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A very bright ($i = 16.44$) quasar in the 'redshift desert' discovered by the Guoshoujing Telescope (LAMOST) *

Xue-Bing Wu[1], Zhao-Yu Chen[1], Zhen-Dong Jia[1], Wen-Wen Zuo[1], Yong-Heng Zhao[2], A-Li Luo[2], Zhong-Rui Bai[2], Jian-Jun Chen[2], Hao-Tong Zhang[2], Hong-Liang Yan[2], Juan-Juan Ren[2], Shi-Wei Sun[2], Hong Wu[2], Yong Zhang[3], Ye-Ping Li[3], Qi-Shuai Lu[3], You Wang[3], Ji-Jun Ni[3], Hai Wang[3], Xu Kong[4] and Shi-Yin Shen[5]

[1] Department of Astronomy, Peking University, Beijing 100871, China; *wuxb@bac.pku.edu.cn*
[2] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[3] National Institute of Astronomical Optics & Technology, Chinese Academy of Science, Nanjing 210042, China
[4] Center for Astrophysics, University of Science & Technology of China, Hefei 230026, China
[5] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China

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Abstract The redshift range from 2.2 to 3 is known as the 'redshift desert' of quasars because quasars with redshifts in this range have similar optical colors as normal stars and are thus difficult to find in optical sky surveys. A quasar candidate, SDSS J085543.40–001517.7, which was selected by a recently proposed criterion involving near-IR $Y - K$ and optical $g - z$ colors, was identified spectroscopically as a new quasar with a redshift of 2.427 by the Guoshoujing Telescope (LAMOST) commissioning observation in 2009 December and confirmed by the observation made with the NAOC/Xinglong 2.16 m telescope in 2010 March. This quasar was not identified in the SDSS spectroscopic survey. Comparing with other SDSS quasars, we found that this new quasar, with an i magnitude of 16.44, is apparently the brightest one in the redshift range from 2.3 to 2.7. From its spectral properties, we derived its central black hole mass to be $(1.4 \sim 3.9) \times 10^{10}\, M_\odot$ and its bolometric luminosity to be $3.7 \times 10^{48}\,\mathrm{erg\,s^{-1}}$, which indicates that this new quasar is intrinsically very bright and belongs to the class of the most luminous quasars in the universe. Our identification supports the notion that quasars in the redshift desert can be found by the quasar selection criterion involving the near-IR colors. More missing quasars are expected to be uncovered by future LAMOST spectroscopic surveys, which is important to the study of the cosmological evolution of quasars at redshifts higher than 2.2.

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

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1 INTRODUCTION

After the discovery of the first quasar (Schmidt 1963), many quasar surveys have been carried out in the optical band and the number of quasars has increased steadily in the past four decades (Richards et al. 2009). In particular, a large number of quasars have been discovered in two recent 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 quasars (Croom et al. 2004), and SDSS has identified more than 100 000 quasars (Schneider et al. 2010; Abazajian et al. 2009). 2dF mainly selected lower redshift ($z < 2.2$) quasars with UV-excess (Smith et al. 2005), while SDSS adopted a multi-band optical color selection method for quasars by mainly excluding the point sources in the stellar loci of color-color diagrams (Richards et al. 2002). Some dedicated methods were also proposed for finding high 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 obviously low in SDSS (Schneider et al. 2010), because quasars with such redshifts usually have similar optical colors as stars and are thus mostly ignored by the SDSS quasar candidate selection algorithm. Therefore, the redshift range from 2.2 to 3 is often regarded as the ‘redshift desert’ of quasars because of the difficulty in identifying quasars within this redshift range.

In addition, the low efficiency of finding quasars with redshifts between 2.2 and 3 has led to an obvious incompleteness in the quasar sample in this redshift range and serious problems in constructing the luminosity function for quasars. More importantly, many studies have shown that quasar activity actually peaks in the redshift range $2 < z < 3$ (see Richards et al. 2006; Jiang et al. 2006). Therefore, uncovering the missing quasars with redshifts between 2.2 and 3 has become an important task in quasar study.

