The Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) Quasar Survey: Quasar Properties from Data Release Two and Three

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Received 2017 May 7; revised 2018 February 12; accepted 2018 February 27; published 2018 April 10

Abstract

This is the second installment for the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) Quasar Survey, which includes quasars observed from 2013 September to 2015 June. There are 9024 confirmed quasars in DR2 and 10911 in DR3. After cross-match with the Sloan Digital Sky Survey (SDSS) quasar catalogs and NED, 12126 quasars are discovered independently. Among them, 2225 quasars were released by SDSS DR12 QSO catalog in 2014 after we finalized the survey candidates. 1801 sources were identified by SDSS DR14 as QSOs. The remaining 8100 quasars are considered as newly founded, and among them, 6887 quasars can be given reliable emission line measurements and the estimated black hole masses. Quasars found in LAMOST are mostly located at low-to-moderate redshifts, with a mean value of 1.5. The highest redshift observed in DR2 and DR3 is 5. We applied emission line measurements to \( \text{H}\alpha, \text{H}\beta, \text{MgII}, \) and \( \text{CIV} \). We deduced the monochromatic continuum luminosities using photometry data, and estimated the virial black hole masses for the newly discovered quasars. Results are compiled into a quasar catalog, which will be available online.

Key words: catalogs – quasars: emission lines – quasars: general – surveys

Supporting material: tar.gz file

1. Introduction

Quasars are some of the most exotic celestial objects in the universe. They emit a broad range of electromagnetic waves from \( \gamma \)-ray to radio (Antonucci 1993) and outshine their host galaxies by hundreds of times. Quasars can be used to trace galaxy evolution (e.g., Schweitzer et al. 2006; Lutz et al. 2008; Bonfield et al. 2011; Dong & Wu 2016) and probe the intergalactic medium (e.g., Hennawi & Prochaska 2007; Huo et al. 2013, 2015).

There have been many dedicated works to find more quasars ever since the first quasar was discovered by Schmidt (1963). The unique spectral energy distribution, high luminosity, and variations of quasars are often used to select quasar survey candidates by separating them from normal galaxies and stars. By far, the most productive quasar survey is the Sloan Digital Sky Survey (SDSS; Schneider et al. 2010; Pâris et al. 2012, 2014). Another noticeable quasar survey is the Two-Degree Fields (2dF) Quasar Redshift Survey (Boyle et al. 2000). Both SDSS and 2dF use ultraviolet/optical photometric data to select their candidates. With the improvements of both quality and quantity of infrared surveys, optical/infrared photometric data provide another important tool to select quasar candidates (e.g., Wu & Jia 2010; Wu et al. 2012; Ai et al. 2016). The extreme-deconvolution method with an optical-infrared color cut is used by the SDSS-III’s Baryon Oscillation Spectroscopic Survey project (XDQSO; Bovy et al. 2011; Myers et al. 2015). Other data-mining and machine-learning algorithms are also adopted for quasar selection (e.g., Peng et al. 2012; Ross et al. 2012).

The Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) Quasar Survey is conducted under the LAMOST ExtraGalactic Survey (LEGAS; Zhao et al. 2012). Its quasar candidates are selected based on multi-color photometry and data-mining. The regular survey began in 2012 September and will continue for the next five to six years. This paper is the second installment in the series of LAMOST quasar survey, after the pilot observations (Wu et al. 2010a, 2010b) and data release one (Ai et al. 2016, Paper I). Here, we report LAMOST quasar survey data releases two and three, which include quasars observed between 2013 September and 2015 June. In Section 2, we briefly review the survey and candidate selections. Section 3 describes the visual inspections of the spectra. The emission line measurements and the black hole mass estimates are discussed in Sections 4 and 5. The parameters released with the quasar catalog are list in Section 6, and we present our summary in the final section. Throughout the paper, we adopt a \( \Lambda \)-dominated cosmology with \( h = 0.7 \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \).

2. Survey Outline

The LAMOST, also known as Guoshoujing Telescope, is a 4 m reflecting Schmidt telescope located at Xinglong Observatory, China (Cui et al. 2012; Zhao et al. 2012). It is equipped with 4000 fibers across a 5° field of view. LAMOST has two sets of spectrographs. The blue channel covers the spectrum from 3700 to 5900 Å, while the red channel covers the spectrum from 5700 to 9000 Å. The spectral resolution \( R \) is about 1800 over the entire wavelength range.
2.1. Target Selections

The potential quasar candidates are required to be point sources in SDSS image survey (Ahn et al. 2012) with a Galactic extinction-corrected i-band Point Spread Function (PSF) magnitude brighter than 20 mag. To avoid saturation and contamination from neighbor fibers, the magnitude upper limit is set to be $i = 16$. The final candidates are selected from this candidate pool via two methods.

