

DISCOVERING THE MISSING $2.2 < z < 3$ QUASARS BY COMBINING OPTICAL VARIABILITY AND OPTICAL/NEAR-INFRARED COLORS*

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Received 2011 May 5; accepted 2011 July 4; published 2011 August 11

ABSTRACT

The identification of quasars in the redshift range $2.2 < z < 3$ is known to be very inefficient because the optical colors of such quasars are indistinguishable from those of stars. Recent studies have proposed using optical variability or near-infrared (near-IR) colors to improve the identification of the missing quasars in this redshift range. Here we present a case study combining both methods. We select a sample of 70 quasar candidates from variables in Sloan Digital Sky Survey (SDSS) Stripe 82, which are non-ultraviolet excess sources and have UKIDSS near-IR public data. They are clearly separated into two parts on the $Y - K/g - z$ color-color diagram, and 59 of them meet or lie close to a newly proposed $Y - K/g - z$ selection criterion for $z < 4$ quasars. Of these 59 sources, 44 were previously identified as quasars in SDSS DR7, and 35 of them are quasars at $2.2 < z < 3$. We present spectroscopic observations of 14 of 15 remaining quasar candidates using the Bok 2.3 m telescope and the MMT 6.5 m telescope, and successfully identify all of them as new quasars at $z = 2.36-2.88$. We also apply this method to a sample of 643 variable quasar candidates with SDSS-UKIDSS nine-band photometric data selected from 1875 new quasar candidates in SDSS Stripe 82 given by Butler & Bloom based on the time-series selections, and find that 188 of them are probably new quasars with photometric redshifts at $2.2 < z < 3$. Our results indicate that the combination of optical variability and optical/near-IR colors is probably the most efficient way to find $2.2 < z < 3$ quasars and is very helpful for constructing a complete quasar sample. We discuss its implications for ongoing and upcoming large optical and near-IR sky surveys.

Key words: galaxies: active – quasars: emission lines – quasars: general

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

Since their discovery in the 1960s (Schmidt 1963), quasars have become important extragalactic objects in astrophysics. They cannot only be used to probe the physics of supermassive black holes and the accretion/jet process, but also are closely related to studies of galaxy evolution, intergalactic medium, large-scale structure, and cosmology. More than 120,000 quasars have been discovered from large optical sky surveys such as the Two-Degree Field Survey (Boyle et al. 2000) and the Sloan Digital Sky Survey (SDSS; York et al. 2000; Schneider et al. 2010). The quasar candidates in these surveys were mainly selected using optical colors; due to strong ultraviolet (UV) and optical emissions, quasars at $z < 2.2$ and $z > 3.0$ can be distinguished from stellar objects in color-color and color-magnitude diagrams based on optical photometry (Smith et al. 2005; Richards et al. 2002; Fan et al. 2000). However, in the redshift range $2.2 < z < 3.0$, the redshifted spectral energy distributions of quasars show similar optical colors to those of regular stars, thus quasar selection using optical color-color diagrams becomes very inefficient due to serious contamination from stars (Fan 1999; Richards et al. 2002, 2006; Schneider et al. 2007). Because of the crucial importance of $z > 2.2$ quasars for studies of the Ly α forest and cosmic baryon acoustic oscillation (BAO; White 2003; McDonald & Eisenstein 2007) and for constructing an accurate luminosity function for studying quasar evolution in

the mid-redshift universe (Wolf et al. 2003; Jiang et al. 2006), we must explore other more efficient ways of identifying the missing $2.2 < z < 3.0$ quasars.

In the last few years, two main approaches have been taken to separating quasars and stars instead of using optical color-color diagrams. The first approach is to use optical variability, as this is one of the well-known properties of quasars (Hook et al. 1994; Cristiani et al. 1996; Giveon et al. 1999). Schmidt et al. (2010) proposed a method of selecting quasar candidates using their intrinsic variability. They showed that quasar structure functions, constructed from the light curves of known quasars in SDSS Stripe 82 (hereafter S82; see also Sesar et al. 2007), can be modeled by a power-law function with amplitude A and power-law index γ . Quasars can be separated from stars in the $A-\gamma$ plane, which enables efficient selection of quasar candidates based on long-term single-band optical photometry (Schmidt et al. 2010). They also pointed out that in the redshift range $2.5 < z < 3.0$, variability can help to select quasars with a completeness of 90%. MacLeod et al. (2011) also developed a method using the damping timescale and asymptotic amplitude of variable sources in S82 to separate quasars from stars with an efficiency higher than 75%. Butler & Bloom (2011) recently presented a similar time-series study of quasars in S82, and proposed using two statistics—a quasar-like variability metric and a non-quasar variability metric—to separate quasar candidates from stars. They claimed that with their method it was possible to achieve nearly a factor of two increase in the number of quasars identified at $2.5 < z < 3.0$. In addition, very recent results from the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS; Eisenstein et al. 2011) also

* Observations reported here were obtained with the Bok telescope at Steward Observatory, and at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

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confirmed the high success rate of spectroscopically identifying variability-selected quasars, which led to a significant increase of $z > 2.2$ quasar density in S82 over a method based on optical colors alone (Palanque-Delabrouille et al. 2011; Ross et al. 2011).

