Research in Astron. Astrophys. **2010** Vol. **10** No. **8**, 745–752
http://www.raa-journal.org *http://www.iop.org/journals/raa*

***R**esearch in*
***A**stronomy and*
***A**strophysics*

Eight new quasars discovered by the Guoshoujing Telescope (LAMOST) in one extragalactic field *

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Received 2010 May 27; accepted 2010 June 12

Abstract We report the discovery of eight new quasars in one extragalactic field (a five-degree field centered at RA=$08^{\rm h}58^{\rm m}08.2^{\rm s}$, Dec=$01^\circ32'29.7''$) with the Guoshoujing Telescope (LAMOST) commissioning observations made on 2009 December 18. These quasars, with i magnitudes from 16.44 to 19.34 and redshifts from 0.898 to 2.773, were not identified in the SDSS spectroscopic survey, though six of them with redshifts less than 2.5 were selected as quasar targets in SDSS. Except for one source without near-IR Y-band data, seven of these eight new quasars satisfy a newly proposed quasar selection criterion involving both near-IR and optical colors. Two of them were found in the 'redshift desert' for quasars (z from 2.2 to 3), indicating that the new criterion is efficient for uncovering missing quasars with similar optical colors to stars. Although LAMOST encountered some problems during the commissioning observations, we were still able to identify 38 other known SDSS quasars in this field, with i magnitudes from 16.24 to 19.10 and redshifts from 0.297 to 4.512. Our identifications imply that a substantial fraction of quasars may be missing in previous quasar surveys. The implication of our results to the future LAMOST quasar survey is discussed.

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

1 INTRODUCTION

Quasars are interesting objects in the universe since they can be used as important tools to probe the accretion power around supermassive black holes, the intergalactic medium, the large scale structure and the cosmic reionization. The number of quasars has increased steadily over the past four decades

∗ Supported by the National Natural Science Foundation of China.

(Richards et al. 2009). In particular, a large number of them have been discovered in two spectroscopic surveys, namely, the Two-Degree Fields (2dF) survey (Boyle et al. 2000) and the Sloan Digital Sky Survey (SDSS) (York et al. 2000). 2dF has discovered more than 20 000 low redshift ($z < 2.2$) quasars showing UV-excess (Croom et al. 2004; Smith et al. 2005), while SDSS has identified more than 100 000 quasars (Schneider et al. 2010; Abazajian et al. 2009). Some dedicated methods were proposed for finding higher redshift quasars (Fan et al. 2001a,b; Richards et al. 2002). However, the efficiency of identifying quasars with redshifts between 2.2 and 3 is still very low in SDSS (Schneider et al. 2010). This is mainly because quasars with such redshifts have very similar optical colors to stars and are mostly overlooked by SDSS spectroscopy. Therefore, the redshift range from 2.2 to 3 is regarded as the 'redshift desert' for quasars because of the difficulty in identifying quasars with redshifts in this range.

However, quasars in the redshift desert are usually more luminous than normal stars in the infrared K-band (Warren et al. 2000) because the spectral energy distributions (SEDs) of quasars are flat. This provides us with an important way of finding these quasars by involving the near-IR colors. Some methods have been suggested by using the infrared K-band excess based on the UKIRT (UK Infrared Telescope) Infrared Deep Sky Survey (UKIDSS) (Warren et al. 2000; Hewett et al. 2006; Maddox et al. 2008). Combining the UKIDSS *YJHK* and SDSS $ugriz$ magnitudes, some criteria to select quasars have been proposed (Maddox et al. 2008; Chiu et al. 2007). More recently, based on a large SDSS-UKIDSS quasar sample, Wu & Jia (2010) proposed using the $Y - K$ vs. $g - z$ diagram to select $z < 4$ quasars and using the $J - K$ vs. $i - Y$ diagram to select $z < 5$ quasars. Although the success of adopting these criteria has been demonstrated by using the existing quasar sample, we still need to apply them to discover new quasars and investigate how many quasars were missed in previous spectroscopic surveys.

The Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST), now called the Guoshoujing Telescope, is a powerful instrument for spectroscopy (Su et al. 1998) and the main construction was finished in 2008. Since 2009, LAMOST has entered its commissioning phase, and some test observations have been done in the winter of 2009. Although LAMOST has not yet reached its full capability, these observations have already led to the discovery of new quasars, including 14 quasars behind M31 (Huo et al. 2010) and a very bright $i = 16.44$ quasar with redshift $z = 2.427$ (in the redshift desert) (Wu et al. 2010; hereafter paper I). In this paper, we report the discovery of more quasars in the same extragalactic field where the very bright quasar was found, including another $z = 2.773$ quasar in the redshift desert.

2 TARGET SELECTION AND OBSERVATION

In the winter of 2009, we selected several extragalactic fields for the LAMOST commissioning observations. In order to test whether the newly proposed quasar selection criterion in the $Y - K$ vs. $g - z$ diagram is efficient in identifying quasars (Wu & Jia 2010), we selected quasar candidates in several sky fields which are overlapped in the UKIDSS and SDSS survey areas. Some additional quasar candidates from the catalog of Richards et al. (2009) were also included. Besides these quasar candidates, we also included many known SDSS quasars in these fields as targets in order to compare the LAMOST spectroscopy with SDSS. Here we report the observational results in one of these fields, which is a five-degree field centered at RA=$08^{\rm h}58^{\rm m}08.2^{\rm s}$, Dec=$01^\circ32'29.7''$ close to the field of GAMA-09 (Robotham et al. 2010).

On December 18, LAMOST made spectroscopic observations of this field, and 357 quasar targets (mostly with $i < 19.1$) together with other objects were observed with an exposure time of 30 min and a spectral resolution of $R \sim 1000$. The spectra were processed using a preliminary version of the LAMOST spectral pipeline. Due to various problems during the LAMOST commissioning observations, the overall quality of the spectra is not satisfactory. Only 99 of 357 quasar targets show obvious spectral features of quasars or stars/galaxies, and the rest of the spectra show

Table 1 Parameters of Eight New Quasars

Name (SDSS J)	RA (°)	Dec (°)	u	g	r	i	z	Y	J	H	K	LAMOST redshift
085307.31+014523.1	133.28049	1.75643	17.715	17.718	17.716	17.566	17.453	17.018	16.767	16.435	15.873	1.952
085543.40–001517.7	133.93086	–0.25493	17.668	16.866	16.617	16.444	16.208	15.573	15.214	14.585	13.834	2.427
085718.29+024017.7	134.32625	2.67160	18.520	18.373	18.128	18.194	18.313	—	—	16.985	16.209	1.154
085727.85+012802.1	134.36605	1.46728	18.480	18.489	18.162	18.152	18.258	17.484	17.143	16.344	16.015	1.363
090148.15+004225.9	135.45065	0.70722	19.777	19.513	19.358	19.345	19.130	18.255	17.462	17.181	16.388	0.898
090437.02+014055.3	136.15428	1.68203	18.585	18.570	18.356	18.072	18.009	17.488	—	16.542	15.917	1.765
090453.24–001426.5	136.22187	–0.24069	19.433	19.261	19.193	18.917	18.889	18.438	18.033	17.390	16.974	1.670
090504.87+000800.5	136.27030	0.13348	20.457	18.863	18.440	18.154	18.162	17.446	16.986	16.515	16.022	2.773

either too low S/N (signal to noise ratio) or only have sky light emissions. Among these 99 objects, 46 of them can be identified as quasars and 53 of them show features of either stars or galaxies. Eight of the 46 identified quasars are new and 38 of them are known SDSS quasars. Among the eight new quasars, SDSS J085543.40–001517.7 is very bright ($i = 16.44$) and was identified as a $z = 2.427$ quasar. This is the first quasar in the redshift desert discovered by LAMOST and its detailed properties have been reported in paper I. For completeness, we also include some of its properties in this paper.