Optical-infrared colors. The foremost purpose of the LEGAS quasar survey is to discover more quasars. Yet quasars at redshift $2-3$ cannot be effectively identified in optical color--color space, because their colors are very similar to stars or galaxies (Schneider et al. 2010). Wu & Jia (2010) and Wu et al. (2012) proposed to use optical-infrared color instead. In the LEGAS survey, we adopted $Y - K > 0.46(g - z) + 0.82$ or $J - k > 0.45(i - Y - 0.366) + 0.64$ (Wu & Jia 2010) for candidates with counterparts within the UKIDSS/Large Area Survey (LAS) DR8 (Lawrence et al. 2007), and $w1 - w2 > 0.57$ or $z - w1 > 0.66(g - z) + 2.01$ (Wu et al. 2012) for those found matches in WISE All-Sky Data Release (Wright et al. 2010). These selections mostly select quasars within redshift 4.

Data-mining algorithms. Some of the quasar candidates are selected using one of the following data-mining algorithms: support vector machine (SVM) classifiers (SVM; Peng et al. 2012), extreme-deconvolution method (Bovy et al. 2011), or kernel density estimator (Richards et al. 2009).

There are also some supplemented candidates selected based on multi-wavelength (optical/X-ray/radio) matching, such as X-ray sources from ROSAT, XM-M-Newton, and Chandra, and radio sources from FIRST and NVSS. We included a group of SDSS DR7, DR9, and DR10 quasars for the purpose of testing LAMOST spectral similarity. SDSS DR12 quasars are not removed because they were not yet released at the time when the candidate list was finalized for LAMOST. They are giving proper flags in the DR2 and DR3 quasar catalog. Some of our candidates overlap with the M31/M33 field (Huo et al. 2015). They are also flagged in the catalog.

2.2. Pipeline for Data Reduction

The details of LAMOST data reduction can be found in Luo et al. (2015). The raw data is reduced by the LAMOST 2D pipeline, which includes dark and bias removal, flat field correction, spectral extraction, sky subtraction, and wavelength calibration. The output spectra are combinations of the blue and red channel spectra.

The LAMOST 1D pipeline provides spectral type classification and radial velocity (for stars) or redshift (for galaxies and quasars) using the cross-correlation method. The primary classifications given by LAMOST 1D pipeline are STAR, GALAXY, QSO, and UNKNOWN. In general QSO and UNKNOWN have fainter magnitudes, and therefore visual inspection is required to confirm their spectral type and assure the redshift measurement. In the next section, we will discuss the visual inspection and compare the results with the pipeline results.

3. Visual Inspections of the Spectra

As mentioned in the previous section, 1D pipeline results are not trustworthy for QSO and UNKNOWN types. A Java program ASERA (Yuan et al. 2013) is used to visually inspect each object with pipeline class QSO and quasar candidates with pipeline class UNKNOWN. The first step is to assure that the object is indeed a quasar. At the same time special objects such as BAL and disk emitter are labeled. In DR2, 9028 objects are identified as quasars, among them 2647 quasars are originally given UNKNOWN by the pipeline. Among the 10911 confirmed DR3 quasars, 3428 quasars are previously UNKNOWN. There are still more than 12000 quasar candidates with an unrecognizable spectral type. They are returned to the candidates pool and will be re-observed in the future. The major reason for UNKNOWN type objects is the low signal-to-noise ratio (S/N). It is either because the quasar candidates with magnitudes close to $i = 20$ are difficult for LAMOST to obtain good spectra, or due to the poor observational conditions at the time. Figure 1 plots the distributions of the spectral S/N and the i-band PSF magnitude. It shows that the UNKNOWN-type spectra are fainter and have slightly lower S/N. If the blue and red channel spectra are improperly stacked, the combined spectrum might have artificial broad emission or absorption features, which also brings difficulties to pipeline classification.

The second step is to visually inspect redshift based on typical quasar emission lines, i.e., [O III], Mg II, C III, and C IV. The poor quality of UNKNOWN-type spectra also causes difficulties for the pipeline to determine the redshift. For those with recognizable quasar emission lines, we visually estimate their redshifts using ASERA. But a flag will be given when there is only one emission line visible. Sometimes, the visual inspected redshift mismatches the pipeline redshift. If there are at least two emission lines available, we manually correct the redshift; otherwise, we give a flag to indicate that the redshift for this object is arguable. Among the visually confirmed quasars, 9484 have already been reported by SDSS. The LAMOST pipeline gives redshifts of 6663 out of 9484, and among them 95.7% have a redshift difference less than 0.2. After visual inspection, another 2440 quasar redshifts are recovered, among them more than 98% have redshift differences less than 0.2 from SDSS. The redshifts of the remaining 381 SDSS-identified quasars cannot be measured using their LAMOST spectra of poor quality. Their redshift “Z_ VI” in the catalog is 999 with Z FLAG = 9. Figure 2 shows the visual inspected redshift distributions of DR2 and DR3. The mean redshifts of DR2 and DR3 are 1.49 and 1.44, respectively. The quasar having the highest redshift in DR2 and DR3 is J132442.44+052438.8, with a redshift of 5.01. When $z \sim 1$, Mg II locates at the overlapped wavelength ranges (around 6000 Å) of the blue and red channels. If the spectral combinations of blue and red channels cause artificial features at the overlapping region, Mg II might become unrecognizable. It explains the missing $z \sim 1$ objects in the distribution plots. Figure 3 plots DR2 and three quasars in the luminosity space, where $M_i(z = 2)$ is K-corrected (Richards et al. 2006) absolute i-band PSF magnitude normalized to $z = 2$.

