Quasar candidate selection and photometric redshift estimation based on SDSS and UKIDSS data

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ABSTRACT

We present a sample of 8498 quasars with both SDSS *ugriz* optical and UKIDSS *YJHK* near-IR photometric data. With this sample, we obtain the median colour-z relations based on 7400 quasars with magnitude uncertainties less than 0.1mag in all bands. By analyzing the quasar colours, we propose an empirical criterion in the $Y - K$ vs. $g - z$ colour-colour diagram to separate stars and quasars with redshift $z < 4$, and two other criteria for selecting high redshift quasars. Using the SDSS-UKIDSS colour-z relations, we estimate the photometric redshifts of 8498 SDSS-UKIDSS quasars, and find that 85.0% of them are consistent with the spectroscopic redshifts within $|\Delta z| < 0.2$, which leads to a significant increase of the photometric redshift accuracy than that based on the SDSS colour-z relations only. As two tests, we compare our colour selection criterion with a small UKIDSS/EDR quasar/star sample and a sample of 4671 variable sources in the SDSS Stripe 82 region with both SDSS and UKIDSS data. We find that they can be clearly divided into two classes (quasars and stars) by our criterion in the $Y - K$ vs. $g - z$ plot. We select 3834 quasar candidates from the variable sources with $g < 20.5$ in Stripe 82, 826 of them being SDSS quasars and the rest without SDSS spectroscopy. We estimate the photometric redshifts for 3519 quasar candidates with all UKIDSS $YJHK$ data and find an accuracy of 87.5% within $|\Delta z| < 0.2$ with the spectroscopic redshifts of 819 SDSS-UKIDSS identified quasars among them. We demonstrate that even at the same spectroscopy limit as SDSS, with our criterion we can at least partially recover the missing quasars with $z \sim 2.7$ in SDSS. The SDSS identified quasars only take a small fraction (21.5%) of our quasar candidates selected from the variable sources in Stripe 82, indicating that a deeper spectroscopy is very promising in producing a much larger sample of quasars than SDSS. The implications of our current results to the future Chinese LAMOST quasar survey are also discussed.

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

1 INTRODUCTION

The number of quasars has increased substantially in the last decade primarily due to two large optical sky surveys, namely the Two Degree Field (2DF) survey (Boyle et al. 2000) and the Sloan Digital Sky Survey (SDSS)(York et al. 2000). 2DF has obtained spectroscopy of more than 20,000 quasars (Croom et al. 2004), and SDSS has identified more than 100,000 quasars (Schneider et al. 2007; Abazajian et al. 2009). Quasar candidates in these surveys were mainly selected based on their optical colours derived from the photometric data. 2DF mainly selected lower redshift ($z < 2.2$) quasars with UV-excess ($u - b_J$ <-0.36)(Smith et al. 2005), while SDSS adopted a multi-band optical colour selection

method for quasar selection mainly by excluding the point sources within the stellar locus of the colour-colour diagrams (Richards et al. 2002). 90% of SDSS quasars have lower redshift ($z < 2.3$), although some dedicated methods were also developed for discovering high redshift quasars (Fan et al. 2001a,b; Richards et al. 2002). The lower efficiency in identifying quasars with redshift between 2 and 3 is obvious in SDSS (Schneider et al. 2007), because these quasars usually have similar optical colours as stars and thus are mostly excluded by the SDSS quasar candidate selection algorithm (Warren et al. 2000).

In order to obtain a more complete sample of quasars, obviously we need to improve the previous quasar candidate selection methods. An important way to do this has been suggested by using the infrared K-band excess to identify the 'missing' quasars with redshift around 2.7 based on the

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UKIRT (UK Infrared Telescope) Infrared Deep Sky Survey (UKIDSS) (Warren et al. 2000; Hewett et al. 2006; Maddox et al. 2008).[1] Although the $z \sim 2.7$ quasars have similar optical colours as stars, they are more luminous in the infrared K-band. In addition, combining the optical colours in SDSS with the infrared colours in UKIDSS, it should be more efficient to separate stars from both lower redshift quasars ($z < 3$)(Chiu et al. 2007) and higher redshift ones ($z > 6$) (Hewett et al. 2006) in the colour-colour diagrams. This advantage needs to be confirmed by future spectroscopic observations on the larger sample of quasar candidates selected with the SDSS and UKIDSS photometric colours.

Multi-band colours are also crucial for the photometric redshift estimations of quasars. Based on the SDSS colour-z relations, about 70% of the photometric redshifts of quasars are consistent with the spectroscopic ones with the difference $|\Delta z| < 0.2$ (Richards et al. 2001; Wu et al. 2004; Weinstein et al. 2004). This percentage can increase to 85% or higher if the extra GALEX UV photometric data (Ball et al. 2007) or Spitzer IRAC data (Richards et al. 2009b) are added. It has been demonstrated that the photo-z accuracy should be improved if combining the UKIDSS infrared photometry with the SDSS optical photometry for galaxies (Maddox et al. 2008). Such improvement can be also expected for quasar candidates with both SDSS and UKIDSS photometric data, but has not been confirmed by the photometric redshift estimations on a large SDSS-UKIDSS quasar sample so far. In addition, the reliable photometric redshift estimations based on multi-band colours are also important for preparing the quasar candidates for the future spectroscopic surveys (Richards et al. 2009a).

Large quasar survey is one of the key projects of the Chinese Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST), which is a novel reflecting Schmidt telescope with 4 meter effective mirror size, 20 square degree field of view (FOV) and 4000 fibres (Su et al. 1998). As the most efficient optical spectroscopic telescope in the world, LAMOST finished its main construction in 2008 and has entered the commissioning phase. A pilot survey and the regular survey have been planned in 2010 and 2011-2015 respectively. Unlike SDSS, LAMOST does not have its own photometric survey. Therefore, the input catalogue of LAMOST quasar survey will largely rely on the photometric data from other existing surveys. Because of the large overlap of the surveyed area between SDSS and UKIDSS, a combination of SDSS and UKIDSS photometric data is expected to help us to efficiently select a large catalogue of quasar candidates and provide reliable photometric redshifts for the LAMOST quasar survey.

In this study, we first present a large quasar sample with both SDSS and UKIDSS data, and then investigate whether there is a more efficient selection criterion for quasars and whether the combination of UKIDSS data can improve the photometric redshift estimations. As two tests, the results are applied to a small UKIDSS/EDR quasar/star sample
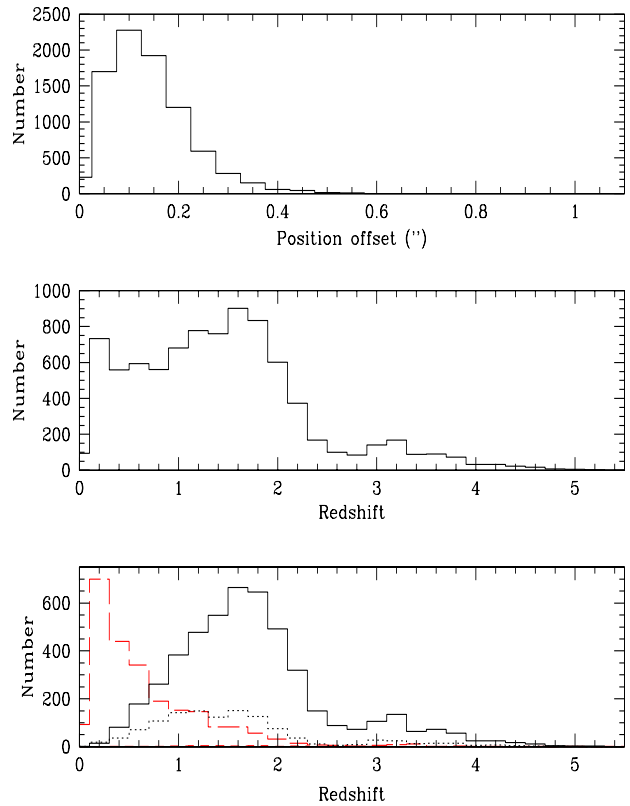
Figure 1. Upper panel: Histogram of the position offsets between SDSS and UKIDSS for 8498 quasars. Middle panel: Histogram of the quasar redshifts. Lower panel: Histograms of the redshifts of quasars with different UKIDSS mergedclass parameter. Solid, dotted, long dashed and short dashed histograms correspond to mergedclass=-1 (star), -2 (probable star), +1 (galaxy) and -3 (probable galaxy), respectively.

and a sample of the variable sources in the SDSS stripe 82 region. The implications of our study to the future LAMOST quasar survey are also discussed.

2 A SAMPLE OF QUASARS WITH BOTH SDSS AND UKIDSS DATA

We cross-identify all quasars in SDSS Data Release 7 (DR7) with the UKIDSS Data Release 3 (DR3), by finding the closest counterparts within $3''$ between the positions in two surveys and requesting all detections in both SDSS ugriz and UKIDSS YJHK bands for each quasar. To do the cross-identifications, we use the CrossID form available at the UKIDSS WFCAM Science Archive website[2], and use only the data in UKIDSS Large Area Survey (LAS) in order to avoid the mis-identifications in the crowded fields with lower Galactic latitudes. This results in a sample of 8498 quasars with both SDSS and UKIDSS data.

