Capability of Quasar Selection by Combining SCUSS and SDSS Observations

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ABSTRACT. The South Galactic Cap u-band Sky Survey (SCUSS) provides a deep u-band imaging of about 5000 deg2 in south Galactic cap. It is about 1.5 mag deeper than the SDSS u-band. In this article, we evaluate the capability of quasar selection using both SCUSS and SDSS data, based on considerations of the deep SCUSS u-band imaging and two-epoch u-band variability. We find that the combination of the SCUSS u-band and the SDSS gri-z-band allows us to select more faint quasars and more quasars at redshift around 2.2 than the selection that uses only the SDSS ugriz data. Quasars have significant u-band variabilities. The fraction of quasars with large two-epoch variability is much higher than that of stars. The selection by variability can select both low-redshift quasars with ultraviolet excess and mid-redshift (2 < z < 3.5) quasars where quasar selection by optical colors is inefficient. The above two selections are complementary and make full use of the SCUSS u-band advantages.

1. INTRODUCTION

Quasars, identified as high-redshift objects, are very distant according to Hubble’s law. The absorption spectra of quasars close to the reionization epoch are the best probes to study the intergalactic medium (IGM) and reionization (Fan et al. 2002). In recent years, large-scale optical surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) have provided numerous and homogeneous data for studying the properties of quasars and other subjects including connections to their host galaxies, IGM, Lyα forests, quasar clustering, central supermassive black holes, and baryon acoustic oscillations (Dunlop et al. 2003; Fan et al. 2006; Ross et al. 2009; Shen 2009; Dawson et al. 2013), etc.

Quasar targets for spectroscopic observations in the SDSS are mainly selected by optical colors (Richards et al. 2002). Outliers away from the star sequence in color space are considered as spectroscopic follow-up candidates. Due to strong ultraviolet excess and emission lines, quasars with redshift lower than 2.2 or higher than 3.0 are obviously far from the star locus in color–color diagrams. A lack of or not so deep u-band would significantly impact the ability to select the low-redshift quasars.

Optical colors of quasars in the redshift range of 2.2 < z < 3.0 are similar to those of A-colored stars (blue horizontal branch stars and blue stragglers) so that it is very difficult and inefficient to select quasars only by simple color cuts (Fan 1999; Richards et al. 2002; Wu et al. 2011). There are two alternatives that can help to pick out those quasar targets more efficiently. One is combining optical and near-infrared (NIR) photometry, e.g., the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), and Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). The decreasing rate of a stellar continuum from optical to NIR wavelength is larger than that of a quasar. Optical colors together with infrared colors are utilized to distinguish quasars at z > 2.2 (Maddox et al. 2008; Wu et al. 2011, 2012).

The optical variability is the other way to select quasar candidates. Its role will become more and more prominent with the ongoing or upcoming time-domain surveys such as the Palomar Transient Factory (PTF; Law et al. 2009), Panoramic Survey Telescope and Rapid Response System (PAN-STARRS; Kaiser 2004), and Large Synoptic Survey Telescope (LSST; LSST Science Collaborations 2009). Light curves have been parameterized by a structure function or a damped random walk model (Schmidt et al. 2010; MacLeod et al. 2011; Butler & Bloom 2011; Palanque-Delabrouille et al. 2011). Quasars, variables, and nonvariable stars can be successfully separated with a great completeness and purity in the parameter space. However, quasar targeting by light curves needs tens of time sampling points, and only limited sky areas have deep time-series photometric observations. The u-band variability is the largest among the five SDSS bands and it becomes larger as the time lag is longer.
The magnitude change in $u$-band might be helpful for quasar targeting selection.

The SCUSS is an imaging survey in the south Galactic cap (SGP) with an SDSS-like $u$ filter (X. Zhou et al. 2014, in preparation). The survey is about 1.5 mag deeper than the SDSS $u$-band. It is expected that, comparing with target selections only by SDSS photometry, one can select more quasars with less star contamination by using both deep SCUSS $u$-band and SDSS other bands if objects present no variability. The SCUSS observations started in 2010 and ended in 2013. The average time lag between SCUSS and SDSS observations is about 2–3 years. We can obtain the two-epoch $u$-band variability between these two surveys. The variability difference between quasars and stars is useful for quasar selection. In this article, we compare the quasar selection by combining the SCUSS and SDSS data with that only using the SDSS data and try to understand the quasar targeting potential and capability when the SCUSS $u$-band is involved. In §2, we give brief descriptions of the SCUSS and our quasar and star samples. §3 presents some advantages of the SCUSS $u$-band photometric data, which are favorable for the quasar selection. Quasar selections by combining SCUSS and SDSS data are analyzed and discussed in §4. §5 is the conclusion.