The second approach to separating $z > 2.2$ quasars from stars is utilizing their near-infrared (near-IR) colors. Because the continuum emission from stars usually decreases more rapidly from optical to near-IR wavelengths compared with that of quasars, the near-IR colors of stars are different from those of quasars. This leads to a method of using K -band excess to identify quasars at $z > 2.2$ (e.g., Warren et al. 2000; Croom et al. 2001; Sharp et al. 2002; Hewett et al. 2006; Chiu et al. 2007; Maddox et al. 2008; Smail et al. 2008; Wu & Jia 2010). Using the photometric data in the $ugriz$ bands of SDSS DR7 (Abazajian et al. 2009) and the $YJHK$ bands of the UKIDSS⁵ Large Area Survey (LAS) DR3, Wu & Jia (2010) compiled a sample of 8498 SDSS-UKIDSS quasars and a sample of 8996 SDSS-UKIDSS stars. Based on these two samples, they compared different optical/near-IR color-color diagrams and proposed an efficient empirical criterion for selecting $z < 4$ quasars in the near-IR $Y-K$ and optical $g-z$ color-color diagrams (i.e., $Y-K > 0.46(g-z) + 0.53$, where all magnitudes are Vega magnitudes). With this criterion, they obtained a completeness rate of 98.6% of recovering $z < 4$ quasars with a misidentifying rate of 2.3% for classifying stars as quasars. A check against the FIRST (Becker et al. 1995) radio-detected SDSS quasars, which are believed to be free of color selection bias, also proved that with this $Y-K/g-z$ criterion a completeness higher than 95% can be achieved for these radio-detected quasars with $z < 3.5$, which seems to be difficult in the case of using the SDSS optical color selection criteria alone where a dip around $z \sim 2.7$ in the redshift distribution obviously exists (Richards et al. 2002, 2006; Schneider et al. 2007, 2010). Recently, Peth et al. (2011) extended the study of Wu & Jia (2010) to a much larger sample of 130,000 SDSS-UKIDSS-selected quasar candidates and re-examined the methods of separating stars and mid-redshift quasars with near-IR/optical colors. Using the $Y-K/g-z$ selection criterion, Wu et al. (2010a, 2010b) also successfully identified some $2.2 < z < 3.0$ quasars during the commissioning period of the Chinese GuoShouJing Telescope (LAMOST), which provides further support to the effectiveness of selecting mid-redshift quasars using optical/near-IR colors.

Although both approaches mentioned above can be used to identify quasars at $2.2 < z < 3.0$, a more ideal approach is to combine the variability and optical/near-IR colors to achieve maximum efficiency. In this paper, we present a case study where we selected a sample of variable, non-UV excess, SDSS-UKIDSS quasar candidates in S82 (Schmidt et al. 2010), and spectroscopically identified 14 new quasars at $z = 2.36-2.88$. We also applied this method to some new variable quasar candidates in S82, recently suggested by Butler & Bloom (2011), and found that 188 SDSS-UKIDSS sources are probably new quasars with $2.2 < z < 3$. We describe the sample selections and spectroscopic observations in Section 2, present new $2.2 < z < 3$ quasar candidates in S82 in Section 3, and discuss the results in Section 4.

