2MASS catalogues is shown, illustrating the sample scatter and that most SDSS DR3 quasars will be found below the 2MASS catalogue limits. (Full-resolution figures will appear in published version, or may be downloaded in the meantime at http://www.astro.ex.ac.uk/people/chiu/chiu.figs.tar.gz)

Extracting quasars from the DR3 catalogue without any imposed constraints, the quasars were then positionally cross-matched with the UKIDSS DR1 database, with a tolerance of 1′′0, matching only the nearest object to the queried position. A total of 2837 SDSS quasars were successfully matched to the UKIDSS DR1 database.

3.2 Matched sample properties

3.2.1 General properties

A portion of the southern equatorial RA/Dec distribution of the resulting sample of SDSS-UKIDSS quasars is shown in Figure 1. Other sky-areas contributing to the SDSS-UKIDSS sample have more complicated geometries (described in Warren et al. 2006), but show similar matched object densities (within ~ 30 per cent due to SDSS spectroscopic plate coverage over-/under-densities). Within the RA-range $1^h$ to $2^h40^m$, of 574 input quasars in the southern equatorial stripe, (corresponding to a sky density of 9 deg$^{-2}$), 567 (98.7 per cent) have a corresponding UKIDSS source with at least one detection in the $YJHK$-bands. We employ the results of all the matches to the UKIDSS DR1 catalogue, irrespective of the number of detections among the four passbands. Figure 2 illustrates the relationship of typical matched quasars to the parent sample of all matched point sources in the joint SDSS-UKIDSS dataset, showing the spectroscopic and photometric sample limits of the catalogues from which the quasars are drawn. Ongoing projects, for example employing the novel AAOmega multifibre spectrograph at AAT (Saunders et al. 2004), aim to extend the SDSS-selected quasar sample to magnitudes below these limits, and improve constraints on the faint and distant quasar luminosity function.

Figure 3 illustrates the redshift and absolute magnitude dependence of the full sample of SDSS-UKIDSS quasars, which show no strong bias from the parent unmatched sample of SDSS quasars. Further, in UKIDSS areas which are imaged in all four UKIDSS $YJHK$ bands, we examined the frequency of quasar detection versus band and found no strong dependence – when a quasar is detected, it can generally be detected in all four bands. Specifically, for example in the above representative area, out of 330 quasars found in the smaller 4-band imaged area, 329 are detected in the $Y$-band, 328 in the $J$-band, 321 in the $H$-band and 325 in the $K$-band, while 319 have detections in all $YJHK$ bands.

3.2.2 Morphology

In the DR3 quasar catalogue, quasars at high redshifts are generally unresolved by the SDSS imaging pipeline (Chiu et al. 2005). The SDSS-UKIDSS sample shows a similar behaviour in the UKIDSS imaging bands, though with a greater fraction of resolved quasars detected at low redshift – 222 of 278 quasars with redshifts $z < 0.5$ are classified as extended in the UKIDSS mergedClass parameter. Because the mergedClass parameter combines weighted measurements
of the measured source profile from each of the available bands, contribution from low redshift quasar host galaxies, particularly in the $K$ band, may influence this trend (see Maddox & Hewett 2006). However, by $z > 1.0$, only $\sim 12$ per cent of quasars are resolved in any UKIDSS band, falling to 7 per cent and 5 per cent by $z > 2.0$ and $z > 3.0$ respectively. In the present sample (without regard to redshift), the majority of the quasars are classified as point sources with good point spread function (PSF) fits (UKIDSS database $\text{mergedClass} = -1$, $N = 1675/2837$), many are classified as extended ($\text{mergedClass} = +1$, $N = 717/2837$), and a smaller fraction possess poor PSF-fits ($\text{mergedClass} = -2$, $N = 435/2837$). Ten objects appear as uncertain extended-source fits ($\text{mergedClass} = -3$), or are classified as noise.