2. DATA

2.1. SCUSS Data

The SCUSS is undertaken by the National Astronomical Observatories of China. The adopted telescope is the 2.3 m Bok telescope located on Kitt Peak, Arizona. The camera deployed at the prime focus provides a field of view of about 1 deg$^2$. The photometric system is the SDSS-like $u$ filter, whose effective wavelength is about 3538 Å and FWHM is about 520 Å (H. Zou et al. 2014, in preparation). The filter is a little bluer than the SDSS $u$-band. The SCUSS covers an area of about 5000 deg$^2$ in the SGP. The exposure time is 5 minutes and the 5-σ magnitude limit is deeper than 23.0 mag.

The detailed image processing and photometry for the SCUSS can be referred to the paper of H. Zou et al. (2014, in preparation). In general, the global astrometric accuracy is about 0.13″. The catalogs include both photometry for stacked images and coadded photometry for single-epoch images. The coadded PSF magnitudes and coadded aperture magnitudes, if a proper aperture radius is chosen, are the best brightness measurements of point sources. In this article, we use the coadded PSF magnitude. The SCUSS magnitude is transformed to the SDSS photometric system using the transformation equation of

\[ u_{\text{SDSS}} = u_{\text{SCUSS}} + 0.0586(u_{\text{SCUSS}} - g) - 0.0207(u_{\text{SCUSS}} - g)^2 - 0.0377, \]

where $0.8 < u_{\text{SCUSS}} - g < 2.8$. The corresponding error of the transformed SCUSS $u$-band magnitude is estimated by error transfer. This transformation is derived by point sources with SCUSS and SDSS photometric errors less than 0.05 mag. It is applied to point sources here and the maximum systematic difference between SCUSS and SDSS is about 0.036 mag. The SDSS magnitudes are PSF magnitudes. In the rest of this article, all magnitudes are corrected by the Galactic extinction map of Schlegel et al. (1998).

2.2. Quasar and Star Samples

The spectroscopically confirmed quasars and stars are obtained by matching objects from the SDSS DR10 with SCUSS catalogs. We require that SCUSS objects are not saturated and not polluted by other sources and the SDSS classifications are point-like. The $i$-band magnitude is limited to the range between 18 and 22.5 mag. There are 42,418 quasars and 56,518 stars in total. Figure 1 shows some properties of these two samples including the distributions of the $u_{\text{SDSS}}$ magnitude, $u_{\text{SDSS}} - g$ color, and redshift (only for quasars). There are two peaks in the redshift distribution of quasars, locating in the ultraviolet-excess region and at intermediate redshift, respectively. Most mid-redshift quasars are obtained by the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013), which plans to map the large-scale structure traced by the Ly $– \alpha$ forest.

3. SCUSS ADVANTAGES FOR QUASAR SELECTION

3.1. Deeper SCUSS Photometry

The SCUSS $u$-band is reported to be 1.5 mag deeper than the SDSS $u$-band. We plot the magnitude error as a function of magnitude in Figure 2. The 5-σ magnitude limits at $\sigma = 0.2$ for the SCUSS and SDSS $u$-bands are 23.45 and 22.03 mag, respectively. The magnitude error of the SDSS $u$-band at 22.0 mag, officially defined as the limiting magnitude of 95% detection repeatability for point sources, is about 0.2 mag, while that of the SCUSS $u$-band is about 0.05 mag.

Another intuitive comparison of the data quality between these two surveys is to plot color–color diagrams and see the color dispersion of faint main-sequence stars. Figure 3 shows the distributions of both quasar and star samples in the color–color plane of $u_{\text{SDSS}} - g$ or $u_{\text{SCUSS}} - g$ versus $g - r$. The color dispersion of stars with SCUSS $u$ is obviously smaller than that with SDSS $u$. The $u_{\text{SCUSS}} - g$ dispersion at $g - r = 1.4$ (mostly faint M stars) is about 0.55, while the $u_{\text{SDSS}} - g$ dispersion is about 0.76. In addition, in the region occupied by quasars with $z > 2.5$, there are many stars initially selected as quasar candidates by the SDSS as shown in the left of Figure 3. They are mostly faint stars with large SDSS $u$-band photometric errors. However, most of these stars are still in the main sequence due to deeper SCUSS $u$-band as seen in the right panel of this figure. The deeper SCUSS $u$-band with SDSS other bands will evidently improve the quasar selection if quasars present no variability.
3.2. Two-Epoch Variability

As seen in Figure 3, many quasars with $2 < z < 3$ are mixed with A-colored stars. The target selections only based on optical colors are inefficient for these quasars. However, quasars usually present light variabilities. In principle, the variability would be larger as the wavelength is shorter and the observation lag is longer. The $u$-band variability is largest among all SDSS bands. There is a typical observation time lag of 2–3 years between the SCUSS and SDSS. Thus, the two-epoch $u$-band variability between these two surveys should be large enough as a useful tool to select quasar targets. The quasar selection by variability should also be complementary to other selection methods based on colors, especially for quasars with $2 < z < 3$.