In the upper panel of Fig.1, we show the distribution of the position offsets between SDSS and UKIDSS for 8498

Table 1. Parameters of 8498 SDSS-UKIDSS quasars

SDSS RA	SDSS Dec	Redshift	SDSS-UKIDSS Offset($''$)	u	g	r	i	z	Y	J	H	K
0.0498394	0.0403587	0.479	0.1452	17.10	17.88	17.70	17.41	17.20	16.97	16.70	15.96	15.03
0.1625516	-0.3010664	2.125	0.2016	18.16	19.04	18.64	18.44	18.21	18.07	17.76	17.43	16.75
0.2212764	-0.6201625	1.321	0.3712	17.80	18.59	18.31	18.10	18.03	17.94	17.82	17.41	16.81
0.2371434	-1.0693223	2.106	0.2559	19.36	20.09	19.36	18.80	18.24	18.28	18.02	17.35	16.52
0.2426759	-0.7795238	1.897	0.6057	17.75	18.82	18.64	18.12	17.85	17.72	17.60	17.19	16.58

Note: All magnitudes are in Vega system. The full table of 8498 quasars is available in the electronic version of the paper.

quasars. Although we use the search radius $3''$ for identifying the UKIDSS counterparts of SDSS quasars, we find that 99.6% of the closest counterparts are within $0.5''$ of the SDSS positions. Only 33 identifications have offsets larger than $0.5''$, and only three of them have the offset larger than $1''$. Therefore, considering the subarcsecond position accuracy in both SDSS and UKIDSS photometry, the chance probability of misidentification should be very small. The middle panel of Fig.1 shows the redshift distribution of 8498 quasars. The redshifts are distributed in a range from 0.01 to 5.29, with 7468 quasars (87.9% of the total sample) having $z < 2.3$ and 1030 quasars (12.1%) having $z > 2.3$. Only five quasars have redshifts larger than 5. This redshift distribution is quite similar as that of the whole quasar sample in SDSS (Schneider et al. 2007). The deficiency of $z \sim 2.7$ quasars can be also clearly observed. In the lower panel of Fig. 1 we show the redshift distribution of the quasars with different UKIDSS mergedclass parameter. Among the 8498 SDSS-UKIDSS quasars, 4905, 1181, 2383 and 29 quasars are classified with UKIDSS mergedclass=-1 (star), -2 (probable star), +1 (galaxy) and -3 (probable galaxy), respectively. It is clear that most quasars with $z < 0.5$ are classified as extended in UKIDSS morphology, which confirms the significant contributions of host galaxy light to the quasar emissions in near-IR (Maddox & Hewett 2006; Chiu et al. 2007). However, the fraction of quasars classified as point sources in UKIDSS morphology becomes dominant at $z > 1$. This is understandable because it is hard to detect the host galaxies of quasars at high redshift even in the near-IR band.

In Fig.2 and Fig.3 we show the distributions of magnitudes and magnitude uncertainties of 8498 quasars in both SDSS $ugriz$ bands and UKIDSS $YJHK$ bands. All magnitudes are in Vega system throughout this paper if not specified. We convert the SDSS AB magnitudes to Vega magnitudes using the following scalings (Hewett et al. 2006): $u = u(AB) - 0.927, g = g(AB) + 0.103, r = r(AB) - 0.146, i = i(AB) - 0.366$ and $z = z(AB) - 0.533$. The magnitudes in SDSS are corrected for the Galactic extinctions using the extinction map of Schlegel et al. (1998). The quasar magnitudes are mostly in a range from 17 to 20 in all SDSS optical bands and UKIDSS Y and J bands, from 16 to 19 in H band and from 15 to 18 in K band. The median magnitudes are 18.3,19.11,18.70,18.37, 18.13 for $ugriz$ and 18.16,17.79,17.22, 16.59 for $YJHK$, respectively. The magnitude uncertainties are typically smaller than 0.05mag in SDSS gri band, 0.1mag in u band, and 0.15mag in SDSS z and UKIDSS $YJHK$ bands. The median values of magnitude uncertainties are 0.03,0.01,0.01,0.01, 0.04 for $ugriz$ and 0.03,0.03,0.04, 0.04 for $YJHK$, respectively. The me-
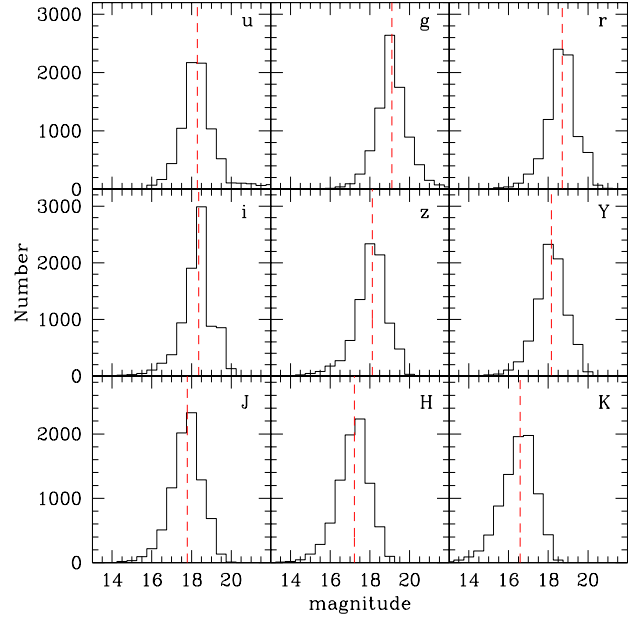

Figure 2. Histograms of the quasar magnitudes (in Vega system) in all SDSS optical bands ($ugriz$) and UKIDSS near-IR bands($YJHK$). Dashed lines indicate the median magnitudes.

dian values of magnitudes and magnitude uncertainties are also indicated in Fig. 2 and Fig. 3.

The parameters of this SDSS-UKIDSS sample of 8498 quasars, including the coordinate, position offset, redshift and all magnitudes in SDSS and UKIDSS bands, are summarized in Table 1 (only a portion is shown here for displaying the content, and the whole table is available in the electronic version).

3 THE COLOUR-Z RELATIONS

With the SDSS-UKIDSS sample of quasars, we can calculate the median colour-z relations from $u - g$ to $H - K$ colours, which have important applications in determining the quasar selection criteria and photometric redshifts. In order to obtain reliable colours in both optical and near-IR bands, we only use the quasars with magnitude uncertainties in all 9 bands ($ugrizYJHK$) less than 0.1mag. This reduces the quasar number from 8498 to 7400. Because the redshift range for our quasar sample is from 0.1 to 5.2, we are only be able to derive the colour-z relations for $z < 5.2$ quasars. We
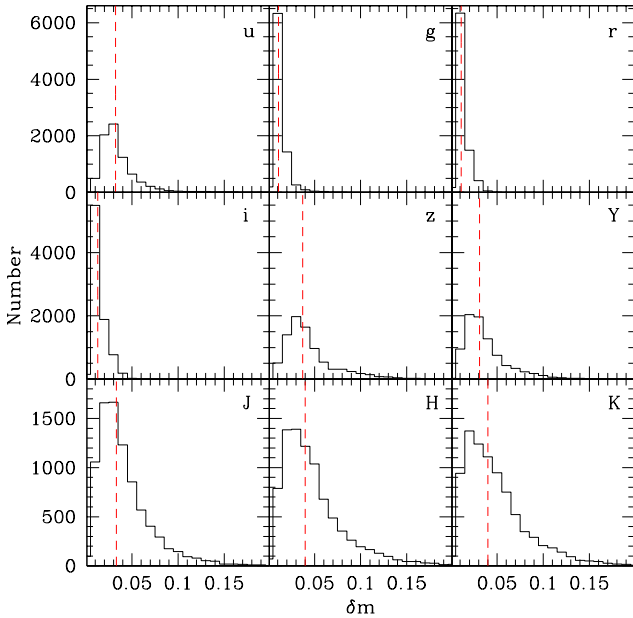
Figure 3. Histograms of the quasar magnitude uncertainties in all SDSS optical bands ($ugriz$) and UKIDSS near-IR bands ($YJHK$). Dashed lines indicate the median values of the magnitude uncertainties.

divide the 7400 quasars into different redshift bins with a bin size of 0.05, 0.1 and 0.2 for $z < 3$, $3 < z < 4.5$ and $z > 4.5$ respectively, and derive the median value of each colour at each redshift bin. We notice that the median $u - g$ and $g - r$ colour values derived from our sample are quite uncertain when the redshift is larger than 3 and 4.3 respectively, due to the small number (< 5) of quasars in the redshift bin. Therefore, we only give the median colour values for $u - g$ at $z < 3$ and $g - r$ at $z < 4.3$.

In a previous work, Hewett et al. (2006) presented three tables of optical/near-IR colours derived for redshifted blue, average and red model quasar spectra, which are based on the quasar model SED given in Maddox & Hewett (2006). Chiu et al. (2007) plotted the colour-z relations generated from a modified version of the above quasar SED and compare them with the observational data of 2837 SDSS-UKIDSS quasars. In Fig. 4 we show the median colour-z relations derived from 7400 SDSS-UKIDSS quasars and the comparisons with the colours of all 8498 quasars in our present SDSS-UKIDSS sample. The colour-z relations given by Hewett et al. (2006) using the mean quasar spectrum are also shown for comparison. The agreement between our median colour-z relations and those in Hewett et al. (2006) is generally very well, especially for all colours in optical bands and $Y - J$ colour in near-IR band. However, the differences of these two colour-z relations can be clearly seen at $z < 0.5$. Comparing with our median colour-z relations and the data, the colour-z relations of Hewett et al. (2006) seem to be redder in near-IR colours (except $Y - J$) and bluer in optical colours for $z < 0.5$ quasars. This is probably due to the continuum shape assumption in Maddox & Hewett et al. (2006) because the host galaxy contribution is significant for $z < 0.5$ quasars. Chiu et al. (2007) modified this con-

tinuum shape and obtained the colour-z relation consistent with observations.