3.2.3 Astrometry

As cosmologically distant point sources, quasars should provide a fixed reference frame on the sky. Therefore, comparisons of the astrometry between different surveys of these same objects can yield a measure of the relative astrometric errors. Using the sample of SDSS-UKIDSS quasars then, the positional offsets between the surveys was determined. The resulting distribution of relative separations is shown in Figure 6 along with a large reference sample of reliably measured normal Galactic stars ($N \sim 30,000$). While a maximum offset of $0.5''$ can be seen for a few quasars (and up to $0.6''$ for the stellar population), the bulk of the sample is well modelled by a Gaussian distribution with a full-width at half-maximum (FWHM) of $0.3''$. In comparison, the stellar population displays a somewhat wider distribution of astrometric residuals, with a FWHM of $\sim 0.35''$. These parameters are consistent with the SDSS/2MASS astrometric comparison in Finlator et al. (2000). We also find a small systematic absolute offset in both RA and Dec of $\sim 0.05''$ between the SDSS and UKIDSS positions.

3.2.4 2MASS magnitudes

In addition to providing SDSS-measured properties, the DR3 quasar catalogue was matched with external datasets, such as FIRST and ROSAT detections, Galactic extinction measurements and 2MASS photometry. Using this information, we examined the differences in quasar photometry between the 2MASS and UKIDSS measurements. For the SDSS-UKIDSS quasars, we extracted any available 2MASS magnitudes in the $JHK$ bands. As can be inferred from the resulting sample in Figure 7, many SDSS-UKIDSS quasars fall well below the nominal 2MASS 5σ limiting magnitudes ($JHK = 16.55, 15.85, 15.05$, Vega). However, a small fraction are still measured in the 2MASS catalogues, down to approximately $J \sim 17.8$, $H \sim 17.2$, and $K \sim 16.5$. In our sample, 474 of 2837 SDSS/UKIDSS matched quasars (17 per cent) were sufficiently bright to be detected in the 2MASS catalogue in any band. Comparing UKIDSS and 2MASS magnitudes in this range then, we find a scatter of $\sigma = 0.3$ mag between the two quasar measurements (above the 5σ 2MASS limits), and similar to the envelope of scatter in reference point sources at these faint magnitudes, which for example ranges from $\sigma = 0.1$ mag at the bright end to $\sigma = 0.4$ mag at the 5σ 2MASS detection limits (Figure 7 left panel). While quasar variability may account for a small portion of the photometric differences, on the order of $\Delta m \sim 0.15$ mag, as Vanden Berk et al. (2004) have discussed previously, here the photometric errors should dominate any such variability contribution.

Although many quasars are individually not detected in the 2MASS imaging, the UKIDSS photometry now allows us to demonstrate the latent detection ability of 2MASS. Selecting 60 SDSS-UKIDSS quasars at $J > 18$ (which cannot be detected in 2MASS), we extracted the 2MASS $JHK$ atlas images around each SDSS-UKIDSS quasar position. The 2MASS atlas images were then stacked, yielding the composite source shown in Figure 8. In areas of sky that will not be covered by UKIDSS, or other future surveys, this technique may allow 2MASS to provide useful information on populations of faint sources (a technique recently demonstrated by White et al. 2006, for example).
4 QUASAR COLOURS

Using the SDSS-UKIDSS quasars, we now examine optical and near-infrared colour properties of the same objects, their relation to stellar properties in the same parameter space, and consider the utility of quasar-star separation. An important preliminary note here is that in all calculations as well as resulting figures and tables in this work, we assume that the magnitude systems returned automatically and with modification by the SDSS and UKIDSS survey databases the case of the SDSS, these are asinh magnitudes on the system (specifically pasMag), while for the UKIDSS, ti are Vega magnitudes calibrated to 2MASS (YJKaperm for point sources). We adopt this approach for the ease of observers querying the joint dataset, so that AB-to-Vega magnitude and colour transformations (which are sometimes accidentally neglected) are not necessary for immediate interpretation of retrieved data in conjunction with results shown here. Also, slight variations in the choice of conversion factors (depending on the spectral template used) will therefore not affect the results discussed. For subsequent analysis however, a single more consistent physical AB magnitude scheme may be preferable, using AB-Vega transformations such as those tabulated in Hewett et al. (2006).