In Figure 1, we show the SDSS finding charts[1] of 8 new quasars in an order of increasing RA. Clearly, they all are point sources in the optical bands. We also checked their morphology types in the UKIDSS images and all of them are also point sources (UKIDSS mergedclass=–1) in the near-IR bands. This is consistent with the morphology type of SDSS-UKIDSS quasars with redshifts larger than 0.5 (Wu & Jia 2010). In Table 1, we list the main properties of these eight quasars, including their coordinates, magnitudes and redshifts. The SDSS $ugriz$ magnitudes are given in the AB system and UKIDSS *YJHK* magnitudes are given in the Vega system. All magnitudes are corrected for Galactic extinction using the map of Schlegel et al. (1998). The offsets between the SDSS and UKIDSS positions are less than $0.21''$ for these eight quasars, indicating that mis-identifications of their UKIDSS counterparts are very unlikely.

In Figure 2, we show the LAMOST spectra of eight new quasars in order of increasing redshift (some sky light emissions were not subtracted very well). The complicated feature around 5900 Å in each spectrum is due to the problem of combining the LAMOST blue and red spectra, which overlap each other from 5700 Å to 6100 Å. From the spectra of six quasars with $z > 1.3$, we can clearly identify at least two broad emission lines and derive their average redshift. For two quasars with $z < 1.3$, only one emission line can reliably be observed and is identified as MgII$\lambda2798$. From the spectrum of SDSS J085718.29+024017.7 ($z = 1.154$), we can actually see a line appearing around the wavelength of 4100 Å although the S/N is not good in the blue part. This is obviously the CIII]$\lambda1909$ line and its presence supports our identification of the MgII line in the red part. Another piece of supporting evidence for these identifications is from the photometric redshift estimation. For four of these eight quasars, Richards et al. (2004) reported the photometric redshifts to be 0.875, 1.075, 1.225 and 1.975, which is consistent with our spectroscopic redshifts of 0.898, 1.154, 1.363 and 1.952, respectively.

We noticed that two of the eight new quasars have redshifts larger than 2.2. Besides SDSS J085543.40–001517.7 ($z = 2.427$) (see Paper I), SDSS J090504.87+000800.5 ($z = 2.773$) is also a quasar in the 'redshift desert.' These quasars are very difficult to identify because of their similar optical colors as stars. However, they can be uncovered by using the near-IR colors. In Figure 3, we show the locations of these eight quasars in three optical color-color diagrams and in the $Y - K$ vs.