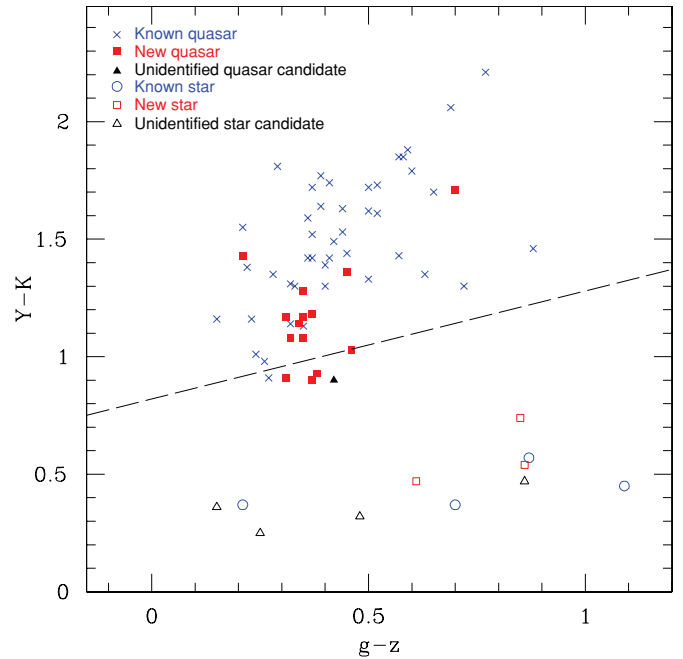


Figure 1. $Y-K$ and $g-z$ colors of 70 SDSS-UKIDSS non-UV-excess variable quasar candidates selected from Schmidt et al. (2010), in comparison with the $z < 4$ quasar selection criterion (dashed line), $Y-K > 0.46(g-z) + 0.82$ (where g and z are in AB magnitudes and Y and K are in Vega magnitudes; proposed by Wu & Jia 2010). Filled squares represent 14 new $2.2 < z < 3$ quasars identified in this paper. Crosses and a filled triangle represent the previously known SDSS quasars and a probable quasar without spectroscopy, respectively. Open circles, squares, and triangles denote the known stars, stars identified in this paper, and probable stars without spectroscopy, respectively. (A color version of this figure is available in the online journal.)

2. TARGET SELECTIONS AND SPECTROSCOPIC OBSERVATIONS

Our purpose is to efficiently select $2.2 < z < 3.0$ quasars by combining the variability and optical/near-IR colors, so we focus on the S82 region where both variability and SDSS-UKIDSS photometric data are available with high quality. We selected a sample of 118 non-UV excess quasar candidates from S82 that have UV-optical colors similar to those of stars (i.e., consistent with the observed colors of quasars at $2.2 < z < 3.0$ and optical variability properties consistent with the region defined by quasars on the $A-\gamma$ plane) using the algorithm presented in Schmidt et al. Seventy of these quasar candidates have near-IR $YJHK$ photometric data from the UKIDSS/LAS DR4.⁶ All photometric magnitudes are corrected for Galactic extinction using a map from Schlegel et al. (1998). We plotted the 70 objects on a $Y-K/g-z$ color-color diagram (see Figure 1). They are clearly separated into two parts on this diagram. Fifty-four sources match the selection criterion of $Y-K > 0.46(g-z) + 0.82$ defined for $z < 4$ quasars (here we convert the original criterion given in Wu & Jia 2010 to a new one to retain the g and z magnitudes in the AB system and Y and K magnitudes in the Vega system; see the dashed line in Figure 1). Five sources are located slightly below but very close to the criterion. Therefore, we think these 59 sources are probably $2.2 < z < 3.0$ quasars. Using the nine-band SDSS-UKIDSS photometric data, the photometric redshifts of these 59 sources are estimated to be from $z = 2.43$ to 3.05 according to a program introduced in Wu & Jia (2010). Indeed, 44 among them

⁵ The UKIDSS project is defined in Lawrence et al. (2007). UKIDSS uses the UKIRT Wide Field Camera (Casali et al. 2007) and a photometric system described in Hewett et al. (2006). The pipeline processing and science archive are described in Hambly et al. (2008).

⁶ Available at <http://surveys.roe.ac.uk/wsa/>.

Table 1
Parameters of 14 New $2.2 < z < 3.0$ Quasars in S82

Name (SDSS)	R.A. (deg)	Decl. (deg)	i	z_{photo}	z_{spec}	Exposure Time (s)	Telescope
J000050.59+010959.1	0.21081	1.16644	19.22	2.58	2.37	3600	Bok
J000121.87−000327.1	0.34113	−0.05754	18.47	2.78	2.88	300	MMT
J002117.11−002841.7	5.32131	−0.47824	18.68	2.68	2.85	300	MMT
J013450.27+003537.1	23.70948	0.59367	17.52	2.68	2.69	3600	Bok
J022836.08+000939.2	37.15035	0.16091	18.34	2.68	2.63	3600	Bok
J034025.90+000807.6	55.10792	0.13545	19.08	2.63	2.64	3600	Bok
J034008.54+010714.8	55.03557	1.12081	18.88	2.83	2.84	2400	Bok
J034337.67−000350.2	55.90698	−0.06395	18.14	2.88	2.85	3600	Bok
J214633.34+000318.5	326.63895	0.05516	17.83	2.83	2.79	600	MMT
J221602.32+005826.5	334.00967	0.97406	17.86	2.83	2.83	1200	Bok
J225257.56+004524.0	343.23984	0.75669	19.25	2.83	2.74	900	MMT
J225355.31+005146.1	343.48050	0.86281	19.24	2.43	2.37	1800	Bok
J231302.58+004105.1	348.26074	0.68475	19.17	2.73	2.63	600	MMT
J233659.54+003843.5	354.24808	0.64543	18.89	2.68	2.72	300	MMT

have been previously spectroscopically identified as quasars by SDSS. These 44 known quasars have spectroscopic redshifts from 0.59 to 3.29, and 35 of them are $2.2 < z < 3.0$ quasars. The spectroscopic redshifts for 40 of these 44 known quasars are consistent with their photometric redshifts within $|\Delta z| \leq 0.3$. This confirms the high efficiency of selecting $2.2 < z < 3.0$ quasars by combining the variability and optical ($g-z$)/near-IR ($Y-K$) colors. Spectroscopic identification of the remaining 15 quasar candidates is needed.