Although they have similar optical colors as stars, quasars in the redshift desert are usually more luminous than normal stars in the infrared K-band because the fluxes of normal stars decrease rapidly in the near-IR bands while quasar SEDs are relatively flat (Warren et al. 2000). An important way of finding these missing quasars has 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 separate quasars from stars have previously been proposed. Maddox et al. (2008) suggested a selection criterion of $z < 4$ for quasar candidates in the $g - J$ vs. $J - K$ diagram. Chiu et al. (2007) investigated the different color-color diagrams in optical and near-IR bands with a sample of 2837 SDSS-UKIDSS quasars, and found that the $g - r$ vs. $u - g$ diagram and the $H - K$ vs. $J - H$ diagram are more effective in separating quasars from stars than other diagrams. They also proposed to use the $Y - K$ vs. $u - z$ diagram to select low redshift ($z < 3$) quasars. Recently, based on an SDSS-UKIDSS sample of 8498 quasars, Wu & Jia (2010) proposed to use the $Y - K$ vs. $g - z$ diagram to select $z < 4$ quasars and use the $J - K$ vs. $i - Y$ diagram to select $z < 5$ quasars. Although with these two criteria we can recover 8447 of 8498 SDSS-UKIDSS quasars (with a percentage of 99.4%), we still need to demonstrate whether we can efficiently discover new quasars, especially those in the redshift desert, by applying our criterion to select quasar candidates in the SDSS spectroscopically surveyed area.

The Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST, now called the Guoshoujing Telescope) is a 4-meter reflecting Schmidt telescope with a 20 square degree field of view (FOV) and 4000 fibers in the focal plane (Su et al. 1998), located at the NAOC/Xinglong station. After finishing its main construction in 2008, LAMOST has entered the commissioning phase since 2009. Some test observations have been done in the winter of 2009. Although LAMOST has not reached its full capability in the commissioning phase, these observations have already led to the discovery of some new quasars, including a bright quasar with a redshift of 2.427, which is the first quasar discovered by LAMOST in the ‘redshift desert’.

2 TARGET SELECTION AND OBSERVATION

In order to test whether our newly proposed quasar selection criterion in the $Y-K$ vs. $g-z$ diagram is efficient in identifying quasars, we selected many candidates in several sky fields which overlapped between the UKIDSS and SDSS survey areas with RA from 0 to 9 hours for the LAMOST commissioning observations in the winter of 2009. Although LAMOST encountered many problems during these commissioning observations, we were still able to identify some new quasars including the one reported here.

SDSS J085543.40–001517.7 is a relatively bright source among our quasar candidates. After the correction of Galactic extinction using the map of Schlegel et al. (1998), its SDSS $ugriz$ magnitudes (in the AB system) are 17.67, 16.87, 16.62, 16.44, and 16.20, respectively and its UKIDSS *YJHK* magnitudes (in the Vega system) are 15.61, 15.24, 14.60, and 13.84, respectively. The offset between its SDSS and UKIDSS positions is $0.05''$.

Figure 1 shows its SDSS finding chart (obtained from *http://cas.sdss.org/dr7/en/tools/chart/chart.asp*). Obviously, SDSS J085543.40–001517.7 is a bright point source, surrounded by several other fainter sources with offsets from $8''$ to $20''$. In Figure 2, we show the location of this source in three optical color-color diagrams and the $Y-K$ vs. $g-z$ 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 $z=z(AB)-0.533$. It is clear that SDSS J085543.40–001517.7

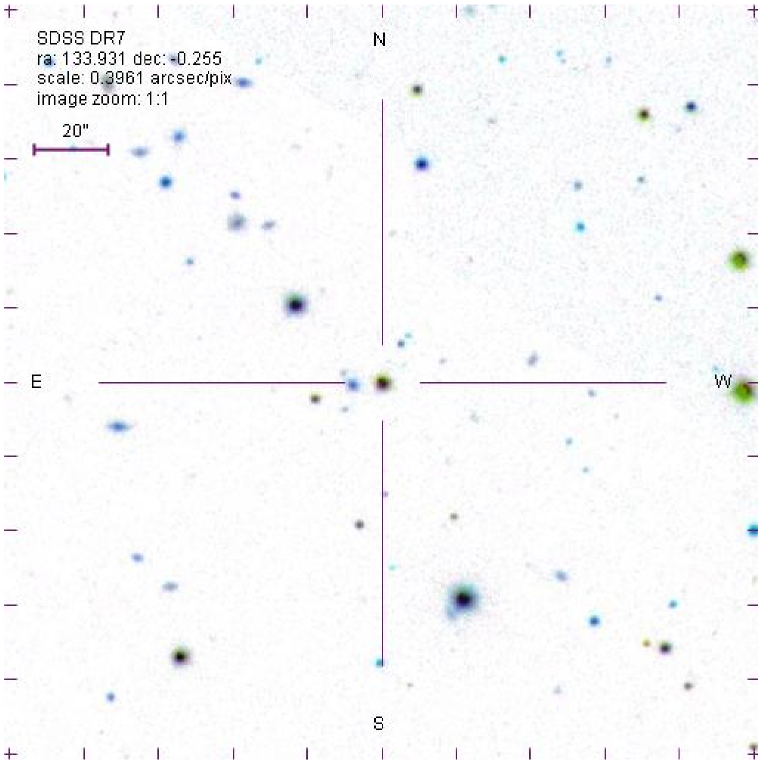

Fig. 1 Finding chart of SDSS J085543.40–001517.7. The size is $200'' \times 200''$.

is located in the stellar locus in three optical color-color diagrams, but is well separated from stars in the $Y-K$ vs. $g-z$ diagram and satisfies the selection criterion, $Y-K > 0.46 \times (g-z) + 0.53$, proposed by Wu & Jia (2010).