[1] Obtained from *http://cas.sdss.org/dr7/en/tools/chart/chart.asp*

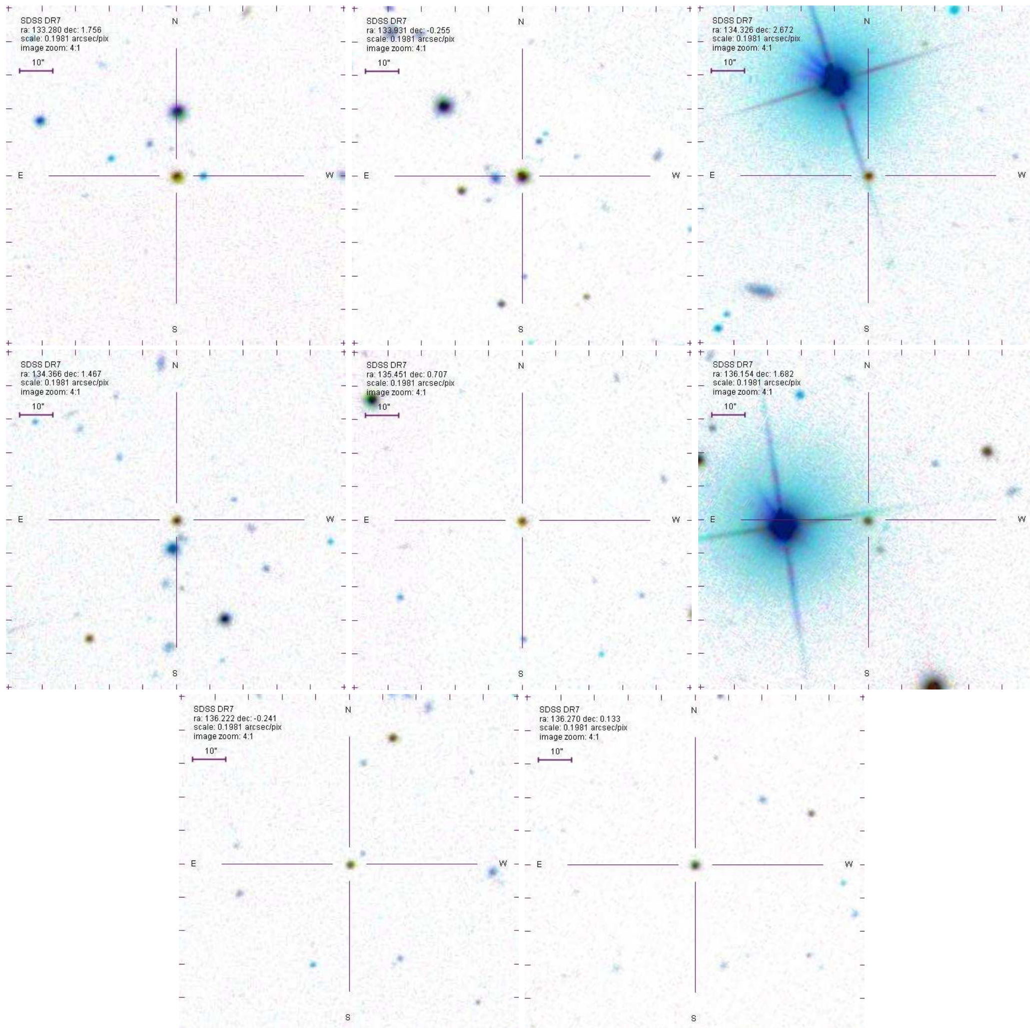

Fig. 1 Finding charts of the eight new quasars are shown in order of increasing RA. The size of each chart is $100'' \times 100''$.

$g-z$ diagram, in comparison with the 8996 SDSS-UKIDSS stars (Wu & Jia 2010). Note that in the $Y-K$ vs. $g-z$ diagram, the magnitudes of g and z have been converted to the magnitudes in the Vega system by using the scalings (Hewett et al. 2006): $g = g(AB)+0.103$ and $z = z(AB)-0.533$. Obviously, these two quasars with redshifts larger than 2.2 are located in the stellar locus in all three optical color-color diagrams, but are separated from stars in the $Y-K$ vs. $g-z$ diagram and satisfy the selection criterion proposed by Wu & Jia (2010). For six quasars with redshifts less than 2.2, although they are separated from the main stellar locus in the $u-g$ vs. $g-r$ diagram, they are still located in or close to the stellar locus in the other two optical color-color diagrams. None of these eight new quasars have an associated SDSS spectrum, although six of them with redshifts less than 2.5 were classified as quasar targets in the item ‘PrimeTarget’ of the SDSS/DR7 database. These