In Table 2 we present our median colour-z relations. For $u - g$ colour at $3 < z < 3.5$, $g - r$ colour at $4.3 < z < 5.0$ and all other colours at $5 < z < 6.4$, the values from the Table 26 in Hewett et al. (2006) are also added for the purpose of determining the quasar selection criteria and photometric redshifts in the following sections.

4 SEPARATING QUASARS AND STARS IN THE COLOUR-COLOUR DIAGRAM

Separating quasars from stars is an important but difficult task in any quasar survey. Usually this can be done by the optical colour selection methods for low redshift quasars with $z < 2.3$, as did by both 2DF and SDSS. At higher redshifts, quasars usually have similar optical colours as stars so the contamination from stars to the quasar candidate selection is serious. However, as suggested by Warren et al. (2000), Chiu et al. (2007) and Maddox et al. (2008), this can be improved by incorporating the near-IR colours of quasars, because quasars are relatively more luminous in K-band than stars even though their optical colours are almost the same in some cases (e.g. for quasars with z~2.7).

In some previous works, the colour-colour diagrams for quasars and stars were analyzed by including the UKIDSS near-IR colours. Hewett et al. (2006) proposed to separate quasars with $6 < z < 7.2$ from dwarf stars in the $i - Y$ vs. $Y - J$ diagram. Maddox et al. (2008) studied the selection criterion of $z < 4$ quasar candidates in the $g - J$ vs. $J - K$ diagram. Chiu et al. (2007) investigated the different colour-colour diagrams in optical and near-IR bands with a sample of 2837 SDSS-UKIDSS quasars, and found $g - r$ vs. $u - g$ diagram and $H - K$ vs. $J - H$ diagram are more effective in separating quasars and stars than other colour-colour diagrams. They also proposed to use the $Y - K$ vs. $u - z$ diagram to select low redshift ($z < 3$) quasars.

In section 2, we have obtained a sample of 8498 quasars, which forms the largest sample of SDSS-UKIDSS quasars currently available. In order to study the quasar-star separation in the colour-colour diagrams, we also cross-identified 8996 stars with both SDSS DR7 and UKIDSS/LAS DR3 data following the same procedure as for our quasar sample. These stars are classified as 'STAR' or 'STAR_LATE' in SDSS spectroscopy. All magnitudes of stars in SDSS $ugriz$ bands are converted to Vega magnitudes and corrected for the Galactic extinction.

We have produced many colour-colour diagrams with our SDSS-UKIDSS quasar and star samples, including five colour-colour diagrams mentioned in the previous works mentioned above. Obviously separating quasars from stars is generally difficult in most colour-colour diagrams, but the colours involving K-band magnitude, such as $H - K$, $J - K$ and $Y - K$, can certainly provide some helps. The best diagram we found to separate quasars with $z < 4$ and stars is the $Y - K$ vs. $g - z$ diagram, which is plotted in Fig. 5. From it, we see that a criterion defined by $Y - K > 0.46 * (g - z) + 0.53$, can well separate the $z < 4$ quasars and stars. This criterion is obtained by searching for the highest efficiency in separating known SDSS-UKIDSS quasars and stars in our samples. With this criterion, we can
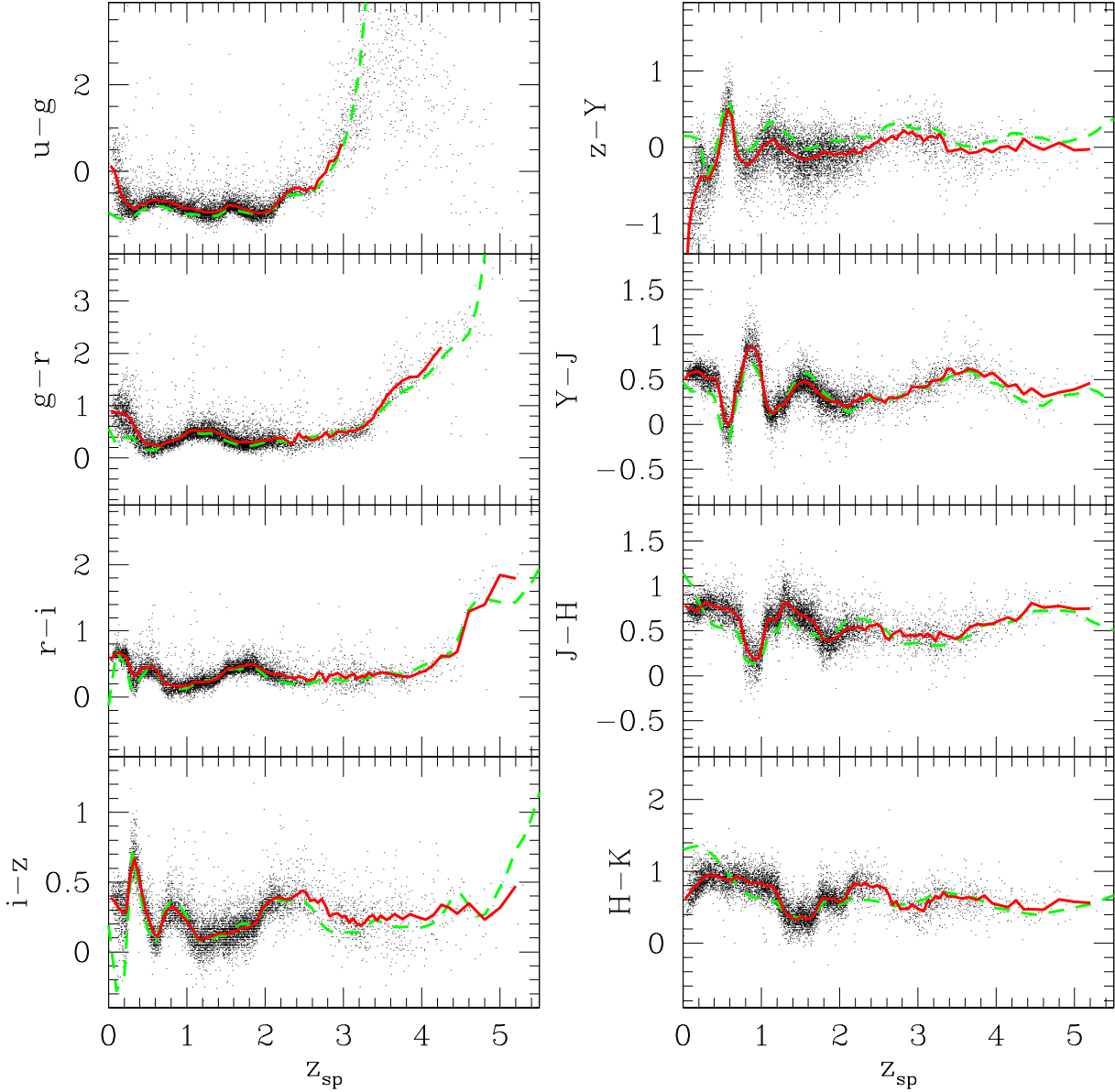
Figure 4. The colour-z relations in optical and near-IR bands. Black dots denote 8498 SDSS-UKIDSS quasars, solid red lines represent the median colour-z relations derived from 7400 quasars with magnitude uncertainties less than 0.1mag. Dashed green lines represent the colour-z relations given by Hewett et al. (2006) for redshifted average model quasar spectrum.

recover 8301 quasars in our sample of 8498 quasars (with a percentage of 97.7%), including 8277 of 8397 $z < 4$ quasars (with a completeness of 98.6%) and 24 of 101 $z > 4$ quasars (with a percentage of 23.8%). For 8996 SDSS-UKIDSS stars, only 204 of them (with a percentage of 2.3%) satisfy this criterion. Although the percentage of mis-identifying stars as quasars is very low, we must bear in mind that the actual contamination rate of stars could be higher than our estimation because SDSS only observed a tiny fraction of stars with particular colours spectroscopically. However, we believe that our selection criterion is still fine as most SDSS untargetted stars (both early type and late type) should be