The spectroscopy of SDSS J085543.40–001517.7 was obtained by LAMOST during the commissioning observations on 2009 December 18, with a spectral resolution of R $\sim$1000 and an exposure time of 30 minutes. The spectrum was processed using a preliminary version of the LAMOST spectral pipeline. In the left panel of Figure 3, we show the LAMOST spectrum of SDSS J085543.40–001517.7 (some sky light emissions were not well subtracted). From the spectrum, we can clearly observe at least four strong emission lines, namely Lyα $\lambda1216$, Si IV $\lambda1400$, C IV $\lambda1549$ and C III] $\lambda1909$. With these four lines we derived an average redshift of $z = 2.427$ for this new quasar. Three weak emission lines, N V $\lambda1240$, O I $\lambda1304$ and C II $\lambda1335$, can be also seen between the Lyα and Si IV lines. The complicated feature around 5900 Å is due to the problem of combining the LAMOST blue and red spectra, which overlap with each other from 5700 Å to 6000 Å. In this figure, we also compare the LAMOST spectrum with the scaled SDSS composite quasar spectrum (Vanden Berk et al. 2001). It is clear that both match well with each other, except in the red end.

On 2010 March 9, we also used the NAOC/Xinglong 2.16 m telescope to do spectroscopy of this new quasar. Because the seeing condition was bad ($4''$–$5''$), we took two 40-minute exposures of this quasar and obtained the median spectrum, which is shown in the right panel of Figure 3 in comparison with the scaled SDSS composite quasar spectrum. Although its signal to noise ratio is lower than the LAMOST spectrum, four strong emission lines can still be clearly observed. Moreover, its continuum shape matches the SDSS composite quasar spectrum better than the LAMOST spectrum, especially in the red end.

3 PROPERTIES OF SDSS J085543.40–001517.7

With the i magnitude of 16.44 and redshift of 2.427, SDSS J085543.40–001517.7 is undoubtedly a very bright quasar. We compared it with other SDSS quasars in the redshift range from 2 to 3.2 and found the new quasar is indeed very bright. In Figure 4, we show the location of the new quasar in the magnitude-redshift diagram in comparison with other SDSS quasars, as well as the histogram of the redshift distribution of SDSS quasars. The redshift distribution clearly shows the presence of the 'redshift desert' in the redshift range from 2.2 to 3. The new quasar is apparently the brightest one in the redshift range from 2.3 to 2.7. Its absolute i magnitude is –30.0 if the cosmological parameters H_0=70 $\mathrm{km\,s^{-1}}$ $\mathrm{Mpc^{-1}}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ are adopted. This quasar clearly belongs to the class of the most luminous quasars in the universe.

We also searched the counterparts of SDSS J085543.40–001517.7 in other wavelength bands. From the VLA/FIRST radio catalog (White et al. 1997), we did not find any radio counterpart within $20''$ from its SDSS position. The closest radio source is $121.5''$ away. Therefore, this quasar is a radio-quiet one, which is also another reason why it was missed by the SDSS spectroscopy. We also searched the ROSAT X-ray source catalog (Voges et al. 1999) and did not find any counterpart within $1'$. The closest X-ray source is $23'$ away. From the GALEX catalog (Morrissey et al. 2007) we failed to find any ultraviolet counterpart within $5''$. One GALEX source is $27''$ away (in the south-western direction) from the optical position of SDSS J085543.40–001517.7, and is clearly the counterpart of another fainter extended source in the SDSS image. Therefore, we believe that SDSS J085543.40–001517.7 is faint in radio, UV and X-ray bands, although it is very luminous in optical and near-IR bands.