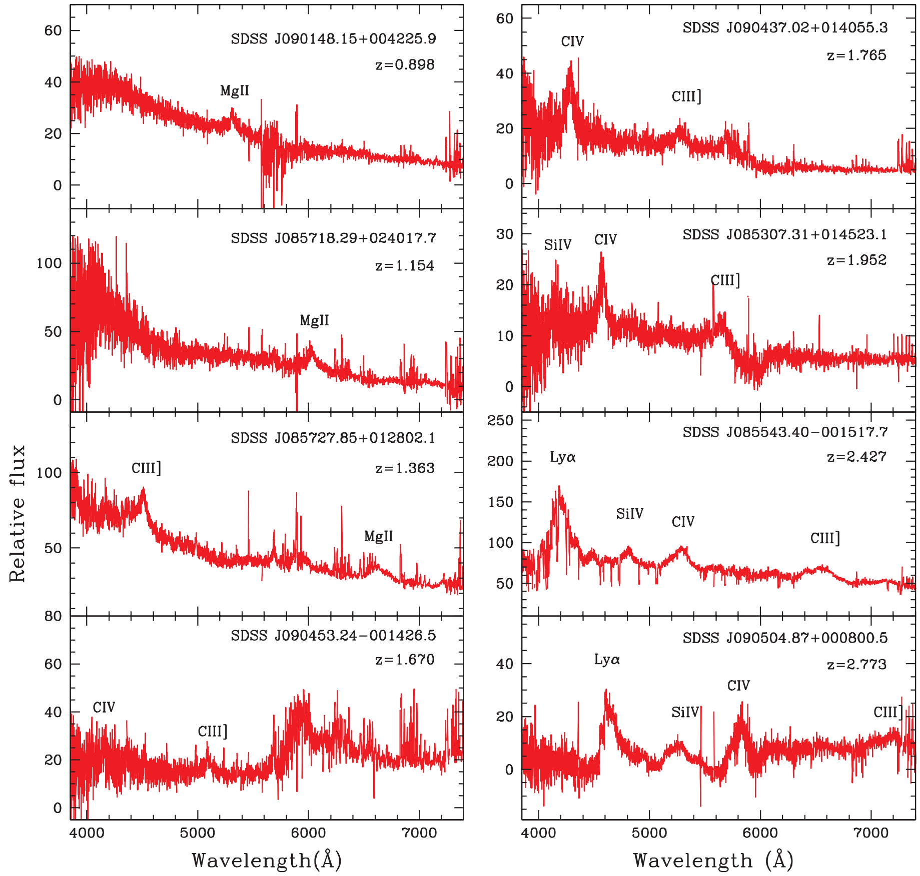

Fig. 2 LAMOST spectra of eight new quasars are shown in order of increasing redshift. The most prominent emission lines are marked in each spectrum.

unidentified quasars in the SDSS spectroscopic survey can be successfully uncovered by applying the selection criterion in the $Y - K$ vs. $g - z$ diagram.

We also searched for the counterparts of these new quasars in other wavelength bands. From the VLA/FIRST radio catalog (White et al. 1997), we did not find radio counterparts for all eight quasars within $30''$ from their SDSS positions. Therefore, these quasars are radio quiet, which is another reason why they were not identified by the SDSS spectroscopy. We also searched the ROSAT X-ray source catalog (Voges et al. 1999) and did not find counterparts for them within $1'$. From the GALEX catalog (Morrissey et al, 2007), we found ultraviolet counterparts within $1''$ from their SDSS positions for five of the six quasars with $z < 2$. However, for a $z = 1.363$ quasar, SDSS J085727.85+012802.1, and two quasars with $z > 2.2$, we failed to find their GALEX counterparts. The high GALEX detection rate (83%) of $z < 2$ quasars and the non-detection in ultraviolet for $z > 2.2$ quasars in our case is very consistent with the previous result of the SDSS-GALEX quasar sample (Trammell et al. 2007).

Although LAMOST encountered some problems during the commissioning observations, we were still able to identify 38 other known SDSS quasars in this field, with i magnitudes from 16.24 to 19.10 and redshifts from 0.297 to 4.512. The number of known SDSS quasars with $i < 19.1$ in