4.1 The UKIDSS filter system

The filter systems of the SDSS and UKIDSS are shown in Figure 7. In particular, while the SDSS ugriz and MKO-based JHK filters are well-known and commonly used, the addition of the novel Z and Y filters of the UKIDSS are a relatively recent development and noteworthy. Proposed by Warren & Hewett (2002), and discussed extensively in Hewett et al. (2006), the UKIDSS Z and Y filters improved upon the existing broadband coverage between the optical and near-infrared in several respects.

The Z and Y bands are defined by interference filters with sharp wavelength cutoffs and, coupled with the high sensitivity of modern infrared detectors, remedy some of the deficiencies in current imaging around \( \lambda \sim 1\mu m \). First, the UKIDSS Z filter is much more sharply defined than the SDSS z, because the SDSS z filter itself has a relatively flat transmission of \( \sim 0.4 \) which continues out beyond 1\( \mu m \) (illustrated by Fukugita et al. 1996). The overall z-band redward cutoff (i.e. total system throughput) then relies on the declining CCD silicon sensitivity to terminate the band, and thus results in a very extended filter profile. The CCD-detector sensitivity envelope, beginning with a minimum in the ultraviolet, rising to a maximum around the r-band, and terminating with a minimum at 1\( \mu m \), largely accounts for the highly peaked shape of the SDSS throughput. This is in contrast to the relatively flat response of the UKIDSS system, owing to the roughly constant sensitivity of the HAWAII-2 HgCdTe detectors throughout the near-infrared.

Continuing redward, the Y-band (used by the UKIDSS LAS) provides a new region of sensitivity in the \( \Delta \lambda \sim 1500\ \AA \) wavelength gap between the z(or Z)-band and the MKO J band. Among other motivations, the Y filter was specifically designed with the selection of very cool brown dwarfs and high-redshift quasars in mind. The increasingly red flux of these objects versus temperature (for brown dwarfs) or redshift (for quasars) has proven highly useful in rare object searches in the last few years (Chiu et al. 2006; Fan et al. 2006; Chiu et al. 2007), but has reached a barrier as current surveys, such as the SDSS, no longer provide sufficient sensitivity in the 1\( \mu m \) range. The high throughput of the UKIDSS system at these wavelengths, combined with sharper band profiles, allow the more precise discrimination of potential quasar candidate redshifts and brown dwarf types, while avoiding unnecessary sky background contamination.

The resulting \( F_{\lambda} \) sensitivity of the UKIDSS imaging is shown in the bottom panel of Figure 7 and compared with the SDSS as well as 2MASS sensitivities in the JHK bands. A composite quasar spectrum at \( z=3 \) is also shown, illustrating the important capability of UKIDSS to detect the typical quasar near-infrared continuum, versus non-detection in 2MASS.

Figure 8. Colours of 2837 SDSS-UKIDSS quasars versus redshift, in ugrizYJHK combinations of interest. The panels generally progress from optical to near-infrared colours. The colours are calculated using the natural magnitude systems of each survey, without conversion between AB or Vega (see §3, i.e. SDSS magnitudes are AB (asinh) magnitudes while UKIDSS magnitudes are Vega-based. The colour-redshift tracks of a composite quasar are overlaid (solid line), generated from a modified version of the model quasar SED described in Maddox & Hewett (2006). (Full-resolution figures will appear in published version, or may be downloaded in the meantime at http://www.astro.ex.ac.uk/people/chiu/chiu.figs.tar.gz).
4.2 Quasar colours vs. redshift

In Figure 8 we plot the 2837 SDSS-UKIDSS quasars, in various colours versus SDSS spectroscopic redshift. In each colour, only those quasars with detected flux in both of the two contributing bands are plotted, i.e. objects with non-detections in the necessary filters (indicated as such as by mag = −9999.99 in the SDSS or UKIDSS catalogues) are omitted.