From the spectral properties, we can estimate the black hole mass and bolometric luminosity of this new quasar. After doing the redshift correction, Galactic extinction correction using the reddening map of Schlegel et al. (1998), continuum fitting and Fe II subtraction using the template from Vestergaard & Wilkes (2001), we measured the C IV line width (FWHM, the Full Width at Half

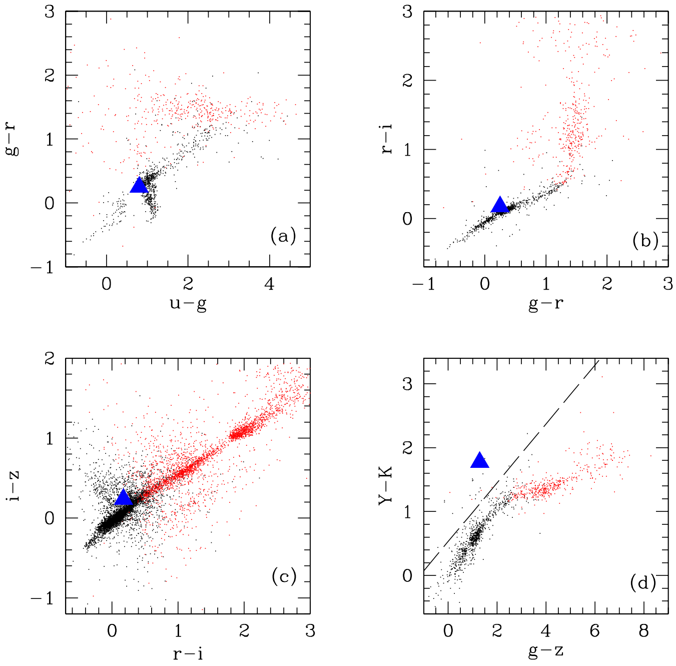

Fig. 2 Location of SDSS J085543.40–001517.7 (*blue triangle*) in three optical color-color diagrams (a,b,c) and the $Y - K$ vs. $g - z$ diagram (d), which can be found by comparing with the 8996 SDSS-UKIDSS stars. Black and red dots represent the normal and later type stars, respectively. The dashed line shows the $z < 4$ quasar selection criterion proposed by Wu & Jia (2010).

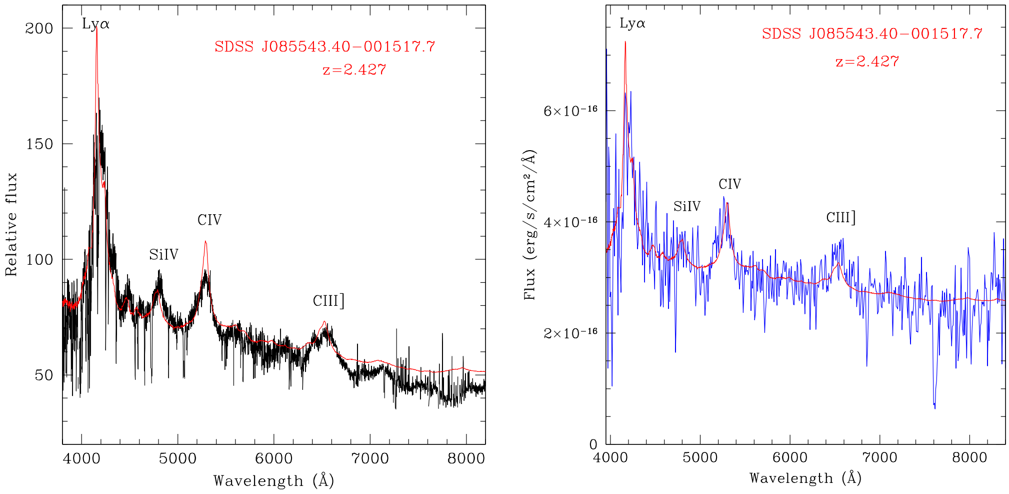

Fig. 3 *Left panel:* LAMOST spectrum of SDSS J085543.40–001517.7. *Right panel:* The spectrum of SDSS J085543.40–001517.7 taken by the NAOC/Xinglong 2.16 m telescope. The scaled SDSS composite quasar spectrum (highlighted in the red color) is shown for comparison.