within the stellar locus of our $Y - K$ vs. $g - z$ diagram and would not be selected as $z < 4$ quasar candidate by SDSS. In Fig. 5 we also show the predicted colours at different redshifts from the median colour-z relations of quasars (see section 3), which also confirm that our criterion is applicable for identifying quasars with $z < 4$. We notice that Chiu et al. (2006) has proposed a selection criterion in the $Y - K$ vs. $u - z$ diagram to select quasars, but their criterion can only be applied to $z < 3$ quasars because the Lyα line moves out of the u-band for $z > 3$ quasars. In comparison, our new criterion has the advantage to select quasars with redshift up to 4. In addition, when we plot our SDSS-UKIDSS data
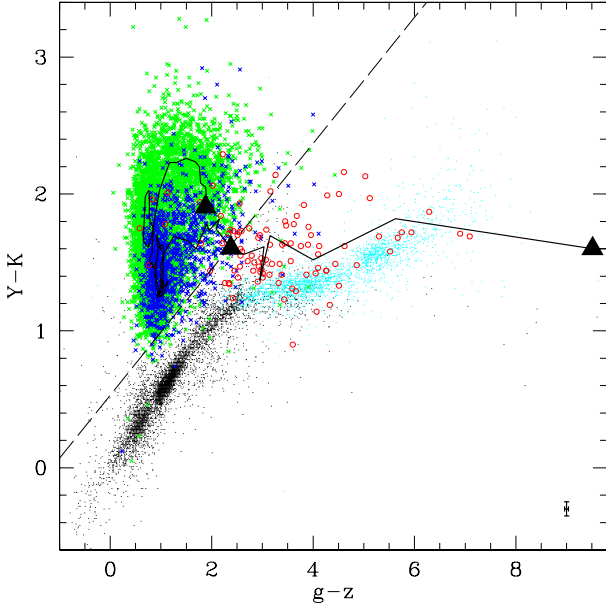
Figure 5. The $Y - K$ vs. $g - z$ colour-colour diagram of the SDSS-UKIDSS quasar and star samples. Green crosses, blue crosses and red circles denote quasars with $z \leqslant 2.2$, $2.2 < z \leqslant 4$ and $z > 4$, respectively. Black dots and cyan dots denote stars classified as 'STAR' and 'STAR_LATE' by SDSS spectroscopy. Dashed line indicates the separation criterion $Y - k > 0.46 * (g - z) + 0.53$. Solid curve is derived from the median colour-z relation (see section 3) of quasars. The solid triangles, from left to right, mark the colours of quasars with z=0.02, 4, and 5 respectively, derived from the colour-z relation. Typical error bars are shown in the lower-right corner.
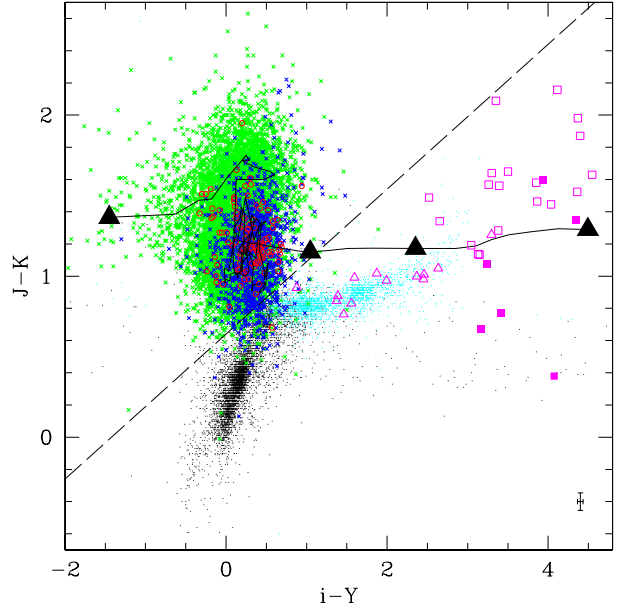

Figure 6. The $J - K$ vs. $i - Y$ colour-colour diagram of the SDSS-UKIDSS quasar and star samples. Open triangles, open squares and solid squares denote M, L and T dwarfs given in Tables 9 and 10 of Hewett et al. (2006). Other symbols have the same meaning as in Fig. 5. Dashed line indicates the separation criterion $J - K = 0.45 * (i - Y) + 0.64$. Solid curve is derived from the colour-z relation (see section 3) of quasars. The solid triangles, from left to right, mark the colours of quasars with z=0.02, 5.3, 5.7 and 6.4 respectively, derived from the colour-z relation. Typical error bars are shown in the lower-right corner.

of quasars and stars, we find that they are more separated in the $Y - K$ vs. $g - z$ plot than in the $Y - K$ vs. $u - z$ plot.

Because the SDSS z-band photometry is not as deeper as in $ugri$ bands, our selection criterion in the $Y - K$ vs. $g - z$ diagram may be problematic for objects with z magnitude fainter than 20.5 (in AB system). Therefore, we also propose another criterion in the $Y - K$ vs. $g - Y$ diagram, namely, $Y - K > 0.32 * (g - Y) + 0.67$, to separate quasars from stars. With this criterion, we can recover 8315 quasars in our sample of 8498 quasars, with a percentage of 97.8%, including 8276 of 8397 $z < 4$ quasars (with a completeness of 98.6%) and 39 of 101 $z > 4$ quasars (with a percentage of 38.6%), but we also select 304 of 8996 stars (with a percentage of 3.4%). The star contamination is higher than the case of using the criterion in the $Y - K$ vs. $g - z$ diagram. In the following study, we will mainly use the criterion in the $Y - K$ vs. $g - z$ diagram for selecting $z < 4$ quasars in order to keep a lower contamination rate of stars.

For quasars with $z > 4$, obviously we need other selection criteria. In most colour-colour diagrams, these high-z quasars have similar colours as late-type stars because the strong Lyα line of quasars moves to the red part of optical spectra. By looking carefully at the various colour-colour diagrams, we realize that the high-z quasars and late-type stars often have different $J - K$ and $i - Y$ colours. We make a $J - K$ vs. $i - Y$ colour-colour diagram (shown in Fig.6) with the data of SDSS-UKIDSS quasars and stars.
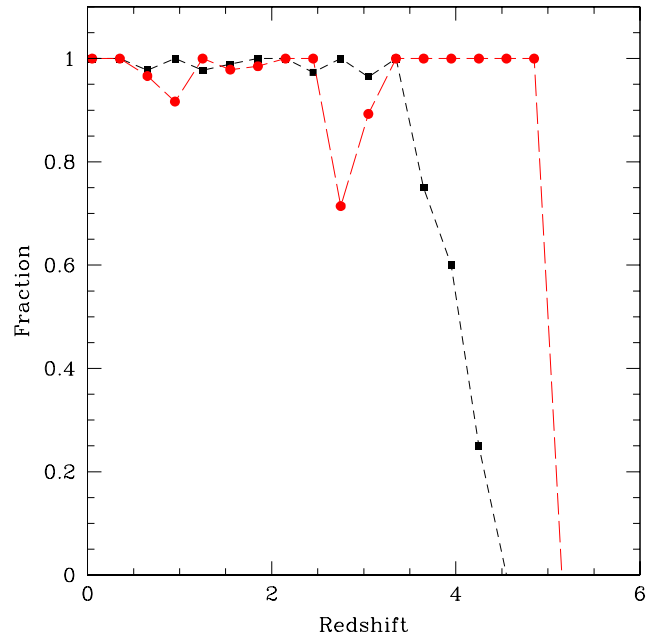

Figure 7. Fraction of the 704 FIRST radio-selected SDSS/UKIDSS quasars recovered by applying two quasar selection criteria. The short and long dashed lines denote the cases of using the criteria in the $Y - K/g - z$ and $J - K/i - Y$ plots, respectively. The redshift bin size is 0.3.
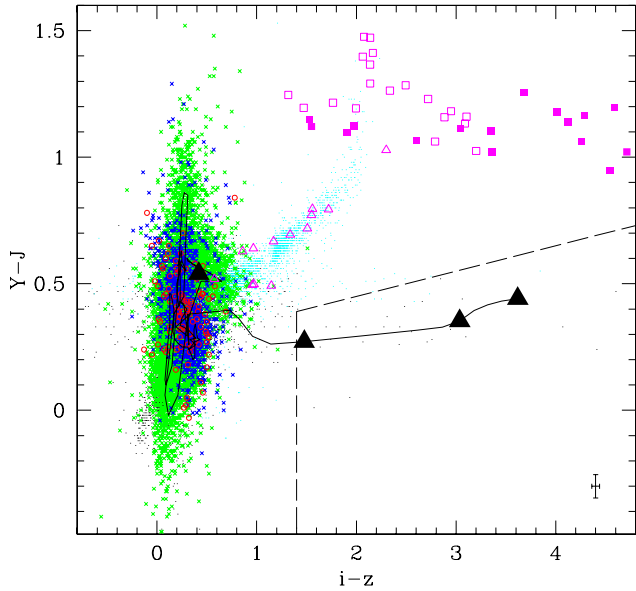
Figure 8. The $Y - J$ vs. $i - z$ colour-colour diagram of the SDSS-UKIDSS quasar and star samples. Symbols have the same meaning as in Fig. 7. Solid curves are derived from the colour-z relation (see section 3) of quasars. The solid triangles, from left to right, mark the colours of quasars with z=0.02, 5.6, 6.0 and 6.4 respectively, derived from the colour-z relation. Straight dashed lines indicate the selection criterion $i - z > 1.4$ & $Y - J < 0.1 * (i - z) + 0.25$ for $z > 5.6$ quasars. Typical error bars are shown in the lower-right corner.

Although some $z < 4$ quasars have the same colours as stars, the $z > 4$ quasars can be well separated from stars with a criterion $J - K > 0.45 * (i - Y) + 0.64$. In Fig. 6 we also show the predicted colours from the median colour-z relations of quasars (see section 3), which also confirm that our criterion is applicable for identifying quasars with $z < 5.3$, although some quasars with $2.5 < z < 3$, whose colours ($i - Y \sim 0.5$ and $J - K \sim 0.8$) are similar as stars in this colour-colour diagram, could be missed by applying this criterion. We check this criterion with our SDSS-UKIDSS sample of quasars and stars, and find that using the criterion $J - K > 0.45 * (i - Y) + 0.64$ we can recover 8289 of 8498 quasars in our sample (with a percentage of 97.5%), including 100 of 101 $z > 4$ quasars (with a percentage of 99.0%) and 8189 of 8397 $z < 4$ quasars (with a percentage of 97.5%). Only one $z > 4$ quasars and 208 $z < 4$ quasars are missed. For 8996 stars, 474 of them (with a percentage of 5.3%) are mis-identified as quasars by our criterion. Therefore, the criterion in the $J - K$ vs. $i - Y$ diagram is better than the criterion in the $Y - K$ vs. $g - z$ diagram for identifying high-z quasars (with $4 < z < 5.3$), although the latter is better for identifying $z < 4$ quasars.