Apart from the above 59 quasar candidates, the other 11 objects are located far below the quasar selection criterion in Figure 1, and their $Y-K$ and $g-z$ colors are indistinguishable from those of stars in the stellar locus (see Figure 5 of Wu & Jia 2010). In addition, 10 of them have very bright optical magnitudes (i.e., $i < 16.5$) and are unlikely to be quasars at the expected redshifts ($2.2 < z < 3.0$). Indeed, four of them (SDSS J034751.14−001730.7, SDSS J035208.92+005919.6, SDSS J224630.25+010018.3, and SDSS J225342.13+011207.1) have already been cataloged as stars in the SIMBAD database.⁷

As we mentioned above, spectroscopic identification is still required for the remaining 15 quasar candidates with $2.2 < z < 3.0$ in S82. All of them have i -band magnitudes brighter than 19.3. In this paper, we present optical spectra for 14 of them.⁸ Eight of them were observed using the Boller & Chivens Spectrograph on the Bok 2.3 m telescope at Kitt Peak in 2010 November. The observation covers a wavelength range of 3620–6900 Å with a spectral resolution of 8.3 Å. The spectra of the other six objects were obtained with the Blue Channel Spectrograph on the MMT 6.5 m telescope at Mt. Hopkins in 2010 December, with a wavelength coverage of 3600–8000 Å and a spectral resolution of 5.8 Å. We reduced the data with IRAF package and some broad-line emissions, such as Ly α +N v, Si iv+O iv], and C iv, were clearly detected in the spectra of all 14 quasar candidates. We measured the redshifts of these 14 new quasars by fitting Gaussian line profiles to the Ly α +N v, Si iv+O iv] λ 1399, and C iv λ 1549 emission lines. The details of the sources and observational results, including their names, coordinates, magnitudes, exposure times, and photometric and spectroscopic redshifts, are summarized in Table 1. The spectra of these 14 new quasars with $z = 2.36$ –2.88 taken with Bok

and MMT are presented in Figures 2 and 3, respectively. These observations clearly demonstrated the high efficiency of selecting $2.2 < z < 3.0$ quasars by combining the variability and optical/near-IR colors.

For the 11 sources located far below the quasar selection criterion of the $Y-K/g-z$ color–color diagram, we also took the spectra of one of them (SDSS J035658.21+003801.8, $i = 18.69$) with the Bok 2.3 m telescope in 2010 November and two of them (SDSS J034950.99+010845.9, $i = 11.63$ and SDSS J035816.05+002351.9, $i = 13.58$) with the 2.16 m telescope of Xinglong/NAOC in 2011 January, and confirmed their nature as stars due to the lack of emission lines and the presence of Balmer absorption features. Together with the other 4 previously known stars, 7 of these 11 sources located in the stellar locus have been identified as stars. Although there are still four sources that remain unidentified, they are obviously too bright ($i < 14$) to be quasars. Therefore, we believe that all 11 of these sources are stars with a certain level of optical variability. Combined with their optical/near-IR colors we can easily separate them from quasars.

3. MORE $2.2 < z < 3.0$ QUASAR CANDIDATES IN SDSS STRIPE 82

In a recent paper, Butler & Bloom (2011) presented a similar time-series study of quasars in S82 as in Schmidt et al. (2010) and MacLeod et al. (2011). They proposed two different statistics, namely, a quasar-like variability metric and a non-quasar variability metric, to separate quasar candidates from stars. They obtained 1875 new quasar candidates in S82 and claimed that with their method they can achieve nearly a factor of two increase in quasars at $2.5 < z < 3.0$. Here we used their variable quasar candidates to cross-correlate with the sources in the UKIDSS/LAS DR5 and obtained 643 new quasar candidates with SDSS-UKIDSS nine-band photometric data. In Figure 4 we plot these sources in the $Y-K/g-z$ diagram, in comparison with the quasar selection criterion suggested by Wu & Jia (2010). Five hundred ninety-seven of these 643 sources (with a fraction of 93%) meet the selection criterion, suggesting that most of them should be real quasars with $z < 4$. This comparison also provides mutual support for the quasar selection method based on variability or optical/near-IR colors.

To more reliably select $2.2 < z < 3.0$ quasars from these 597 quasar candidates, we used a program introduced in Wu & Jia

⁷ <http://simbad.u-strasbg.fr/simbad/>

⁸ The only one left is SDSS J220808.97+002858.3 with a photometric redshift of 2.78. We are planning to observe it in the fall of 2011.