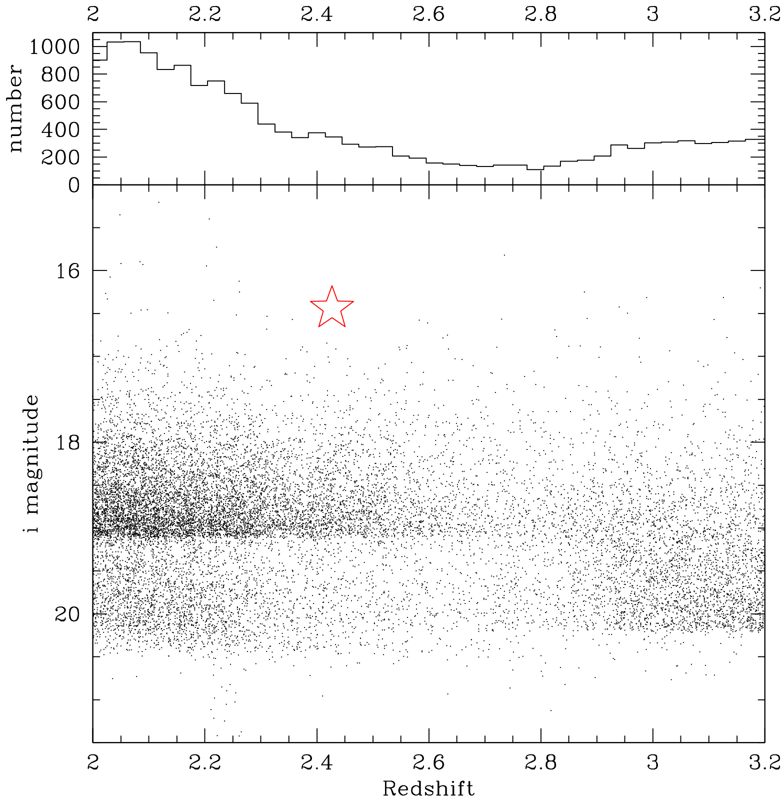

Fig. 4 Location of SDSS J085543.40–001517.7 (*star*) in the magnitude-redshift diagram in comparison with the SDSS DR7 quasars in the redshift range from 2 to 3.2. The redshift distribution of SDSS quasars is also shown in the upper panel, in which the redshift desert (with redshifts from 2.2 to 3) is clearly presented.

Maximum) and the rest frame 1350 Å continuum flux from the spectrum. Because we did not do the absolute flux calibration of the LAMOST spectrum of SDSS J085543.40–001517.7, we used the ultraviolet continuum window 1320 Å–1330 Å to calibrate the LAMOST spectrum with the spectrum taken by the 2.16 m telescope. The C IV FWHM values measured from LAMOST and the 2.16 m spectrum are 8520 $\mathrm{km\ s^{-1}}$and 11040 $\mathrm{km\ s^{-1}}$, respectively. Due to the lower signal to noise ratio of the 2.16 m spectrum (see the right panel of Fig. 3), we took the C IV FWHM value from the LAMOST spectrum in the following calculation. The black hole mass estimation was done with two similar formulae proposed by Kong et al. (2006) and Vestergaard & Peterson (2006), both involving the C IV line width and the 1350 Å continuum luminosity. The first one gives $M_{\rm BH} = 1.4 \times 10^{10}\, M_\odot$ and the latter one gives $M_{\rm BH} = 3.9 \times 10^{10}\, M_\odot$. Using a scaling between the 1350 Å luminosity and bolometric luminosity, $L_{\rm bol} = 4.62\, L_{1350}$, given by Vestergaard (2004) based on the SED of radio-quiet quasars (Elvis et al. 1994), we estimated the bolometric luminosity of this new quasar as 3.7×10^{48} erg $\mathrm{s^{-1}}$, which is about $(0.5 \sim 1.4)$ times the Eddington luminosity if the above estimated black hole mass is adopted. Obviously, this quasar is intrinsically very bright, and is accreting matter with an accretion rate around the Eddington limit.

4 DISCUSSION

Quasars with redshifts in the range from 2.2 to 3 are very important for studying their cosmological evolution, and the relation between quasar activity and star formation activity which peaks at redshifts between 1 and 2 (Madau et al. 1998). However, because these quasars have similar optical colors as normal stars, it is very difficult to find them in previous quasar surveys. The low efficiency of finding quasars in the 'redshift desert' has led to the obvious incompleteness of the 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).

In this paper, we have presented a case study to find a very bright new quasar in the redshift desert by the LAMOST commissioning observation. The spectroscopic identification of an $i = 16.44$ source, SDSS J085543.40–001517.7, as a $z = 2.427$ quasar gives us confidence to discover more missing quasars in the future LAMOST quasar survey. This discovery also supports the idea that, by combining the UKIDSS near-IR colors with the SDSS optical colors, we are able to efficiently uncover the missing quasars. In the winter of 2009, LAMOST has made test observations on several sky fields and we are now searching for more quasars from the spectra taken in these fields. The discovery of more new quasars in these fields will be reported in future works. We hope that in the next few months, great progress will be made in improving the capability of LAMOST spectroscopy and the spectral processing pipeline. As long as LAMOST can reach its design capability after the commissioning phase, we expect to find several hundred-thousand quasars in the LAMOST quasar survey. This will form the largest quasar sample in the world and will play a leading role in quasar study over the next decade.

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