Perhaps a better way is to combine these two criteria for identifying quasars with redshift up to 5.3, namely,

$$Y - K > 0.46 * (g - z) + 0.53, \text{ or} \tag{1}$$

$$J - K > 0.45 * (i - Y) + 0.64. \tag{2}$$

With the above criteria, we can recover 8447 of 8498 quasars in our sample (with a percentage of 99.4%), including 8347

of 8397 $z < 4$ quasars (with a percentage of 99.4%) and 100 of 101 $4 < z < 5.3$ quasars (with a percentage of 99.0%). However, we would also mis-identify 566 stars as quasars, with a percentage of 6.3% of the total number of stars in our current SDSS-UKIDSS sample. In this case, we can achieve the highest efficiency in recovering both $z < 4$ and $4 < z < 5.3$ quasars, but the contamination rate of stars is also higher than using the individual criterion we proposed above.

Because the radio quasars identified in SDSS were not selected by the colour-based methods (Richards et al. 2002), we can make a check with the FIRST radio-detected SDSS quasars to estimate the completeness of applying our selection criteria, similar as what has been done in Richards et al. (2006). In our sample of 8498 SDSS/UKIDSS quasars, 704 of them were detected by FIRST. With their photometric data in SDSS and UKIDSS, we can check how many of them can be recovered by our quasar selection criteria in the $Y - K/g - z$ and $J - K/i - Y$ colour-colour diagrams. In Fig. 7 we show the fraction of recovered quasars at each redshift bin for two criteria we proposed above for $z < 4$ and $4 < z < 5.3$ quasars respectively. It is clear that with our $Y - K/g - z$ criterion we can achieve the fraction higher than 95% in each redshift bin with $z < 3.5$, while with our $J - K/i - Y$ criterion we can recover all FIRST quasars with $3.5 < z < 5$. Especially with our $Y - K/g - z$ criterion, we can recover the quasars with $z \sim 2.7$ very well, which seems to be difficult in the case of using the SDSS quasar selection criteria alone (Richards et al. 2006). Such a check supports that with our two criteria we can identify quasars at a completeness higher than 95% if their redshifts are smaller than 5.

Although our current SDSS-UKIDSS quasar sample does not include any quasar with $z > 5.3$, we can explore how to improve the high-z quasar selection by using the colour-z relations. For quasars with $z > 5.3$, especially those with $z > 5.7$, from Fig. 6 we can see clearly that the contaminations of M, L and T dwarfs are much serious in the $J - K$ vs. $i - Y$ diagram. This is a problem already known for identifying high-z quasars (Fan et al. 2001b; Hewett et al. 2006), and the methods to solve it all involved near-IR colours. Fan et al. (2001b) proposed a selection criterion for $z \sim 6$ quasars in the $z - J$ vs. $i - z$ diagram by requesting $i - z > 2.2$ and $z - J < 1.5$. Hewett et al. (2006) mentioned that $z > 6$ quasars can be identified in the $i - Y$ vs. $Y - J$ diagram as they have bluer $Y - J$ colours than L and T dwarfs. Here we present another colour-colour diagram ($Y - J$ vs. $i - z$) in Fig. 8 and propose another selection criterion for high-z quasars: $i - z > 1.4$ and $Y - J < 0.1 * (i - z) + 0.25$. It is clear that using both i drop-out and near-IR colour can help us to separate $z > 5.6$ quasars from stars and low-z quasars, as well as T and L dwarfs effectively, though the contaminations from some stars are still unavoidable. Further spectroscopic observations on some high-z quasar candidates selected with our criterion are expected.

5 PHOTOMETRIC REDSHIFT ESTIMATION

With the colour-z relations derived in section 3, we can estimate the photometric shifts of quasars by comparing the observed colours with the predicted colours at certain redshift by the colour-z relations. Combining SDSS *ugriz* and
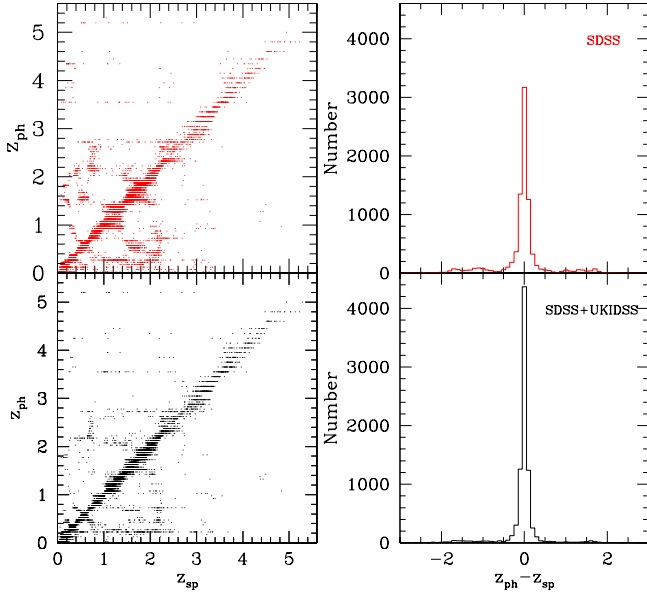
Figure 9. Comparison of photometric redshift estimation results of 8498 SDSS-UKIDSS quasars for the cases of using SDSS colours only (upper panels) and using SDSS-UKIDSS colours (lower panels). z_{ph} and z_{sp} denote photometric and spectroscopic redshifts respectively.

UKIDSS $YJHK$ magnitudes, we can obtain 8 colours from optical $u - g$ colour to near-IR $H - K$ colour for the quasar candidates, then using the χ^2 minimization method we can obtain the most probable photometric redshifts for them. Here the χ^2 is defined as (see Wu et al. 2004):

$$\chi^2 = \sum_{ij} \frac{\left[(m_{i,cz} - m_{j,cz}) - (m_{i,observed} - m_{j,observed}) \right]^2}{\sigma^2_{m_{i,observed}} + \sigma^2_{m_{j,observed}}}, (3)$$

where the sum is obtained for all 8 SDSS-UKIDSS colours, $m_{i,cz} - m_{j,cz}$ is the colour in the colour-z relations, $m_{i,observed} - m_{j,observed}$ is the observed colour of a quasar, $\sigma_{m_{i,observed}}$ and $\sigma_{m_{j,observed}}$ are the uncertainties of observed magnitudes in two SDSS-UKIDSS bands.

We notice that the Lyα emission line moves out of the u band and g band when the redshift is larger than 3.5 and 5 respectively, so in our derived colour-z relation in section 3, we don't have the $u - g$ value for $z < 3.5$ and both the $u - g$ and $g - r$ values for $3.5 < z < 5$. This means that we can only use 7 and 6 of 8 SDSS-UKIDSS colours if the input redshift is larger than 3.5 and 5 respectively. In order to compare the χ^2 values for the cases of using different number of colours at different redshifts, we actually use the χ^2/N (where N is the number of colours and is 8,7,6 respectively for input redshift $z < 3.5, 3.5 < z < 5$ and $z > 5$) instead of χ^2 to determine the photometric redshift by obtaining the minimum of χ^2/N at certain redshift. An IDL program is made for searching the photo-z of quasars by taking the above procedures into account.

We estimate the photometric redshifts of 8498 SDSS-UKIDSS quasars with our program. In order to see more clearly whether using the UKIDSS colours can improve the

photo-z estimation, we also estimate the photometric redshifts of these quasars using the 4 SDSS colours only. Similarly as we did above, actually only 3 and 2 of 4 SDSS colours can be used for input redshifts larger than 3.5 and 5, and photometric redshift is determined by searching the minimum of χ^2/N. In Fig. 9 we show the comparison of the photo-z results obtained with SDSS and SDSS-UKIDSS colours respectively. It is obvious that using both SDSS and UKIDSS colours can improve the photo-z accuracy substantially. For 8498 quasars, 7223 of them (with a percentage of 85.0%) have photometric redshifts given by the SDSS-UKIDSS colours consistent with the spectroscopic redshifts within $|\Delta z| \leqslant 0.2$. 6102 of them (with a percentage of 71.8%) have $|\Delta z| \leqslant 0.1$. In comparison, if using the SDSS colours only, 6179 of quasars (with a percentage of 72.7%) have photometric redshifts consistent with the spectroscopic redshifts within $|\Delta z| \leqslant 0.2$, and 4898 of them (with a percentage of 57.6%) $|\Delta z| \leqslant 0.1$. Therefore, by adding the UKIDSS $YJHK$ data, the accuracy of photo-z can be improved with a percentage of 12.3% for $|\Delta z| \leqslant 0.2$ and 14.2% for $|\Delta z| \leqslant 0.1$, respectively. This substantial improvement is really what we expected. From Fig. 9 we notice that there are still large failures in the photo-z estimations for some quasars, even if the UKIDSS data are added. This is mainly due to the photo-z degeneracy (the χ^2/N minimum values are comparable at two or more different input redshifts) (Wu et al. 2004), and different colours of some special quasars, such as the reddened quasars (Weinstein et al. 2004). More dedicated approaches, such as using the additional morphology and colour information, could help to further improve the photo-z accuracy.