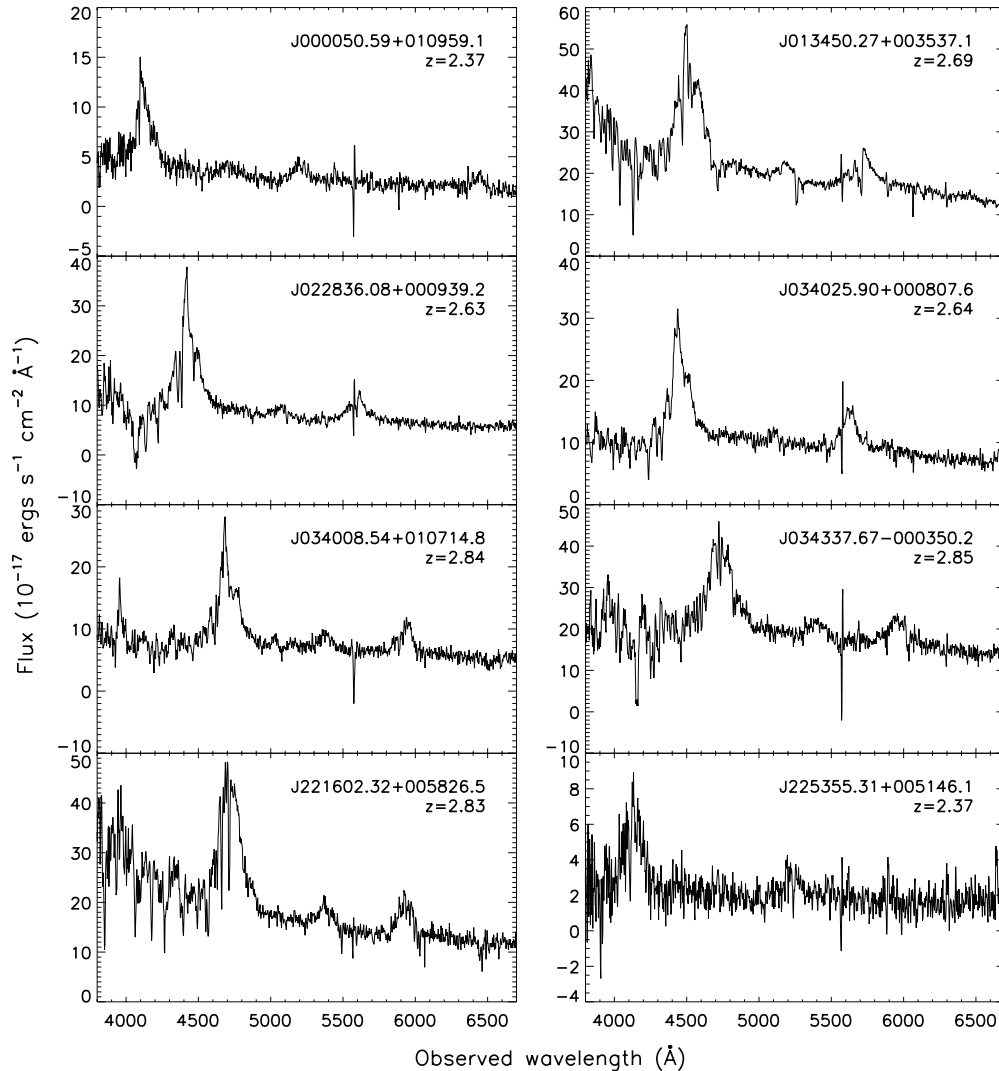


Figure 2. Bok spectra of the eight new quasars at $2.2 < z < 3$ selected by the combination of variability and optical/near-IR colors. The strongest emission line in each spectrum is $\text{Ly}\alpha + \text{N v}$.

(2010) to estimate the photometric redshifts of quasar candidates based on their SDSS-UKIDSS nine-band photometric data. In the upper panel of Figure 5, we show the photometric redshift distribution of these 596 new quasar candidates. Although they are located in a broad redshift range from 0.1 to 3.8, obviously a large fraction of them are at $2.2 < z < 3.0$. Among these 597 quasar candidates, 244 sources have photometric redshifts larger than 2 and 188 of them are $2.2 < z < 3.0$ quasar candidates. Considering the fact that only 948 quasars at $2.2 < z < 3.0$ in S82 have been identified in the SDSS DR7 (Schneider et al. 2010), the fraction of $2.2 < z < 3.0$ quasar candidates in our SDSS-UKIDSS variable source sample is significantly higher. This is understandable because the SDSS quasar survey mainly focused on finding quasars with $z < 2.2$ and $z > 3.5$ (Richards et al. 2002). Many quasars with $2.2 < z < 3.0$ are therefore missing in the SDSS quasar survey but can be discovered by combining the variability and optical/near-IR colors as we suggest in this paper.