We compare the two-epoch magnitude differences of both stars and quasars in Figure 4. Only objects with photometric errors less than 0.05 mag are considered. The standard deviations of the distributions for stars and quasars are about 0.06 mag and 0.3 mag, respectively. The scatter of stars mainly
comes from the photometric error, while the scatter for quasars might come from the photometric error, intrinsic variability, and photometric system difference between the SCUSS and SDSS. In any case, the difference of the distributions between quasars and stars are distinct. It can be used to separate these two kinds of objects. The large two-epoch magnitude differences of quasars are also implied in the broader $u$ SCUSS $- g$ color distributions in the right of Figure 3.

### 3.3. Larger Photometric System Difference for Quasars

The SCUSS $u$ filter is very similar to the SDSS $u$ filter, but it is a little bluer. The central wavelength of the SCUSS $u$-band is about 3538 Å, while that of the SDSS $u$ is about 3562 Å (H. Zou et al. 2014, in preparation). Stellar spectra are dominated by the continuum, so their photometric differences between the SCUSS and SDSS as shown in equation (1) is small. The photometric effect due to different photometric systems is less than 0.036 mag for main-sequence stars. However, quasar spectra present strong ultraviolet excess and emission lines. Their photometric differences should be much bigger.

We get 4000 quasar spectra with different redshifts from the SDSS DR10. The wavelength of SDSS spectra ranges from 3800 to 9200 Å, which is out of the $u$-band wavelength coverage. These quasar spectra are blue-shifted by $z = 0.3$ so that they can be convolved with two $u$ filter responses to generate synthetic magnitudes. Here, both SCUSS and SDSS filter responses are the ones with atmospheric extinction at the typical airmass of 1.3 (H. Zou et al. 2014, in preparation). The resulting magnitude difference between these two filters is plotted as a function of redshift in Figure 5. In another way, we redshift the quasar composite spectrum by different redshift values and check the systematic variation with redshift as also shown in Figure 5. These two data sets present a coincident variation. Most quasars lie in a narrow band along the redshift. The wave-shape variation along the redshift is because of different emission lines entering and departing from the $u$-band. The magnitude difference is less than 0.03 when $z < 2.0$. It goes up to about 0.1 mag when $z > 2.0$, which is caused by the strongest Ly$\alpha$ line in quasar spectra. In contrast with stars, it is evident that quasars present much more difference induced by different photometric filters. This kind of difference is helpful for discriminating quasars from stars. Thus, we do not need to correct it and assume the magnitude difference mainly come from intrinsic variability if the photometric error is ignorable.
3.4. Quasar Variability Independent on Redshift

Figure 6 shows photometric magnitude differences of quasars between the SCUSS and SDSS $u$-bands as a function of redshift. The photometric errors are limited to 0.1 mag, which approximately corresponds to the quasar redshift up to about 3. We find that the average quasar variability varies at a level of 0.04 mag in the redshift range of $0 < z < 3$. Thus, the two-epoch variability is almost independent on the redshift, which can help to discover more quasars with $0 < z < 3.5$ where variability is still available. The independence of variability on redshift in gri-bands was also confirmed by Zuo et al. (2012) who divided the quasars into different subsamples with different physical parameters.

4. QUASAR SELECTION AND ANALYSIS

4.1. Ignorable Variability

Quasar target selections in this section are investigated based on the consideration of whether objects presenting variability. Those objects with two-epoch variability less than three times the photometric errors are regarded as sources with ignorable or small variabilities, which can be expressed as

$$\Delta m = |u_{\text{SCUSS}} - u_{\text{SDSS}}| \leq 3\sigma,$$

where

$$\sigma = \sqrt{\sigma^2_{u_{\text{SCUSS}}} + \sigma^2_{u_{\text{SDSS}}}}$$

and $\sigma_{u_{\text{SCUSS}}}$ and $\sigma_{u_{\text{SDSS}}}$ are the SCUSS and SDSS $u$-band magnitude errors, respectively. There are 68.4% quasars and 96.9% stars of their total samples with $\Delta m \leq 3\sigma$. These objects have deeper SCUSS $u$-band and hence deeper intrinsic colors. It is imaginable that the SCUSS $u$-band instead of the SDSS $u$-band would undoubtedly improve the efficiency of the quasar selection when combined with SDSS other bands.