As has been discussed in Richards et al. (2002), Richards et al. (2003), Maddox & Hewett (2006), and Richards et al. (2006a), the behaviour of quasar colours is suprisingly well-modeled across extended redshift and luminosity ranges by a single composite SED. The passage of the strong emission lines in and out of the various filters controls the small-scale fluctuation of the quasar colours versus redshift, while the extended underlying continuum provides the distinguishing characteristic separating quasar colours from those of stars. Importantly, for certain applications, such as the $z > 6$ $i$-dropout selection used by Fan et al. (2006), absorption by the intervening intergalactic medium provides a strong spectral discontinuity allowing the identification of quasars. This effect can be seen for example in the rapidly rising $r - i$ colour at redshifts $z > 4$, as more quasar flux in the $r$ band is absorbed by the intergalactic medium with increasing redshift.

The observed quasar sample beyond $z \sim 2.5$ is affected by the declining space density of the quasar population and the small volumes probed. As a result, the flux-limited sample becomes quite sparse (Figure 9). In order to extend the useful predicted colour-redshift values further than $z \sim 2.5$, we generated synthetic photometry and colours of a composite quasar spectrum to predict the median redshift-colour evolution track. The technique has been described previously (‘quasar cloning’ – Maddox & Hewett 2006; Richards et al. 2006a; Hewett et al. 2006; Chiu et al. 2005), and we follow a similar approach here. The modified composite quasar based on the spectrum of Maddox & Hewett was employed as the model SED, updated to include a base continuum contribution, which dominates at $\lambda < 10000$ Å, consisting of a dual power-law form

$$\alpha = \begin{cases} -0.5 & \lambda < 2600\text{Å} \\ -0.2 & \lambda > 2600\text{Å}, \end{cases}$$

where $\alpha$ specifies the quasar continuum slope, $f_\nu \propto \nu^\alpha$. A blackbody component, with $T = 1850$ K, dominates at $\lambda > 10000$ Å, resulting in an overall spectral shape similar to the composite spectrum of Glikman et al. (2006). For each redshift bin in steps of $\Delta z = 0.1$, the model SED was redshifted and the average effect of intervening Lyman-$\alpha$ absorption added. The resulting quasar spectra were used to generate magnitudes and colours, again with SDSS magnitudes on the AB system, and UKIDSS magnitudes on the Vega system, as would naturally be found in the respective survey databases. These are overlaid in Figure 8. Similar colour-redshift loci, based directly on the various composite quasar spectra available (e.g. Francis et al. 1991; Brotherton et al. 2001; Vanden Berk et al. 2001), are frequently employed for a variety of purposes. It should be stressed that the significant contribution of host galaxy light in the low-luminosity quasars that typically dominate the composite spectra at wavelengths $> 5000$ Å leads to predictions that are far too red in the optical-near-infrared colours, compared to the observations, at redshifts $z > 2$.

In addition, given the large magnitude range covered by the SDSS-UKIDSS quasars, we investigated whether the observed distribution of quasar colours showed dependence on luminosity. This was accomplished by selecting two subsets of quasars, those bright enough to be detected in 2MASS, and the remaining ones detected only in UKIDSS. The colour differences between the two samples were calculated in redshift bins of size $\Delta z = 0.2$ and are shown in Figure 9. No significant difference is seen between the two samples.

4.3 Quasar colours versus normal stars

To compare the quasar colours with those of normal stars, we extracted a stellar sample from the UKIDSS/SDSS database. This was accomplished by querying the UKIDSS reliableLasPointSource table, which returned relatively bright objects displaying good photometric errors ($\sigma < 0.1$ mag), unresolved shape/flux profiles, and in uncrowded areas. Then, for a few selected two-colour spaces of interest, the stellar and quasar samples are plotted in Figure 10.