6 TESTS WITH A SMALL UKIDSS/EDR SAMPLE AND VARIABLE SOURCES IN SDSS STRIPE 82 REGION

In the two sections above, we presented the selection criteria of quasar candidates at different redshift and the photometric redshift estimation method. Obviously more tests on these techniques need be done with some existing photometric and spectroscopic samples before their applications to a large quasar survey.

First we test our selection criteria with a sample of 209 objects classified as QSOs and 252 objects classified as A, K, and M stars in Maddox et al. (2008). These objects (with K$\leqslant 17.0$) were selected from UKIDSS/LAS Early Data Release and observed with the AAOmega multi-object spectrograph. In Fig. 10 we plot these objects in the $Y - K$ vs. $g - z$ diagram and compare them with our quasar selection criterion, $Y - K > 0.46 * (g - z) + 0.53$. Among 209 quasars, 186 of them have $z \leqslant 2.2$ and 182 can be found with our criterion, 23 of them have $2.2 < z < 4$ and 19 of them meet our criterion. Therefore, using our proposed selection criterion we can recover 201 of 209 quasars (with a percentage of 96.2%) in Maddox et al. (2008). However, 13 of 252 stars, including one A stars, nine K stars and three M stars, also satisfy our criterion. The fraction of these mis-identified stars is 5.2% of the total number of stars and 6.1% of the total number of objects satisfying our selection criterion. Because all 209 quasars in this sample have $z < 4$, this test confirms that our criterion is indeed applicable for identifying $z < 4$ quasars.
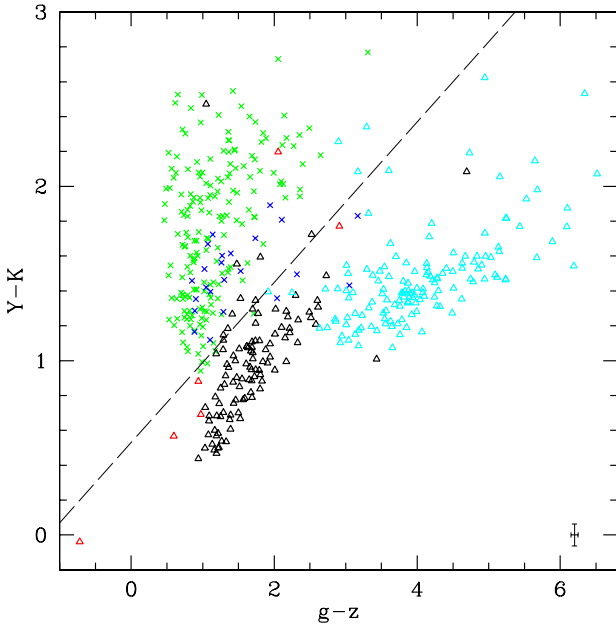
Figure 10. Testing the quasar selection criterion in $Y-K$ vs. $g-z$ colour-colour diagram with the observational data in Maddox et al. (2008). Red, black, and cyan triangles denote the A, K, and M stars respectively. Green and blue crosses denote quasars with $z \leqslant 2.2$ and $2.2 < z \leqslant 4$. Dashed line represents our quasar selection criterion shown in Fig. 6. Typical error bars are shown in the lower-right corner.

Figure 12. Upper panel: $Y-K$ vs. $g-z$ colour-colour diagram of all 4671 variable sources in SDSS Stripe 82 (Sesar et al. 2007) with SDSS-UKIDSS data. Green solid circles denote the 169 RR Lyrae star candidates. Lower panel: Only the variable sources with SDSS spectroscopy are shown. Green and blue crosses denote the quasars with $z \leqslant 2.2$ and $2.2 < z < 4$ respectively. Black and cyan triangles denote the sources classified as STAR and STAR_LATE by SDSS respectively. Dashed lines in both panels represent the quasar selection criterion shown in Fig. 6.
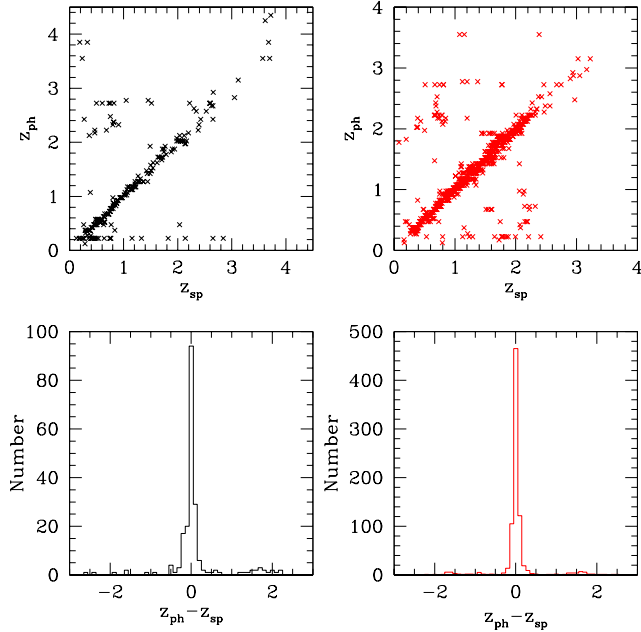

Figure 11. Comparison of the photometric redshifts with the spectroscopic redshifts for 209 quasars (left panels) in Maddox et al. (2008) and 819 SDSS identified quasars (right panels) in a sample of variable sources in Stripe 82.
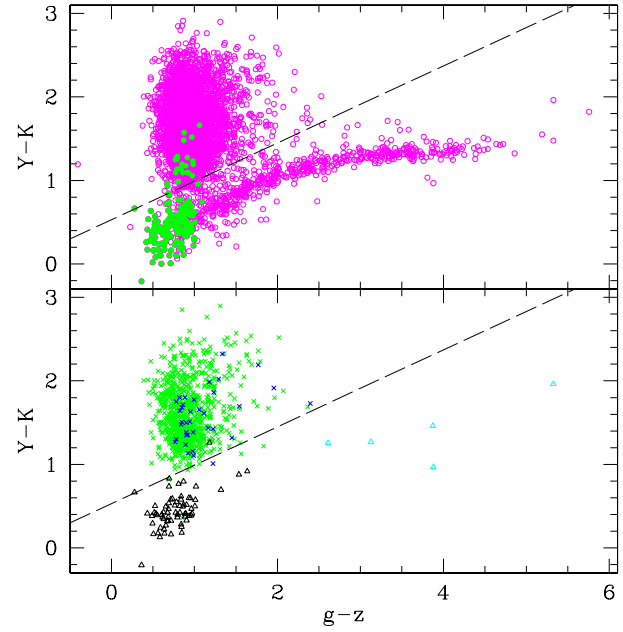
Maddox et al. (2008) indicated that 17 quasars in their sample do not have SDSS spectra, therefore, this test also implies that with our criterion we are able to recover these SDSS missing quasars. In the left panels of Fig. 11 we show the comparison of the photometric redshifts estimated by our program (see section 5) with the spectroscopic redshifts for 209 quasars in this sample. 158 quasars have $|\Delta z| \leqslant 0.2$ and 131 quasars have $|\Delta z| \leqslant 0.1$, with a percentage of 75.6% and 63.2% of the total 209 quasars, respectively. This also confirms the robustness of our photometric redshift estimations.

The second test we made is for a sample of variable sources in SDSS Stripe 82, which is a region of 290deg^2 located along the celestial equator in the southern Galactic cap and was repeatedly observed by SDSS photometry (Ivezic et al. 2007). Sesar et al. (2007) presented 13051 candidate variable sources with criteria $g < 20.5$, $\sigma(g,r) \geqslant 0.05$mag and $\chi^2(g,r) \geqslant 3$ (here $\sigma(g,r)$ and $\chi^2(g,r)$ are the variability amplitude and χ^2 per degree of freedom in g and r bands respectively) from 1.4 million unresolved sources in Stripe 82 observed at least 4 times in each of SDSS $ugri$ bands. Following the same procedure as in section 2, we cross-identify their near-IR counterparts with the UKIDSS/LAS DR3 and find 4671 of 13051 sources with detections in both Y and K bands. In the upper panel of Fig. 12 we plot the colours of these 4671 variable sources in the $Y-K$ vs. $g-z$ diagram and compare them with our quasar selection criterion. The SDSS magnitudes of these 4671 variable sources are taken to
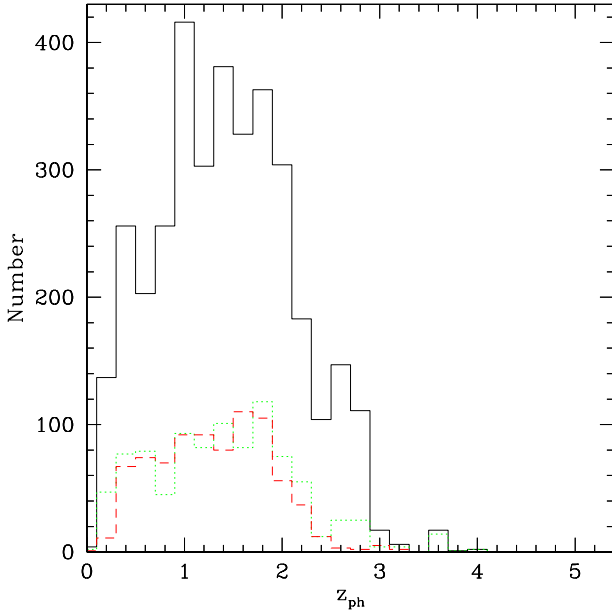
Figure 13. Histogram of photometric redshifts of 3539 quasar candidates selected with our criterion from variable sources with $g < 20.5$ in Stripe 82. Red dashed histogram shows the spectroscopic redshift distribution of 819 SDSS identified quasars. Green dotted histogram shows the redshift distribution of quasar candidates with $i_{\mathrm{vega}} < 19.1$, which is the SDSS spectroscopic limit for $z < 2.3$ quasars.

be the mean magnitudes given in Sesar et al. (2007). It can be clearly seen that these variable sources are divided into two categories approximately by our criterion. 3834 of these 4671 sources (with a percentage of 82.1%) satisfy our criterion, while 837 sources, which do not satisfy our criterion, obviously locate in the stellar locus as we see in Fig. 5 and Fig. 10. In Fig. 12 we also plot 169 sources in this sample, which meet the selection criteria for RR Lyrae stars (Ivezic et al. 2005; Sesar et al. 2007). 145 sources of these 169 RR Lyrae candidates (with a percentage of 85.8%) locate in the stellar locus, and we believe that they are most likely real RR Lyrae stars. However, 24 of these RR Lyrae candidates meet our quasar selection criterion. Future spectroscopic observations on these 24 RR Lyrae candidates will help us to clarify their nature.