In the lower panel of Figure 5, we show the distribution of the dereddened i -band magnitudes of 597 quasar candidates, as well as that of 188 quasar candidates at $2.2 < z < 3.0$. Clearly, the majority of them are located between $i = 19.1$ and $i = 20.5$. This is also the reason why they are missing in the SDSS survey

because most of the known SDSS quasars have $i < 19.1$. We expect that the ongoing BOSS survey in SDSS-III, which aims to discover 150,000 quasars with $z > 2.2$ (Eisenstein et al. 2011; Ross et al. 2011), could confirm the nature and redshifts of these quasar candidates soon. In Table 2 we list the coordinates, photometric redshifts, and SDSS and UKIDSS magnitudes of the 188 quasar candidates at $2.2 < z < 3.0$. We also note that three bright sources ($i < 19.3$) among them were spectroscopically identified by us in Section 2.

4. DISCUSSION

We have presented a case study to demonstrate that we can effectively select $2.2 < z < 3.0$ quasars by combining the optical variability and optical/near-IR colors. Our successful spectroscopic identifications of 14 new quasars at $z = 2.36$ – 2.88 with the Bok 2.3 m telescope and the MMT 6.5 m telescope provide further support to this combination approach, which can be used to select quasars with high efficiency (here we define the efficiency as the percentage of quasars identified from the spectroscopic targets, similar to the definition in SDSS-III; Ross et al. 2011). We also compiled a catalog of 188 quasar candidates with photometric redshifts at $2.2 < z < 3.0$ from

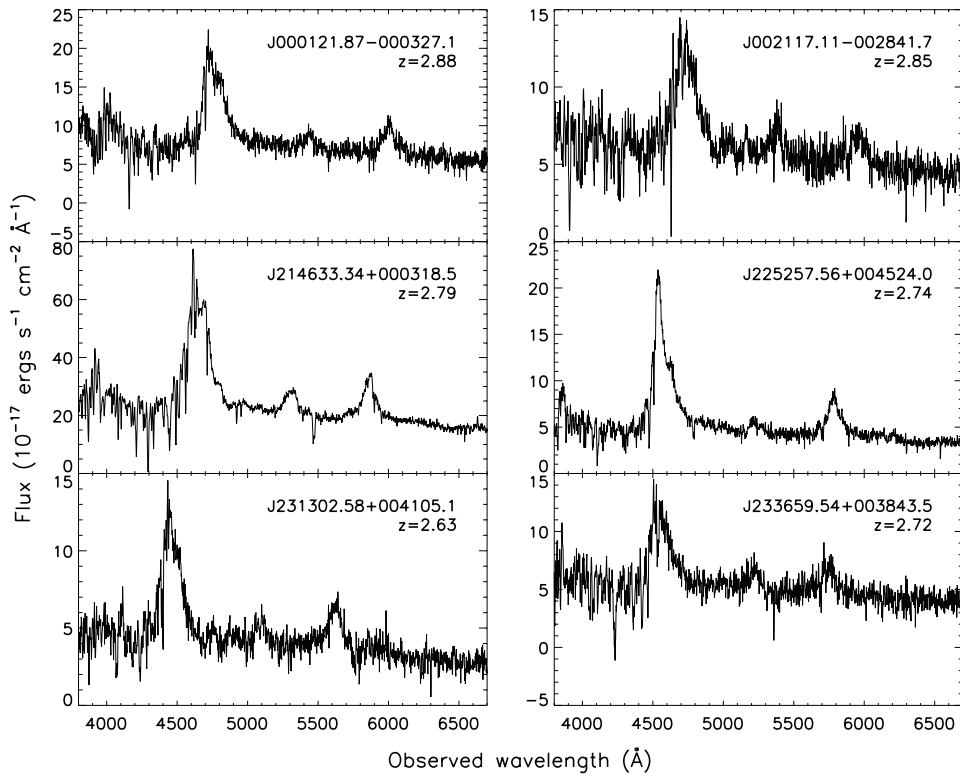


Figure 3. MMT spectra of the six new quasars at $2.2 < z < 3$ selected by the combination of variability and optical/near-IR colors.

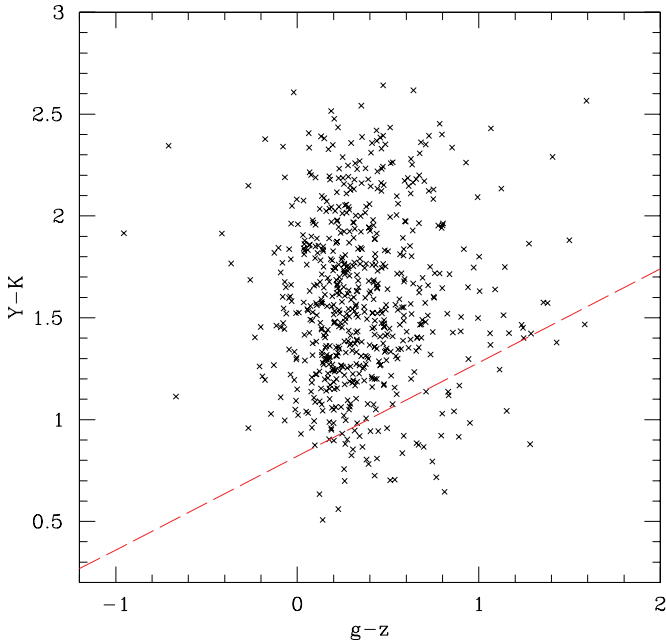


Figure 4. $Y - K$ and $g - z$ colors of 643 variable quasar candidates with SDSS-UKIDSS nine-band photometric data, selected from 1875 new quasar candidates in Butler & Bloom (2011). Five hundred ninety-seven of them meet the $z < 4$ quasar selection criterion (shown with the dashed line) given by Wu & Jia (2010).