In order to show the advantage of the quasar selection based on SCUSS data, we introduce a flux-based quasar target selection algorithm, XDQSO, which applies the extreme-deconvolution method to evaluate the probability that an object is a quasar (Bovy et al. 2011). By applying the XDQSO method to the above nonvariable samples, we can know how many more quasars can be selected with SCUSS $u$ and SDSS griz data than with SDSS-only data. The probability of an object that selected as a quasar in XDQSO is set to be larger than 0.9.

After the XDQSO method is applied to the nonvariable samples with SCUSS $u$ and SDSS griz photometric data, about 46.6% quasars and 2.9% stars are selected. When it is applied to SDSS $ugriz$ data, about 41.4% quasars and 2.4% stars are selected. There are about 24.0% quasars that are exclusively selected by XDQSO with SCUSS $u$ and SDSS griz data. These numbers are summarized in Table 1. Figure 7 shows the magnitude and redshift distributions of quasars selected by these two methods. The target selection with SCUSS data can select more faint quasars with magnitude peak at 21.5 mag and more quasars with redshift between 2 and 3 (peak at $z = 2.2$). We also check the quasar selection efficiencies within two different redshift ranges: $0 < z < 2$ and $2 < z < 3.5$, which are also presented in Table 1. As a result, there are, respectively, 15.6% and 31.2% more quasars that are selected by the XDQSO with SCUSS data than that with SDSS-only data. The selection here is based on known quasar samples.
most of which are selected through SDSS optical colors. The SCUSS $u$-band is deeper than that of the SDSS, which implies that a part of potential quasars close to the SDSS $u$-band magnitude limit are missing. The SCUSS data can help us find more faint quasars than the above experiment only based on the known samples.

### 4.2. Obvious Variability

Objects with $\Delta m > 3\sigma$ are considered as sources with obvious or large variability. About 31.6% quasars and only 3.1% stars have obvious two-epoch variability. The fraction of stars having large variability is much smaller than that of quasars, so the objects with $\Delta m > 3\sigma$ is regarded as quasar candidates. We compared the selection by the two-epoch variability with that by the XDQSO method applied to the SDSS $ugriz$ data of large-variability samples. About 80% quasars and 11.2% stars are selected by XDQSO. There are 25.7% quasars exclusively selected by variability. These numbers are summarized in Table 2. Figure 8 shows the magnitude and redshift distributions of quasars obtained by these two selections. The selection by two-epoch variability can select more faint quasars with magnitude peak at 20.5 mag. It also can select more low-redshift quasars with ultraviolet excess (peak at $z = 0.7$) and more mid-redshift quasars with $2 < z < 3$ (peak at $z = 2.5$). There are 17.3% and 43.3% quasars exclusively selected by variability for the two redshift ranges as specified in the previous section, which are also shown in Table 2.

The SDSS $u$-band photometric error is larger than the SCUSS $u$-band, which is more prominent close to the SDSS magnitude limit. So the selection by variability is limited to a brighter magnitude range than the XDQSO selection with SCUSS $u$ plus SDSS $griz$ data. The XDQSO selection with the SCUSS plus SDSS data can select more fainter quasars and quasars with redshift peaked at 2.2, while the selection by variability can select more low-redshift and mid-redshift quasars. These

![Fig. 7.—Magnitude (a) and redshift (b) distributions of quasars selected by the XDQSO method, respectively applied to SCUSS $u$ plus SDSS $griz$ data (green) and SDSS-only data (blue). Distributions of the total quasar samples with ignorable variability (black) and quasars exclusively selected by XDQSO with SCUSS plus SDSS data (red) are also overlapped.](image-url)

### Table 1

| Star    | Quasar     | $0 < z < 2$ | $2 < z < 3.5$ |
|---------|------------|-------------|---------------|
| Total   | 56518      | 42418       | 20074         | 21366         |
| $\Delta m \leq 3\sigma$ | 54744 (96.9%) | 29011 (68.4%) | 11458 (57.1%) | 16610 (77.7%) |
| SCUSS $u$ + SDSS $griz$ | 1570 (2.9%) | 13511 (46.6%) | 5998 (52.3%) | 7274 (43.8%) |
| SDSS $ugriz$ | 1335 (2.4%) | 12024 (41.4%) | 5548 (48.4%) | 6266 (37.7%) |
| Exclusive | ...        | 2884 (24.0%) | 865 (15.6%)  | 1958 (31.2%)  |