Among 4671 variable sources with both SDSS and UKIDSS Y and K band data, 834 of them have been identified by SDSS spectroscopy as quasars with redshifts $0.1 < z < 3.3$. In the lower panel of Fig. 12 we also compare their colours with our selection criterion. We can clearly see that 826 of them (with a percentage of 99.0%) satisfy our criterion, and only 8 quasars are exceptions (5 of them actually locate very close to our criterion line in Fig. 12). 72 of 4671 sources have been identified as 'STAR' and 'STAR_LATE' by SDSS spectroscopy respectively. Two of them (with a percentage of 2.8%) satisfy our quasar selection criterion, and the rest 70 stars clearly locate in the stellar locus in Fig. 12. This again proves the robustness of our quasar selection criterion. Among 834 SDSS identified quasars, 819 of them have UKIDSS data in all $YJHK$ bands. We es-

timate their photometric redshifts with our photo-z program and compare their photometric redshifts with spectroscopic ones. The results are shown in the right panels of Fig. 11. 717 quasars have $|\Delta z| \leqslant 0.2$ and 627 quasars have $|\Delta z| \leqslant 0.1$, with a percentage of 87.5% and 76.6% of the total 819 quasars, respectively. This tight agreement demonstrates again that using both SDSS and UKIDSS colours we can obtain more accurate photometric redshifts for quasars.

Among 3834 quasar candidates selected with our selection criterion in the $Y - K$ vs. $g - z$ diagram from 4671 variable sources in Stripe 82, 3539 sources have all UKIDSS $YJHK$ detections. We estimate their photometric redshifts with our photo-z program and the results are shown in Fig. 13. 3519 quasar candidates have $z_{ph} \leqslant 3.5$, 20 candidates have $3.5 < z_{ph} < 5$, and none candidate has $z_{ph} > 5$. This is understandable because our selection criterion in the $Y - K$ vs. $g - z$ diagram is mainly for selecting $z < 4$ quasars (we also used our second criterion in the $J - K$ vs. $i - Y$ diagram to select possible $z > 4$ quasar candidates, but this only contributed 61 additional candidates). In Fig. 13 we also show the spectroscopic redshift distribution of 819 SDSS identified quasars with all UKIDSS $YJHK$ detections, and the photometric redshift distribution of our quasar candidates with i magnitude in Vega system $i_{\mathrm{AB}} < 19.1$, which is the SDSS spectroscopic limit for $z < 2.3$ quasars. Comparing these two redshift distributions, we realize that even at the same magnitude limit, with our criterion we can probably select more quasars with $z \geqslant 2$ than SDSS. Especially for $z \sim 2.7$ quasars, which are largely missing in SDSS because of their similar colours as stars, can be at least partially recovered with our quasar selection criterion. For our 3834 quasar candidates (with Y and K detections), only 826 of them were identified as quasars by SDSS spectroscopy, which is only a small fraction (21.5%) of our quasar candidates selected from variable sources in Stripe 82. This is mainly because the SDSS spectroscopic limit is $i_{\mathrm{AB}} < 19.1$ for low-z quasars, which is shallow than $g_{\mathrm{AB}} < 20.5$ for selecting variable sources in Stripe 82 (Ivezic et al. 2007; Sesar et al. 2007). We also notice that 207 sources of our quasar candidates in Stripe 82 have been recently identified as 199 new $z < 3$ quasars, 2 white dwarfs and 6 unclassified objects by the 2dF-SDSS LRG and QSO survey (2SLAQ) (Croom et al. 2009). Therefore, deeper spectroscopy than SDSS, such as LAMOST quasar survey which is expected to reach a limit of $i_{\mathrm{AB}} = 20.5$, will hopefully produce a much larger sample of quasars in the future.

In addition, we found that 837 of 4671 variable sources with both SDSS and UKIDSS (Y and K) data do not satisfy our quasar selection criterion in the $Y - K$ vs. $g - z$ diagram. They clearly locate in the stellar locus in this diagram and most of them are probably stars. These 837 star-like sources only take a small fraction (17.9%) of our 4671 SDSS-UKIDSS variable sources in Stripe 82, which confirms that the variability study is very helpful for discovering quasars (Sesar et al. 2007). Our results suggest that with the near-IR photometric data we can further improve the accuracy of selecting quasars from optical variability study. This is probably important for the variability study in the future large photometric surveys, such as that with the Pan-STARRS (Kaiser et al. 2002) and Large Synoptic Survey Telescope (Tyson 2002).

7 DISCUSSIONS

Quasar candidate selections largely rely on the multi-band photometric colours. We have demonstrated that combining the UKIDSS $YJHK$ data with SDSS $ugriz$ data will lead to significant improvements in both quasar selection efficiency and photometric redshift accuracy. With our quasar selection criteria involving both SDSS and UKIDSS colours, we can probably select more $z > 2$ quasar candidates than SDSS even at the same spectroscopic magnitude limit. We believe that at least some SDSS missing quasars with $z \sim 2.7$ can be recovered with our selection criteria. Deeper spectroscopic observations on the quasar candidates selected with our criteria are expected to confirm our results and produce a more complete and much larger quasar sample in the future.

The quasar selection criteria we proposed in this paper are fairly simple, involving only cuts in the two-colour diagrams for optical point sources. More complicated approaches, such as the multi-dimensional search, would be more optimal. To check this, we have tried several different ways to search the criteria for separating quasars and stars, including 3-dimensional colour-colour diagrams, support vector machine (SVM) and Bayesian classification algorithm, but we did not find significant improvements. The detailed comparisons of the results by adopting these different approaches with our current work will be presented in a separated paper.

The study presented in this paper is mainly based on the SDSS-UKIDSS sample of 8498 quasars. Although the cross-identifications were done by finding the closest UKIDSS counterparts of the SDSS quasars and the offsets between the SDSS and UKIDSS positions are mostly within $0.5''$, the mis-identifications of some sources are unavoidable. However, by checking the colour-z relations and colour-colour diagrams of these SDSS-UKIDSS quasars, we believe that the fraction of such mis-identifications should be very low. Therefore, the main results obtained in this paper will not be affected by the mis-identifications of some sources.

Because there is no quasar with $z > 5.3$ in our SDSS-UKIDSS quasar sample, our quasar selection criteria can only be applied to identify $z < 5.3$ quasars. Although we present a criterion in the $Y - J$ vs $i - z$ diagram for finding $z > 5.6$ quasars based on the colour-z relation given by Hewett et al. (2006), this criterion obviously needs to be tested with a large sample of $z > 5.6$ quasars with both SDSS and UKIDSS data. Moreover, for the high-z quasars with $z > 5$, the photometric redshift estimation will largely rely on the UKIDSS colours because both $u - g$ and $g - r$ colours are not available. We also need a sample of $z > 5$ quasars with both SDSS and UKIDSS photometric data to check the accuracy of our photometric redshift estimations. This is expected to be done in the future when a larger high-z quasar sample is available.

Although we made two tests using a UKIDSS/EDR sample and a sample of variable sources in SDSS Stripe 82 to check the robustness of our quasar selection criteria and the photometric redshift method, obviously we still need more tests. We have selected some quasar candidates with $i_{\rm AB} < 19.1$ using our criteria from the variable sources in Stripe 82, which do not have SDSS spectroscopy, and will identify them with optical spectroscopy. This will provide direct evidence for whether using our SDSS/UKIDSS selection criteria can help to find missing quasars in SDSS. On the other hand, finding quasars with certain criteria and comparing them with those in the existing spectroscopic surveys may not be enough for testing the completeness, as most known quasars were identified with the colour selection methods. A better way to do it may be to run simulated colours of quasars, with assumptions on their continuum, emission line and reddening, for different redshift and luminosity (Fan 1999), and check how many simulated quasars can be found with the selection criteria. This will be studied in our future work.

