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Discovery of six high-redshift quasars with the Lijiang 2.4m telescope and the Multiple Mirror Telescope

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摘要 Quasars with redshifts greater than 4 are rare, and can be used to probe the structure and evolution of the early universe. Here we report the discovery of six new quasars with i-band magnitudes brighter than 19.5 and redshifts between 2.4 and 4.6 from the YFOSC spectroscopy of the Lijiang 2.4m telescope in February, 2012. These quasars are in the list of $z > 3.6$ quasar candidates selected by using our proposed $J-K/i-Y$ criterion and the photometric redshift estimations from the SDSS optical and UKIDSS near-IR photometric data. Nine candidates were observed by YFOSC, and five among six new quasars were identified as $z > 3.6$ quasars. One of the other three objects was identified as a star and the other two were unidentified due to the lower signal-to-noise ratio of their spectra. This is the first time $z > 4$ quasars have been discovered using a telescope in China. Thanks to the Chinese Telescope Access Program (TAP), the redshift of 4.6 for one of these quasars was confirmed by the Multiple Mirror Telescope (MMT) Red Channel spectroscopy. The continuum and emission line properties of these six quasars, as well as their central black hole masses and Eddington ratios, were obtained.

Key words: quasars: general — quasars: emission lines — galaxies: active — galaxies: high-redshift

1 INTRODUCTION

The number of known quasars has increased steadily in the past four decades since their discovery in 1963 (Schmidt 1963). Especially, a large number of quasars have been discovered in two large spectroscopic surveys, namely, the Two-degree Field (2dF) survey (Boyle et al.

2000) and the Sloan Digital Sky Survey (SDSS) (York et al. 2000). 2dF mainly selected low redshift ($z < 2.2$) quasar candidates with UV-excess (Smith et al. 2005) and has discovered more than 20 000 quasars (Croom et al. 2004). SDSS adopted a multi-band optical color selection method for quasars mainly by excluding the point sources in the stellar locus of the color-color diagrams (Richards et al. 2002) and has identified more than 120 000 quasars (Schneider et al. 2010). 90% of SDSS quasars have low redshifts ($z < 2.2$), though some dedicated methods were also proposed for finding high redshift quasars ($z > 3.5$) (Fan et al. 2001b,a; Richards et al. 2002).

High-redshift quasars are rare, and those with redshifts greater than 4 represent only 1% in the total quasar population. In the SDSS DR7 quasar catalog (Schneider et al. 2010), only 1248 (392) among 105783 quasars have redshifts greater than 4 (4.5). Since these $z \sim 4$ quasars exist when the universe is at age of 1.57 Gyr, they can be used to probe the structure and evolution of the early universe (Smith et al. 1994; Constantin et al. 2002). Especially, the absorption line spectra of these quasars can give valuable information on the nature of intergalactic medium at high redshift. However, discovering $z \sim 4$ quasars is a big challenge because they are fainter than the low redshift quasars due to the larger distances. Moreover, the Lyα emission lines for $z \sim 4$ quasars move to the red end of optical spectra, making them hard to be distinguishable from stars due to similar optical colors. Recently, Wu & Jia (2010) proposed to use the $Y - K/g - z$ criterion to select $z < 4$ quasars and use the $J - K/i - Y$ criterion to select $z < 5$ quasars with the SDSS optical and UKIDSS (UKIRT Infrared Deep Sky Survey)[1] near-IR data based on a K-band excess technique (Warren et al. 2000; Hewett et al. 2006; Chiu et al. 2007; Maddox et al. 2008). With these two criteria, it is expected to obtain more complete quasar samples than previous ones. Recent optical spectroscopic observations made by the GuoShouJing Telescope (LAMOST) and MMT have demonstrated the success of finding the missing quasars with redshifts between 2.2 and 3 using the $Y - K/g - z$ criterion (Wu et al. 2010a,b, 2011). We also hope to discover some $z \sim 4$ quasars with the $J - K/i - Y$ criterion, which is expect to be applicable for selecting the candidates of quasars with redshifts up to 5 (Wu & Jia 2010).