Photometric searches for quasars generally compete against heavy contamination by stellar objects with similar colours, due to the intrinsic rarity of quasars. The relative distributions of quasars versus stars in a chosen colour combination will generally control the search efficiency, i.e. how many contaminants must be observed to return one object...
Figure 10. SDSS-UKIDSS quasars (small dots) in colour-colour diagrams (ugrizYJHK) with the density of normal stars shown as contours. Quasar-star separation is highly effective in colours involving the bluest bands, such as $u - g$, but then decreases in utility in the optical. With near-infrared and particularly $K$-band imaging, quasar-star separation again can provide a powerful selection method. Note: colours here are calculated from natural magnitude systems of each survey, without conversion between AB or Vega — i.e. SDSS magnitudes are AB (asinh) magnitudes while UKIDSS magnitudes are Vega based (see §4). Quasar symbol colours are encoded as follows — black: $z < 0.5$, blue: $0.5 < z < 1.0$, green: $1.0 < z < 2.0$, yellow: $2.0 < z < 3.0$, red: $3.0 < z < 6.0$ (Full-resolution figures will appear in published version, or may be downloaded in the meantime at http://www.astro.ex.ac.uk/people/chiu/chiu.figs.tar.gz)

From the desired sample. The progression of the two-colour plots in Figure 10 illustrates the varying success of distinguishing quasars from normal stars using different colours. For colours involving the ultraviolet, such as in $(u - g)$, $(g - r)$, the strong short-wavelength quasar continuum flux is well known to provide a separation from stars via the ultraviolet-excess (UVX) technique. Relatively clear separation of the two populations is observed here and provides a highly successful selection method for low redshift quasars.

In the optical bands, adjacent filter combinations provide little discrimination between the quasar and stellar populations. However, with the addition of near-infrared data, and particularly $K$-band imaging, the extended quasar continua again results in an effective differentiation between quasars and stars. This attribute, exploited by the ‘KX’ method (Warren et al. 2000), can provide a useful selection at high redshift, $z \geq 2.5$, where the UVX technique is unsuccessful due to the effect of absorption by the IGM in the bluest passbands.

Looking farther into the infrared, an additional area of significant interest in the future may be the combination of deep near-infrared surveys such as UKIDSS with mid-infrared legacy imaging from the Spitzer Space Telescope. As has been demonstrated by Stern et al. (2005), Hatziminaoglou et al. (2005), and Richards et al. (2006b), quasar-star separation is highly successful in the mid-infrared bands, and also benefits from high sensitivity due to the suppressed background (15$\mu$Jy in 90 s at 3.6$\mu$m). In areas with good optical, near-infrared, and proposed mid-infrared imaging coverage from Spitzer, such as the southern equatorial stripe, the combination of the resulting catalogues has the potential to reach new distant and faint quasar populations while providing nearly continuous bandpass coverage as emission lines and continuum flux shift with redshift.

5 QUASAR COLOUR SELECTION STRATEGIES

The utility of quasars in probing the distant universe has been demonstrated to great effect in the past few years, with these high redshift objects illuminating not only their own properties, but also the physical state of the IGM and the distant universe. However, the discovery of quasars in
certain redshift intervals is, in practice, a laborious enterprise. In the absence of information from the wavelength extremes, identifying quasars by special properties such as radio or X-ray flux, discovery of quasars at redshifts near \( z \approx 2.5 \), \( z \approx 5.6 \), and \( z > 6 \) remains a significant challenge. Observers fight the combination of the intrinsically declining numbers of the target population and the increasing numbers of contaminating Galactic stars. In previous work we have outlined some of the selection techniques and numbers of quasars to be expected in the SDSS and UKIDSS, and have found that the UKIDSS-SDSS joint dataset is capable of selecting quasars at \( z > 6.5 \) (Hewett et al. 2004; Chiu et al. 2003; Warren & Hewett 2002). However, at the magnitude limits of the UKIDSS \((m_{AB} \sim 20 - 21)\), the \( N \sim 90 \) expected quasars at \( z > 6.5 \) on the whole sky clearly places this parameter space in the category of rare, high-value, but resource-intensive targets.