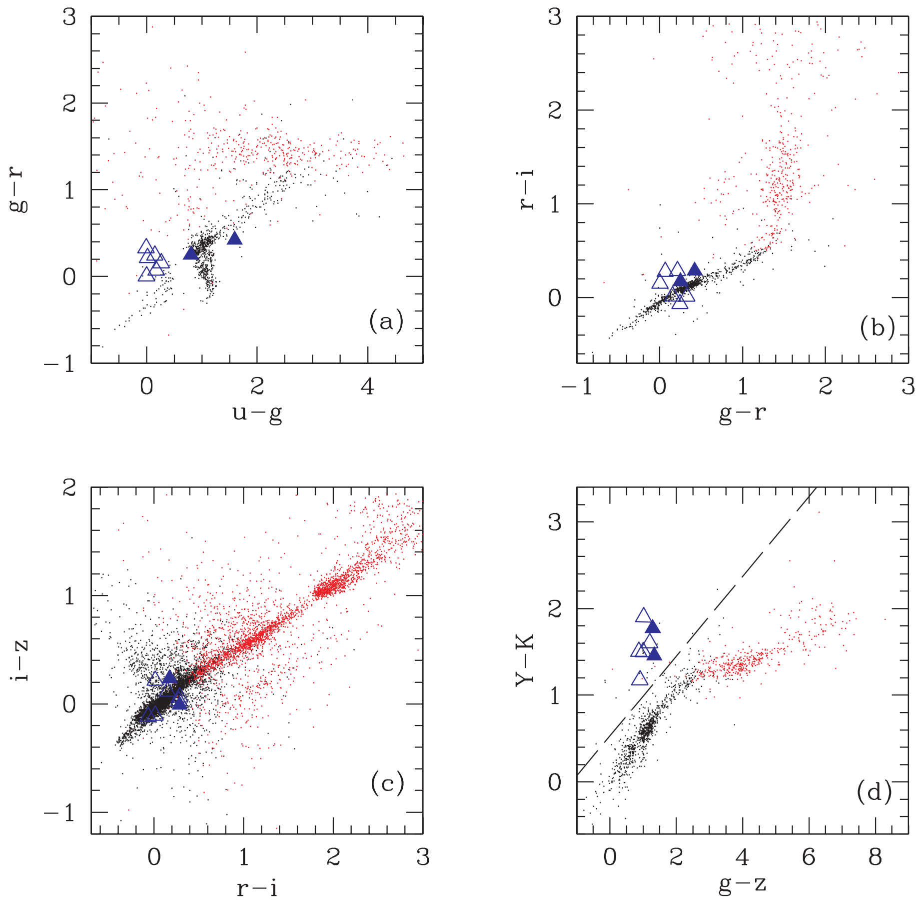

Fig. 3 Location of two new $z > 2.2$ quasars (*solid triangles*) and six new $z < 2.2$ quasars (*open triangles*) in three optical color-color diagrams (a,b,c) and the $Y - K$ vs. $g - z$ diagram (d), which can be found by comparing with the 8996 SDSS-UKIDSS stars (Wu & Jia 2010). Black and red dots represent the normal and later type stars, respectively. The dashed line shows the $z < 4$ quasar selection criterion proposed by Wu & Jia (2010). In diagram (d) only seven quasars are shown because one quasar does not have the Y band data.

this five degree field is 177, and our 38 identified SDSS quasars represented a fraction of 22% of them. In the upper and lower panels of Figure 4, we show the histograms of the redshift distribution of 177 known SDSS quasars with $i < 19.1$ and 38 SDSS quasars identified by LAMOST in this field. The contributions of eight new quasars to these two histograms are also demonstrated. The ratio between the 8 new quasars and 38 known SDSS quasars identified by us in this field is 21%, implying that a substantial fraction of the quasars may have been missed by SDSS at the magnitude limit $i < 19.1$. In particular, only 4 of 177 known SDSS quasars with $i < 19.1$ in this field have redshifts larger than 2.4. Our discovery of two new quasars with $z > 2.4$ adds a significant fraction to the known group. Obviously, this still needs to be confirmed by more complete spectroscopic identifications of quasars in this field. In addition, from the lower panel of Figure 4 we can see that the fraction of quasars with redshifts around 1.2 is relatively low, which is partly due to the lower CCD efficiency around 6000 Å where the blue and red spectra overlap. If we take the spectrum of

