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

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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 Lyα 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–γ 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
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; Croon 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 UKIDSS* 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 $2.2 < z < 3.0$. 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.

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* 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).

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**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), $Y - K > 0.46 \times (Y - K) + 0.82$ (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 $A_y$ 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. All photometric magnitudes are corrected for Galactic extinction using a map from Schlafly 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
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 $(g-z)/\text{near-IR}$ $(Y-K)$ 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.

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. 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$\alpha$+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$\alpha$+N v, Si iv+O iv] $\lambda$1399, and C iv $\lambda$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.

### Table 1

| Name (SDSS) | R.A. (deg) | Decl. (deg) | $i$ | $\zeta_{\text{photo}}$ | $\zeta_{\text{spec}}$ | 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 |
| J031350.27+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 |
| J034337.67−003050.2 | 334.00967 | 0.97406 | 17.83 | 2.83 | 2.79 | 600 | MMT |
| J214633.34+000318.5 | 326.63895 | 0.05516 | 17.83 | 2.83 | 2.79 | 600 | MMT |
| J221602.32+000582.6 | 334.00967 | 0.97406 | 17.86 | 2.83 | 2.83 | 3600 | 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 |

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.

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
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 Ly$\alpha$ + N$\lambda$

(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
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 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...
et al. 2008). The multi-epoch photometry in multiple bands is ongoing and upcoming large projects utilizing both photometric
us to obtain the most quasars. Fortunately, there are also several
series and color information for quasar candidate selection in
with variability. However, even if we may not have both time-
sky areas, which significantly limits efforts to discover quasars
related to quasars have been performed only on some smaller
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
skys, 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; Ivezic 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 (Arnaud et al. 2007) will be carried out in the near-IR \( YJK \) 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 \( 2 < z < 4 \) (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.

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### Table 2

| R.A. (deg.) | Decl. (deg.) | \( z_{\text{photo}} \) | \( u \) | \( g \) | \( r \) | \( i \) | \( z \) | \( Y \) | \( J \) | \( H \) | \( K \) |
|------------|------------|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 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 | 18.373 | 18.499 | 18.386 | 18.452 | 17.578 | 17.212 | 16.799 | 16.529 |
| 0.42223718 | 0.54044873 | 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 | 0.07452072 | 2.425 | 21.735 | 20.360 | 20.146 | 20.089 | 19.735 | 19.245 | 18.777 | 18.296 | 17.136 |
| 0.54000096 | 0.03205993 | 2.675 | 20.864 | 19.865 | 19.728 | 19.802 | 19.773 | 18.913 | 18.825 | 18.170 | 17.920 |
| 0.54369966 | 0.12404081 | 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 | 1.17871945 | 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.)
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**Facilities:** Beijing:2.16m, Sloan, UKIRT, Bok, MMT

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