Here, we discuss the more tractable question of improving the effectiveness of quasar selection at redshifts \( z \sim 2.5 \) and \( z \sim 5.6 \) where colour-selected samples in the optical encounter particular difficulties (Schneider et al. 2003). The relatively deep UKIDSS, and future VISTA, limiting magnitudes in the near-infrared, and the high rate of success in matching the present sample of SDSS quasars to UKIDSS, suggests that quasars at \( z \sim 2.5 \) and \( z \sim 5.6 \) may be recovered by employing \( K\)-band information. Figure 11 shows, for example, a more detailed view of the quasar-star separation in colour space when \( K\)-band information is added. While the population overlap (and thus contamination) is significant for predicted quasar colours around \( z \approx 1.4 \), the colour separation becomes large from \( z = 2.0 \) to \( z = 3.5 \). Because the quasars shown are gathered from optical selection techniques, this implies that independent (or joint) use of the near-infrared photometry on unidentified stellar sources in such a region should yield additional quasars.

Thus, an appropriate choice of optical and near-infrared colours can select quasars in the redshift ranges of interest. Figure 12 illustrates one example of a successful quasar identification/separation scheme in the \((u - z), (Y - K)\) colour space which more cleanly separates normal Galactic stars from quasars by sampling the underlying characteristic spectral break/inflexion features, as described by Warren et al. (2000) and Richards et al. (2006a).

This colour selection boundary illustrated is given by the following criteria:

\[
\begin{align*}
(u - z) &< 4.5 \\
(Y - K) &> 0.6 \\
(Y - K) &> 0.35(u - z) + 0.425,
\end{align*}
\]

which results in a completeness of 97 per cent (measured by the fraction of quasars selected by the above cut) for those quasars with magnitudes in these bands. The overall success of the selection will vary as a function of the magnitudes of the target population compared to the limiting magnitudes in each passband. For instance, the selection of \( z > 3 \) quasars would be most sensitive (and efficient) using colour cuts in the SDSS \( g\) band and beyond, such as \((r - Y)\), \((Y - K)\).

As illustrated above, the availability of photometry covering the rest-frame optical and near-infrared wavelength regions offers the prospect of obtaining a more complete census of the quasar population, both in terms of the redshift range accessible and the variety of quasar SEDs included. A consequence of the extended restframe wavelength range accessed through observations spanning the \( u \) through \( K \) bands for quasars with redshifts \( 0 < z \lesssim 7 \), is the importance of incorporating realistic model quasar SEDs in order to interpret...
the properties of the quasar population reliably. The simple power-law approximation to quasar SEDs, modulated only by the presence of the strongest emission lines, that is relatively effective when interpreting observations probing only the restframe wavelength region $\lambda \lambda \lambda 1200 - 5000$ Å of high-luminosity quasars over redshifts $0.5 \lesssim z \lesssim 2.5$ is entirely inadequate when analysing quasar samples of the type presented here. To illustrate the point graphically, Figure 13 shows a composite quasar spectrum constructed from Glikman et al. (2006) and Vanden Berk et al. (2001) is shown to illustrate the importance of incorporating information about the SEDs of the target population(s).

The median colours of the matched quasars agree well with predictions generated using a model quasar SED and provide a guide for higher redshift selection techniques. Optical and near-infrared colours, in appropriate combinations, provide effective separation of stars and known quasars over essentially the full redshift range $0 < z < 7$, overcoming the limitations of employing only optical colours in the redshift ranges $z \sim 2.5$ and $z \sim 5.6$.

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