In this letter we report our discovery of six new high redshift quasars from the spectroscopic observations with the Lijiang 2.4m telescope and MMT in February, 2012. The successful identifications of these high redshft quasars further demonstrate the effectiveness of using our newly proposed criteria for discovering the missing quasars including high-redshift ones.

2 TARGET SELECTION AND SPECTROSCOPIC OBSERVATIONS

Richards et al. (2009) presented a catalog of about 1million quasar candidates selected from the SDSS DR6 photometric data using Bayesian methods. Photometric redshifts for these candidates were also provided based on the SDSS $urgiz$ magnitudes. From this catalog we selected all unidentified candidates with the photometric redshift greater than 3.6, the photometric redshift probability larger than 0.6 and the i-band magnitude brighter than 19.5.

[1] The UKIDSS project is defined in Lawrence et al. (2007). UKIDSS uses the UKIRT Wide Field Camera (WFCAM; 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).

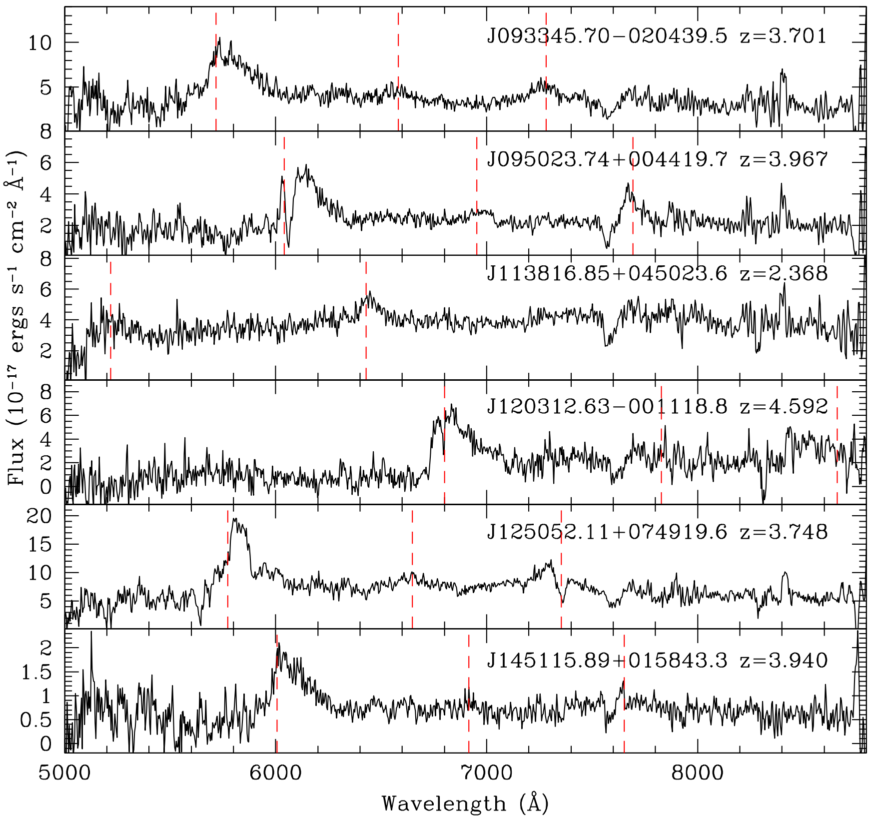

图 1: The YFOSC spectra of six new quasars. From the left to right, the red dashed lines mark the wavelengths of Lyα, SiIV and CIV emission lines at the estimated redshift for five $z > 3.6$ quasars, while for SDSS J113816.85+045023.6 they mark the wavelengths of CIV and CIII].