NOTE. — The second and third columns show the selection efficiencies with the total star and quasar samples. The fourth and fifth columns show the quasar selection efficiencies within two different redshift ranges. The second row gives sample numbers. The third row gives corresponding samples with ignorable variability ($\Delta m \leq 3\sigma$). The third and fourth rows, respectively, present the selection efficiencies of two target selections: XDQSO with SCUSS $u$ plus SDSS $griz$ data and XDQSO with SDSS-only data. The last row gives the quasars exclusively selected by XDQSO with SCUSS $u$ and SDSS $griz$ data relative to XDQSO with SDSS-only data.
two selections are complementary and make the most of the SCUSS u-band advantages.

### 4.3. Application of our Selection

We randomly select a region of about 10 deg$^2$ with consistent SCUSS imaging quality to demonstrate the capability of our quasar selection with full point sources from the SDSS. The quasar probability in XDQSO is still set to be larger than 0.9. The SCUSS u-band apparent magnitude is limited to 23.5 mag. The $i$-band magnitude is between 18 and 22.5 mag. Isolated sources classified as point-like by the SDSS are considered. When objects present ignorable variability, the selection with SCUSS and SDSS data can find 29% more quasar targets than the one only with the SDSS data. On the other hand, the selection by variability can find 168.7% additional targets, although star contamination would be more serious. In total, we find that our selection can select 87.7% additional quasar targets. However, its actual application with alterable parameters, such as the quasar probability in the XDQSO and the variability amplitude (several times larger than the photometric error), should be dependent on the requirements of the density and homogeneity of quasar targets, the selection efficiency, and magnitude range, etc.

### 5. CONCLUSION

The SCUSS provides a deep and wide imaging survey in an about 5000 deg$^2$ area of the south Galactic cap with u-band. The SCUSS u-band is deeper than the SDSS u-band and the observation time lag between the SCUSS and SDSS provides an opportunity to investigate the two-epoch variability. Through combining the SCUSS and SDSS data, we evaluate the capability of the quasar selection in consideration of the advantages of the SCUSS u-band data.

The deeper SCUSS u-band photometry makes stars and quasars more tightly distributed in the color-color diagrams if SDSS other bands are included and objects present no variability. It helps to select more fainter quasars. Quasars have power-law continua and many strong emission lines. The photometric difference for quasars due to different photometric systems is larger than that of stars, which is helpful for the separation of these two objects. The average variability of quasars is about 0.3 mag. The distribution of the two-epoch variability between the SCUSS and SDSS for quasars is quite different from that of stars. Besides, the quasar two-epoch variability is independent on redshift at a level of 0.04 mag ($0 < z < 3$).

Based on the above advantages, we analyze the quasar selection in two ways: one is combining the SCUSS deeper u-band

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**TABLE 2**

|        | Star | Quasar |
|--------|------|--------|
| Total  | 56518| 42418  |
| $\Delta m > 3\sigma$ | 1774 (3.1%) | 13407 (31.6%) |
| SDSS ugriz | 199 (11.2%) | 10669 (79.6%) |
| Exclusive | … | 2738 (25.7%) |
|    | 20074 | 21366 |

**NOTE.**—Similar to Table 1, but for quasars with large variability. Objects with the two-epoch variability $\Delta m > 3\sigma$ are considered as quasar targets. The last row gives the quasars exclusively selected by variability relative to the selection by XDQSO with SDSS-only data.

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**FIG. 8.**—Magnitude (a) and redshift (b) distributions of quasars selected by the two-epoch variability (black) and XDQSO method with SDSS-only data (blue). Distributions of the total quasar samples with obvious variability (black) and quasars exclusively selected by variability (red) are also plotted.
data and SDSS griz data when objects present ignorable variability; the other is utilizing the two-epoch variability. The XDQSO method, which gives the quasar probability, is introduced for comparisons. We find that the XDQSO method with SCUSS u and SDSS griz data can select more faint quasars and quasars with redshift around 2.2 than the XDQSO with SDSS ugriz data. There are about 24.0% quasars exclusively selected by the former. The SCUSS data can also help us find the missing quasars close to the SDSS u-band magnitude limit. We regard objects with $\Delta m > 3\sigma$ as quasar candidates with obvious variability, because there are relatively small fraction of stars with such large variability. The quasar selection by variability can select both low-redshift quasars and mid-redshift quasars with $2 < z < 3$. There are 25.7% quasars exclusively selected by variability. The above two quasar selections are complementary, which make full use of the SCUSS advantages. When applying to the full SDSS point sources, our method can also select about 87.7% additional quasar targets.

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