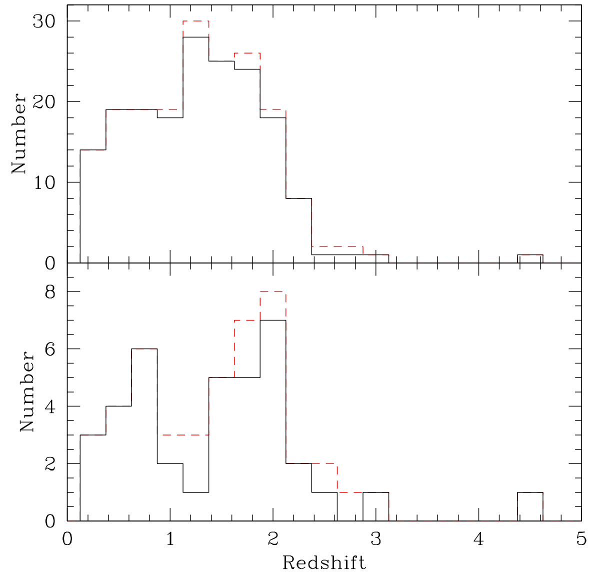

Fig. 4 *Upper panel:* Histogram of the redshift distribution of 177 known SDSS quasars with $i < 19.1$ in this field. *Lower panel:* Histogram of the redshift distribution of 38 SDSS quasars identified by LAMOST in this field. The contributions of eight new quasars to these two histograms are also demonstrated by the dashed lines.

a quasar with $z \sim 1.2$ with LAMOST, the MgII$\lambda 2798$ line will appear around 6000 Å as the only one prominent emission line in the optical band and will be difficult to identify due to the current problems in combining the LAMOST blue and red spectra around 6000 Å. This situation will be improved after we solve the problem of combining spectra.

3 DISCUSSION

In this paper, we presented the discovery of eight new quasars with redshifts from 0.898 to 2.773 in one extragalactic field close to GAMA-09 by the LAMOST commissioning observations. This discovery supports the idea that, by combining the UKIDSS near-IR colors with the SDSS optical colors, we are able to efficiently uncover the unidentified quasars in the SDSS spectroscopic survey, even at the magnitude limit $i < 19.1$. Our results indicate that not only are there some quasars in the redshift desert but also some quasars with lower redshifts which were probably missed in the SDSS survey. These missing quasars may account for a substantial fraction of the quasars at the magnitude limit of SDSS spectroscopy. Obviously, this still needs to be confirmed by more complete identifications of quasars in this field, because our identifications during the LAMOST commissioning observations are incomplete.

Nevertheless, the success of identifying eight new quasars (including two quasars in the redshift desert) in one extragalactic field gives us more confidence that we can discover more missing quasars in future LAMOST observations. In the winter of 2009, LAMOST made test observations of several sky fields and we are now searching for more quasars from the spectra taken in these fields. We believe that more missing quasars will soon be discovered.

A complete quasar sample is very important for the construction of the quasar luminosity function and for the study of cosmological evolution of quasars. However, as we demonstrated in this paper, because some quasars have similar optical colors as normal stars, it is very difficult to find them in optical quasar surveys. The low efficiency of finding quasars in the redshift desert (z from 2.2 to 3) has led to an obvious incompleteness in the SDSS quasar sample in this redshift range and serious problems in constructing the luminosity function for quasars around the redshift peak (between 2 and 3) of quasar activity (Richards et al. 2006; Jiang et al. 2006). Therefore, uncovering the missing quasars will become an important task in the future quasar survey. We hope that in the next few months great progress will be made in improving the capability of LAMOST spectroscopy. As long as LAMOST can reach its designed capability after the commissioning phase, we expect to obtain the largest quasar sample to date using the LAMOST quasar survey. This sample will undoubtedly play a leading role in future quasar studies.

Acknowledgements We thank Michael Strauss for clarifying the SDSS target status of these new quasars. This work was supported by the National Natural Science Foundation of China (Grant No. 10525313) and the National Key Basic Research Science Foundation of China (2007CB815405). The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST, now called the Guoshoujing Telescope) is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by the National Astronomical Observatories, Chinese Academy of Sciences. We acknowledge the use of LAMOST, as well as the archived data from SDSS, UKIDSS, FIRST, ROSAT and GALEX.

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