Then we cross-matched them with the UKIDSS Large Area Survey (LAS) DR7 catalog using a positional offset of 3 arcsec to find the closest counterparts. From this sample with both SDSS $ugriz$ data and UKIDSS $YJHK$ data, we adopted our $J-K/i-Y$ criterion (Wu & Jia 2010), namely, $J-K > 0.45(i-Y)+0.48$ (where YJK are the Vega magnitudes and i is the AB magnitude), to make further selection of $z \sim 4$ quasar candidates. We also used our own program to estimate the photometric redshifts of these candidates with SDSS and UKIDSS 9-band photometric data (Wu & Jia 2010; Wu et al. 2004), and excluded the sources whose photometric redshifts estimated from the 5-band SDSS photometric data in Richards et al. (2009) are inconsistent with ours. After these procedures we obtained a final list of about 20 high-redshift ($z > 3.6$) quasar candidates.

The spectroscopic observations were carried out in February 26–28, 2012, with the Yunnan Faint Object Spectrograph and Camera (YFOSC) instrument of the Lijiang 2.4m telescope in Yunnan Astronomical Observatory. Due to the cloudy weather, 9 candidates were observed with YFOSC using a low resolution grism with the central wavelength around 6500 Å, the spectral resolving power of 870, and a long slit with of 2.5″ width. The typical seeing is around 2″. In Table 1 we summarize the details of the observations for these 9 candidates. Six of them were idenfied as quasars, one as a G-type star and two as unidentified due to the lower signal-to-noise ratios of their spectra.

表 1: Parameters of 9 objects observed by YFOSC

Name (SDSS J)	Date	Exposure (s)	u	g	r	i	z	Y	J	H	K	Result
075733.86+190403.1	2012-02-26	2700	21.37	20.40	19.45	19.00	18.53	17.88	17.02	16.63	15.68	low S/N
085203.84+020437.7	2012-02-27	6000	21.67	20.99	19.69	19.09	18.66	17.82	17.47	16.66	15.72	low S/N
092740.04-023347.5	2012-02-28	4200	21.01	20.50	19.55	19.08	18.86	18.42	18.01	17.11	16.42	G star
093345.70-020439.5	2012-02-27	3600	23.77	20.72	19.55	19.47	19.41	19.21	18.66	18.46	17.88	quasar
095023.74+004419.7	2012-02-27	6600	23.97	20.97	19.75	19.48	19.36	18.83	18.40	17.76	17.25	quasar
113816.85+045023.6	2012-02-27	6000	21.26	20.70	19.67	19.27	19.06	18.30	17.96	16.90	16.46	quasar
120312.63-001118.8	2012-02-28	5400	25.38	22.34	20.29	19.14	18.95	18.32	18.00	17.19	16.64	quasar
125052.11+074919.6	2012-02-26	5400	23.56	20.08	18.75	18.63	18.43	18.14	17.35	16.81	16.15	quasar
145115.89+015843.3	2012-02-27	4800	23.72	20.42	19.30	19.23	19.09	18.61	18.02	17.56	16.92	quasar

Notes: The SDSS $ugriz$ magnitudes are given in AB system and the UKIDSS $YJHK$ magnitudes are given in Vega system.

The spectra of six new quasars, after the flat-field correction and both wavelength and flux calibrations, are shown in Figure 1. The strongest emission lines for five $z > 3.6$ quasar are Lyα lines, while for SDSS J113816.85+045023.6 the strongest line around 6400 Å is CIII]. The redshifts for these quasars are the average values given mostly by the Lyα and CIV lines for five $z > 3.6$ quasar and by the III] and CIV lines for SDSS J113816.85+045023.6.

Thanks to the Chinese Telescope Access Program[2], SDSS J120312.63-001118.8 was also observed with the Red Channel Spectrograph on the MMT 6.5m telescope[3] at Mt. Hopkins, Arizona, USA on Feb. 29, 2012, with a wavelength coverage of 5100–8600 Å and a spectral resolution of 1.6 Å. It was observed twice, with the exposures of 10 minutes and 15 minutes respectively. The spectrum was processed using the IRAF Echellette package and is shown in Figure 2. The average redshift estimated from Lyα and SiIV (1400 Å) emission lines is 4.601±0.008, consistent with the result ($z = 4.592 \pm 0.048$) obtained from the YFOSC observation.