The Chinese LAMOST quasar survey will be done in the next a few years with the most efficient spectroscopic telescope in the world, and is expected to obtain a much larger quasar sample (with the magnitude limit of i=20.5 or 21) than the previous surveys. The results of our current study, if confirmed with further spectroscopic observations, will be helpful for preparing the input catalog of quasar candidates and estimating their photometric redshifts for the LAMOST quasar survey, especially in the overlapped sky area between SDSS and UKIDSS. By doing necessary tests of various selection criteria with the spectroscopic observations in the pilot survey, we will determine the best criteria for quasar candidates selections and apply them to the LAMOST quasar survey. Although the UKIDSS/LAS will cover only a sky area of $4000\deg^2$, with the near-IR colours we will be able to select more complete quasar samples with redshift up to 5 than previous surveys. This large and complete quasar sample will be very important to many further studies such as those on the quasar luminosity function, quasar clustering, and large scale structure in the universe.

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Table 2. Median colour-z relations of SDSS-UKIDSS quasars

Redshift	$u-g$	$g-r$	$r-i$	$i-z$	$z-Y$	$Y-J$	$J-H$	$H-K$
0.025	0.09	0.88	0.58	0.42	-1.87	0.54	0.76	0.61
0.075	-0.02	0.87	0.65	0.39	-1.02	0.57	0.74	0.65
0.125	-0.37	0.87	0.66	0.35	-0.69	0.58	0.74	0.73
0.175	-0.64	0.84	0.64	0.3	-0.48	0.60	0.72	0.76
0.225	-0.74	0.83	0.62	0.31	-0.30	0.59	0.76	0.85
0.275	-0.86	0.72	0.42	0.54	-0.38	0.54	0.80	0.90
0.325	-0.91	0.55	0.30	0.65	-0.40	0.51	0.80	0.95
0.375	-0.84	0.42	0.32	0.57	-0.28	0.51	0.80	0.92
0.425	-0.78	0.31	0.42	0.44	-0.24	0.51	0.77	0.95
0.475	-0.75	0.25	0.43	0.30	0.04	0.35	0.76	0.92
0.525	-0.72	0.21	0.41	0.21	0.34	0.06	0.74	0.91
0.575	-0.69	0.23	0.40	0.12	0.49	-0.02	0.75	0.88
0.625	-0.67	0.20	0.37	0.08	0.39	0.06	0.71	0.89
0.675	-0.70	0.23	0.29	0.17	-0.04	0.38	0.67	0.93
0.725	-0.71	0.26	0.20	0.27	-0.15	0.45	0.65	0.91
0.775	-0.72	0.29	0.18	0.29	-0.18	0.69	0.44	0.90
0.825	-0.77	0.30	0.16	0.31	-0.23	0.85	0.29	0.87
0.875	-0.77	0.35	0.15	0.28	-0.18	0.86	0.21	0.83
0.925	-0.84	0.38	0.14	0.25	-0.13	0.81	0.17	0.84
0.975	-0.87	0.44	0.18	0.24	-0.04	0.72	0.20	0.83
1.025	-0.88	0.48	0.16	0.20	0.03	0.40	0.42	0.83
1.075	-0.89	0.49	0.19	0.15	0.08	0.18	0.60	0.79
1.125	-0.93	0.49	0.20	0.09	0.10	0.10	0.63	0.80
1.175	-0.96	0.49	0.22	0.08	0.10	0.12	0.62	0.75
1.225	-0.96	0.50	0.23	0.10	-0.01	0.21	0.67	0.62
1.275	-0.97	0.51	0.23	0.10	0.03	0.21	0.79	0.47
1.325	-0.98	0.50	0.24	0.11	-0.02	0.27	0.81	0.39
1.375	-0.96	0.48	0.26	0.13	-0.06	0.34	0.76	0.37
1.425	-0.93	0.45	0.31	0.13	-0.10	0.42	0.71	0.32
1.475	-0.89	0.39	0.37	0.13	-0.14	0.45	0.69	0.36
1.525	-0.81	0.37	0.42	0.12	-0.14	0.46	0.68	0.37
1.575	-0.80	0.33	0.43	0.14	-0.16	0.46	0.64	0.32
1.625	-0.84	0.31	0.44	0.15	-0.15	0.44	0.64	0.34
1.675	-0.86	0.29	0.46	0.17	-0.12	0.40	0.58	0.39
1.725	-0.90	0.27	0.46	0.17	-0.12	0.35	0.51	0.50
1.775	-0.92	0.27	0.47	0.16	-0.07	0.31	0.40	0.62
1.825	-0.97	0.27	0.48	0.18	-0.05	0.28	0.39	0.63
1.875	-0.97	0.27	0.47	0.20	-0.05	0.27	0.39	0.60
1.925	-0.98	0.29	0.42	0.25	-0.10	0.25	0.40	0.62
1.975	-0.95	0.31	0.39	0.31	-0.07	0.25	0.42	0.58
2.025	-0.94	0.32	0.35	0.34	-0.06	0.22	0.47	0.56
2.075	-0.90	0.34	0.34	0.36	-0.10	0.20	0.51	0.63
2.125	-0.80	0.34	0.32	0.38	-0.06	0.21	0.53	0.74
2.175	-0.70	0.35	0.32	0.38	-0.03	0.25	0.52	0.83
2.225	-0.60	0.34	0.31	0.38	-0.06	0.25	0.53	0.85
2.275	-0.50	0.30	0.28	0.37	-0.07	0.28	0.53	0.80
2.325	-0.44	0.25	0.30	0.37	-0.02	0.32	0.50	0.84
2.375	-0.43	0.28	0.25	0.39	-0.01	0.34	0.56	0.80
2.425	-0.45	0.34	0.26	0.41	0.04	0.29	0.54	0.77
2.475	-0.43	0.31	0.24	0.43	0.06	0.28	0.54	0.80
2.525	-0.45	0.34	0.23	0.38	0.06	0.27	0.55	0.78
2.575	-0.45	0.33	0.23	0.32	0.09	0.24	0.41	0.76
2.625	-0.44	0.35	0.24	0.39	0.09	0.26	0.46	0.57
2.675	-0.21	0.35	0.27	0.33	0.15	0.28	0.45	0.53
2.725	-0.14	0.40	0.35	0.39	0.13	0.29	0.50	0.58
2.775	0.10	0.50	0.24	0.31	0.19	0.32	0.49	0.46
2.825	0.14	0.39	0.30	0.24	0.23	0.34	0.43	0.48
2.875	0.33	0.40	0.28	0.25	0.16	0.37	0.41	0.49
2.925	0.37	0.46	0.30	0.30	0.19	0.40	0.43	0.53
2.975	0.60	0.47	0.29	0.23	0.11	0.43	0.45	0.50
3.05	0.61	0.48	0.31	0.22	0.10	0.41	0.45	0.46
3.15	1.23	0.50	0.30	0.20	0.13	0.46	0.44	0.56
3.25	2.29	0.57	0.28	0.20	0.14	0.50	0.43	0.64
3.35	4.24	0.70	0.32	0.23	0.06	0.55	0.46	0.68
3.45	6.67	0.94	0.35	0.25	-0.06	0.59	0.41	0.66
3.55	—	1.13	0.35	0.21	-0.03	0.57	0.44	0.60
3.65	—	1.34	0.31	0.25	-0.05	0.63	0.52	0.63
3.75	—	1.41	0.29	0.25	-0.01	0.59	0.56	0.59
3.85	—	1.55	0.31	0.29	0.01	0.55	0.60	0.67
3.95	—	1.49	0.37	0.23	-0.08	0.58	0.59	0.58
4.05	—	1.76	0.38	0.24	-0.05	0.46	0.62	0.53
4.15	—	1.92	0.49	0.23	0.03	0.43	0.64	0.49
4.25	—	2.10	0.66	0.27	-0.07	0.42	0.61	0.59
4.35	—	2.00	0.63	0.32	0.05	0.26	0.65	0.46
4.45	—	2.25	0.59	0.31	0.10	0.38	0.84	0.48
4.60	—	2.38	1.32	0.30	0.05	0.30	0.75	0.48
4.80	—	3.87	1.57	0.19	0.05	0.33	0.78	0.71
5.00	—	7.37	1.81	0.33	-0.19	0.38	0.68	0.54

Table 3. Table 2 continued

Redshift	$u-g$	$g-r$	$r-i$	$i-z$	$z-Y$	$Y-J$	$J-H$	$H-K$
5.20	—	—	1.44	0.73	0.16	0.40	0.612	0.54
5.30	—	—	1.58	0.82	0.23	0.36	0.57	0.58
5.40	—	—	1.73	0.96	0.33	0.29	0.53	0.63
5.50	—	—	1.95	1.14	0.37	0.26	0.51	0.67
5.60	—	—	2.13	1.48	0.34	0.27	0.49	0.69
5.70	—	—	2.05	2.07	0.29	0.29	0.47	0.70
5.80	—	—	2.06	2.62	0.24	0.32	0.46	0.72
5.90	—	—	2.47	2.86	0.24	0.33	0.46	0.73
6.00	—	—	2.99	3.04	0.26	0.35	0.50	0.73
6.10	—	—	3.57	3.18	0.33	0.39	0.52	0.74
6.20	—	—	4.34	3.32	0.47	0.42	0.52	0.76
6.30	—	—	5.56	3.46	0.67	0.43	0.50	0.79
6.40	—	—	7.61	3.62	0.88	0.44	0.48	0.81

Note: All colours are derived from magnitudes in Vega system. The $u-g$ colour at $3 < z < 3.5$, $g-r$ colour at $4.3 < z < 5.0$ and other colours at $5 < z < 6.4$ are adopted from Table 26 of Hewett et al. (2006).