(A color version of this figure is available in the online journal.)

variable SDSS-UKIDSS sources in S82, and expect that the ongoing SDSS-III spectroscopy will confirm their quasar nature and redshifts soon.

We noticed that although combining the optical/near-IR colors and time-series information can help increase the efficiency

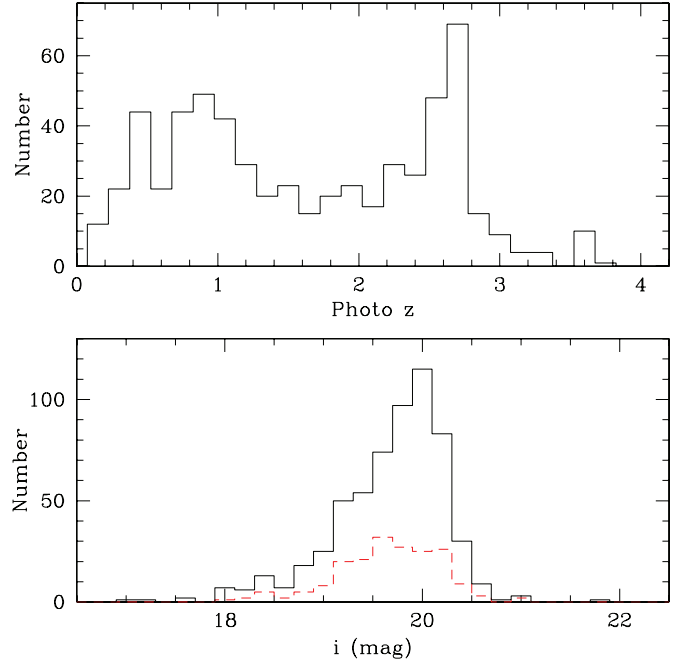


Figure 5. Upper panel: the distribution of photometric redshifts of 597 variable SDSS-UKIDSS quasar candidates satisfying the $Y - K / g - z$ selection criterion of $z < 4$ quasars. A large fraction of sources are at $2.2 < z < 3$. Lower panel: the distribution of SDSS dereddened i -band magnitudes of 597 variable SDSS-UKIDSS quasar candidates. The dashed histogram represents the distribution of 188 quasar candidates with photometric redshifts of $2.2 < z < 3$.

(A color version of this figure is available in the online journal.)

in identifying quasars, it may decrease the completeness of quasars if both selection criteria on colors and variability are required. This can also be seen from Figures 1 and 4 as some

Table 2
Quasar Candidates with $2.2 < z < 3.0$ in S82

R.A. (deg.)	Decl. (deg.)	z_{photo}	u	g	r	i	z	Y	J	H	K
0.21081127	1.16643864	2.575	19.731	19.138	19.090	19.181	18.985	18.294	18.142	17.669	16.891
0.34113037	-0.05754064	2.825	19.751	18.737	18.499	18.386	18.452	17.578	17.212	16.799	16.529
0.42223178	-0.29444873	2.425	20.592	19.933	19.786	19.754	19.469	18.910	18.494	18.290	17.374
0.44474748	0.66631052	2.775	20.408	19.471	19.249	19.215	19.244	18.437	18.166	17.645	17.079
0.50900025	-0.70452072	2.425	21.735	20.360	20.146	20.089	19.735	19.245	18.777	18.296	17.136
0.54000096	-0.03205093	2.675	20.864	19.865	19.728	19.802	19.773	18.913	18.825	18.170	17.920
0.54369966	-1.02404081	2.775	21.279	19.679	19.220	19.206	19.267	18.204	17.953	17.524	17.044
0.55005872	0.54818141	2.675	20.648	19.664	19.610	19.555	19.472	18.729	18.538	18.192	17.671
0.90385887	-1.17817945	2.325	20.304	19.843	19.953	19.934	19.889	19.346	19.307	18.910	18.002
1.06989716	0.24487200	2.475	21.075	20.298	20.305	20.353	20.079	19.190	19.119	18.678	17.877

Note. The SDSS *ugriz* magnitudes are AB magnitudes and the UKIDSS *YJHK* magnitudes are Vega magnitudes.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

quasars selected by variability do not meet our color selection criterion. One possible way to avoid this is to decrease the threshold for each criterion. For example, relaxing our color criterion to $Y - K > 0.46(g - z) + 0.50$ would include all variability-selected quasars in Figure 1 and 98.8% of variability-selected quasar candidates in Figure 4, without increasing much contamination from stars as most of them are less variable and still far away from our color selection criterion. However, how to best combine both the optical/near-IR colors and time-series information to select quasars with both higher efficiency and higher completeness obviously requires further investigation in the future based on complete samples of quasars and stars in certain sky areas.