3 SPECTRAL ANALYSES AND PROPERTIES OF SIX HIGH-REDSHIFT QUASARS

The redshift corrected rest-frame YFOSC spectra of six quasars are first corrected for the Galactic extinction using the extinction map of Schlegel et al. (1998). They are then fitted with an IDL code MPFIT (Markwardt 2009). We fit the spectra with the pseudo-continuum model consisting of the featureless nonstellar continuum and FeII emissions. The continuum is assumed to be a power-law, so two free parameters (the amplitude and the slope) are required. The UV FeII template (Vestergaard & Wilkes 2001; Tsuzuki et al. 2006) is convolved with a velocity dispersion and shifted with a velocity, assuming the line width of FeII lines are same with emission lines in the corresponding wavelength range. During the fitting, the amplitude and slope of the power-law continuum and the amplitude, velocity shift and broadening width of the FeII emission, are set to be free parameters. The initial value of the power-law continuum is obtained by fitting a simple power law to the data in the chosen windows, which are free

[2] http://info.bao.ac.cn/tap/

[3] Observation reported here was obtained at the MMT Observatory, a joint facility of of the Univeristy of Arizona and the Smithsonian Institution.

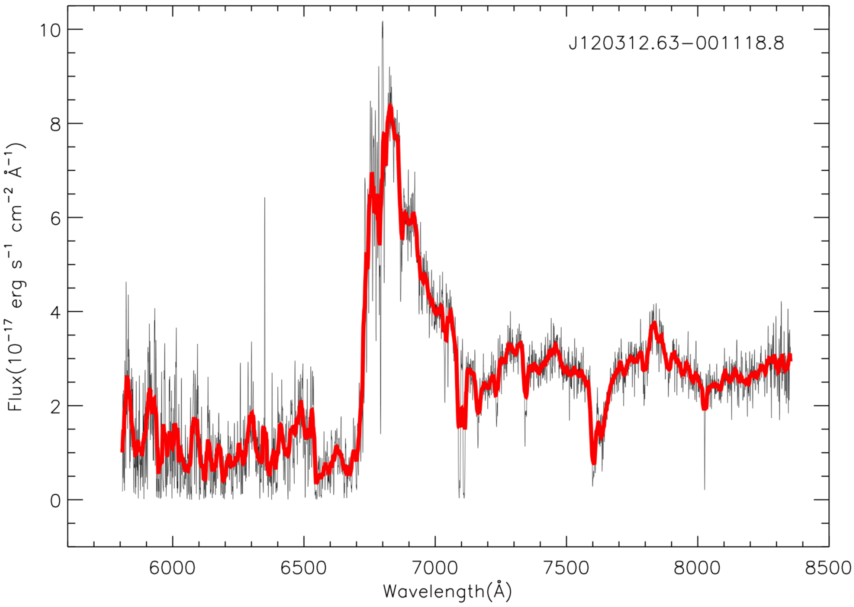

图 2: The MMT Red Channel spectrum of SDSS J120312.63–001118.8. The average redshift estimated from Lyα and SiIV (1400 Å) emission lines is 4.601. The red line refer to the smoothed spectrum with a binsize of 8 Å.

from emission-line contamination. The initial value of broadening width of the FeII emissions is set to be the line width of the strong emission line CIV. Then we use the pseudo-continuum model to fit a set of continuum windows with strong FeII emissions but no other emission lines, as mentioned in Hu et al. (2008), slightly adjusted interactively for each individual spectrum in order to avoid broad absorption features or extended wings of emission lines.