To use this combination approach, we need both the optical variability measurements and optical/near-IR photometry in a large sky area. Deeper imaging and multi-epoch photometry are especially necessary to find $z > 2.2$ quasars. However, so far both variability and optical/near-IR photometric observations have been realized for only a small part of the sky, such as in S82. Because the typical variability timescales of quasars are usually in years in the optical band, we need to measure the variability of sources for many epochs over at least several years in order to obtain better statistics to determine their variability features. That is why so far the variability studies related to quasars have been performed only on some smaller sky areas, which significantly limits efforts to discover quasars with variability. However, even if we may not have both time-series and color information for quasar candidate selection in most sky areas, utilizing both as much as possible often allows us to obtain the most quasars. Fortunately, there are also several ongoing and upcoming large projects utilizing both photometric and variability information, such as Pan-STARRS (Kaiser et al. 2002) and the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008). The multi-epoch photometry in multiple bands covering a large part of the sky by these facilities will hopefully provide better opportunities to use variability to construct a much larger sample of quasars than the one currently available.

On the other hand, several ongoing and upcoming optical and near-IR photometric sky surveys will also provide crucial extensions to the SDSS-UKIDSS optical/near-IR color selection of quasars to larger and deeper fields. In addition to SDSS-III (Eisenstein et al. 2011), which has extended imaging 2500 deg² farther in the south Galactic cap, SkyMapper (Keller et al. 2007) and the Dark Energy Survey (The Dark Energy Survey Collaboration 2005) will also present multi-band optical

photometry in 20,000/5000 deg² of the southern sky, with magnitude limits of 22 and 24 mag in the *i*-band, respectively. The VISTA Hemisphere Survey (Arnaboldi et al. 2007) will be carried out in the near-IR *YJHK* bands for 20,000 deg² of the southern sky with a magnitude limit of $K = 20.0$, which is about 5 mag and 2 mag deeper than the Two Micron All Sky Survey (Skrutskie et al. 2006) and UKIDSS/LAS limits (Lawrence et al. 2007), respectively. Therefore, the optical and near-IR photometric data obtained with these ongoing and upcoming surveys will provide a large database of quasar candidates. By combining the optical variability and optical/near-IR colors, we expect that a much larger and more complete quasar sample can be efficiently constructed in the near future.

Although by combining the variability and optical/near-IR colors we can efficiently select quasar candidates and reliably estimate their photometric redshifts, spectroscopic identifications are still crucial to determine their nature and redshifts. The ongoing BOSS project in SDSS-III has identified 29,000 quasars with $z > 2.2$ and expects to obtain the spectra of 150,000 quasars at $2.2 < z < 4$ (Eisenstein et al. 2011; Ross et al. 2011). We believe that many $2.2 < z < 3.0$ quasars, including the candidates we listed in this paper, should be spectroscopically identified by BOSS. In addition, LAMOST (Su et al. 1998), a spectroscopic telescope with 4000 fibers currently in the commissioning phase, is also aimed at discovering 0.3 million quasars with magnitudes brighter than $i = 20.5$ (Wu et al. 2010b). By combining the variability and optical/near-IR colors, large input catalogs of reliable quasar candidates will be provided to these quasar surveys for future spectroscopic observations. Therefore, we expect that a much larger and more complete quasar sample covering a wider range of redshifts will be constructed in the near future, which will play an important role in studying extragalactic astrophysics, including the physics of accretion around supermassive black holes, galaxy evolution, intergalactic medium, large-scale structure, and cosmology.

We thank Zhaoyu Chen and Wenwen Zuo for taking the spectra of two star candidates with the 2.16 m telescope at Xinglong/NAOC. X.-B.W. is supported by the National Natural Science Foundation of China (11033001) and the National Key Basic Research Science Foundation of China (2007CB815405). He thanks his colleagues at Steward Observatory, University of Arizona for their hospitality during his visit there in the spring of 2011 as a senior visiting fellow supported by

the Chinese Scholarship Council. R.W. acknowledges support from the National Radio Astronomy Observatory (NRAO) through the Jansky Fellowship program. The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. K.B.S. is funded by and would like to thank the Marie Curie Initial Training Network ELIXIR, which is funded by the Seventh Framework Programme (FP7) of the European Commission. K.B.S. is a member of the International Max Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg (IMPRS-HD), Germany. This work was partially supported by the Open Project Program of the Key Laboratory of Optical Astronomy, NAOC, CAS. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is <http://www.sdss.org/>.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

Facilities: Beijing:2.16m, Sloan, UKIRT, Bok, MMT

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