After constructing the pseudo-continuum, the CIV line should be fitted with two Gaussians, one for the narrow component and another for the broad component. However, except SDSS J095023.74+004419.7, the spectra of other five quasars have low signal-to-noise ratio, so we used only one Gaussian to fit the CIV emission line. Absorption features are evident in the spectra of four quasars, and one more negative Gaussian was added in the fitting. We measure the Full Width at Half Magnitude of CIV line ($\mathrm{FWHM_{CIV}}$), luminosity at 1350 Å (L_{1350}) from the spectra (except for SDSS J113816.65+004419.7, where 1350 Å is not within the wavelength coverage, we estimate the luminosity at 1500 Å instead). The black hole mass is estimated based on $\mathrm{FWHM_{CIV}}$ and L_{1350} with equation (7) in Vestergaard & Peterson (2006)(see also Kong et al. 2006). Using a scaling between L_{1350} and bolometric luminosity L_{bol}, $L_{\mathrm{bol}} = 4.62 L_{1350}$, we estimated the bolometric luminosity for the six quasars. Based on the estimated black hole mass and bolometric luminosity, we also estimated their Eddington ratios. The results are summarized in Table 2. Although the uncertainties of these values are probably quite large due to the low spectral quality and the unusual properties of CIV, we noticed that the overall properties of these six quasars are consistent with those of typical SDSS quasars at high redshift (Shen et al. 2011).

表 2: Spectral parameters and black hole masses of six new quasars

Name (SDSS J)	Redshift	FWHM (CIV) ($\mathrm{km\ s^{-1}}$)	$\log(L_{1350})$ ($\mathrm{erg\ s^{-1}}$)	$\log(M_{\mathrm{BH}})$ ($M_\odot$)	$\log(L_{\mathrm{bol}})$ ($\mathrm{erg\ s^{-1}}$)	R_{EDD}
093345.70−020439.5	3.701±0.011	6749	46.457	9.621	47.122	−0.588
095023.74+004419.7	3.967±0.035	4500	46.300	9.185	46.964	−0.310
113816.85+045023.6	2.368±0.011	5144	46.000	9.118	46.664	−0.543
120312.63−001118.8	4.592±0.048	4865	46.431	9.323	47.096	−0.316
125052.11+074919.6	3.748±0.030	5424	46.805	9.615	47.469	−0.235
145115.89+015843.3	3.940±0.006	4507	45.682	8.859	46.346	−0.602

4 DISCUSSION

A complete quasar sample is crucial for studying the large scale structure of the universe. The current available quasar samples are mostly biased towards low redshifts ($z < 2.2$) and more efforts are needed to find quasars at high redshift. Wu & Jia (2010) proposed to obtain a large complete quasar sample with redshifts up to five by combining the $J - K/i - Y$ criterion with the $Y - K/g - z$ criterion to select quasar candidates. Some recent optical spectroscopic observations have demonstrated the success of finding the missing quasars with redshifts between 2.2 and 3 using the $Y - K/g - z$ criterion (Wu et al. 2010a,b, 2011). Our discovery of six high redshift quasars (five with $z > 3.6$) from the spectroscopic observations with the Lijiang 2.4m telescope and MMT further demonstrates the effectiveness of using the $J - K/i - Y$ criterion for discovering quasars with redshifts up to five. Moreover, the identification of five quasars with $z > 3.6$ from nine candidates with photometric redshift larger than 3.6 also confirms the robustness of the photometric redshifts estimated by the SDSS and UKIDSS photometric data. We noticed that two among our five $z > 3.6$ new quasars do not meet the SDSS *gri* or *riz* selection critrion for $z > 3.6$ quasars (Fan et al. 2001b,a; Richards et al. 2002), which suggests that about 40% of such quasars may be missed in the SDSS spectroscopic survey. This obviously needs to be confirmed by future observations of a large sample of $z > 3.6$ quasars.

Our identification of a $z = 4.6$ quasar demonstrates that $z > 4$ quasars can be identified with the 2-meter size telescopes in China. We hope more high redshift quasars will be discovered by the future LAMOST quasar survey (Wu & for the LAMOST Extragalactic Survey Team 2011), which is aiming at discovering 0.3–0.4 million quasars from 1 million quasar candidates with $i < 20.5$, by taking the advantages of 4000 fibers and 5 degree field of view of LAMOST (Su et al. 1998; Zhao et al. 2012). The new quasar selection criteria, such as those based on SDSS, UKIDSS and the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) data (Wu et al. 2012), will be applied for selecting quasar candidates in the LAMOST quasar survey. This will hopefully provide the largest quasar sample in the next five years for further studies of AGN physics, large scale structure and cosmology.

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