4. Spectral Parameter Measurements

In this section, we describe the procedures of typical quasar emission line measurement. For detailed discussions, please refer to Paper I.

Before the measurement, the LAMOST spectrum is corrected with Galactic extinction using the extinction map of Schlegel et al. (1998) and the reddening curve of Fitzpatrick (1999). Then, the spectrum is shifted back to the rest frame.
Figure 1. \(i\)-band PSF magnitude and the S/N of the spectrum. Red dots are pipeline QSOs. Black dots are pipeline UNKNOWNs but visually identified as quasars. The mean S/N of pipeline QSOs is 4.2, higher than the value of UNKNOWNs, which is 2.8. The mean \(i\)-band magnitude of pipeline QSOs is 18.8 slight brighter than the UNKNOWNs' 19.1.

Figure 2. The visual inspected redshift distributions of DR2 (dark-gray) and DR3 (light-gray) quasars. The mean redshifts are 1.49 for DR2 and 1.43 for DR3, respectively. The quasar having the highest redshift in DR2 is J132442.44+052438.8, with \(z = 5.01\). The quasar having the highest redshift in DR3 is J112811.44+302255.9, with \(z = 4.90\). There are clear gaps in both DR2 and DR3 around \(z \sim 1\). This is mostly due to the artificial features at the spectral stacking region.
Instead of fitting the continuum for the entire spectrum, we fit a local pseudo-continuum around each emission line (Shen et al. 2008). Two components are used for continuum fitting: a power law with its normalization and slope as free parameters; and an FeII multiplet emission with normalization, velocity shift relative to the systemic redshift, and broadening velocity as free parameters. After subtraction of the local pseudo-continuum, the leftover of the spectrum is used for emission line fitting.

4.1. Hα

Hα is only available when $z \leq 0.3$. The regions used for pseudo-continuum fitting are 6000–6250 Å and 6800–7000 Å. The template of optical FeII emission is from Véron-Cetty et al. (2004). Hα is modeled with one narrow and one broad component. The broad component is fitted with as many Gaussians as statistically justifiable (Dong et al. 2008). The narrow component is fitted with a single Gaussian with an upper limit of FWHM = 1200 km s$^{-1}$. The velocity offsets and line widths of $[\text{N II}]\lambda \lambda 6548,6584$ and $[\text{S II}]\lambda \lambda 6717,6731$ are tied to Hα narrow component. The relative flux ratio of the two $[\text{N II}]$ components is fixed to 2.96. Figure 4 gives an example of Hα fit.

4.2. Hβ

When $z \leq 0.75$, Hβ is available. The regions for pseudo-continuum fitting are 4435–4700 Å and 5100–5535 Å. The template of optical FeII emission is from Véron-Cetty et al. (2004). Hβ is also modeled with a narrow and a broad component. The broad component is fitted with as many Gaussians as statistically justifiable (Dong et al. 2008). The narrow component is fitted with a single Gaussian with an upper limit of FWHM = 1200 km s$^{-1}$. For each line of the $[\text{O III}]\lambda \lambda 4959,5007$ doublet, two Gaussians are used: one for the core and another for a possible blue wing. The doublets are assumed to have same redshifts and profiles, with their flux ratio fixed to 3. The velocity offsets and line widths of the doublet core components are tied to the Hβ narrow component. Figure 5 gives an example of Hβ fit.

4.3. Mg II

Mg II is measured when the quasar redshift is between 0.40 and 1.76. The pseudo-continuum is fitted using data from 2200–2700 Å and 2900–3090 Å. An ultraviolet FeII template from Tsuzuki et al. (2006) is included in the continuum fitting. One narrow component and one broad component are used to fit each of the Mg II $\lambda \lambda 2796,2803$ doublets. The narrow component is fitted with a single Gaussian with an upper limit of FWHM = 900 km s$^{-1}$. The broad component is a truncated five-parameter Gauss–Hermite series. The broad component of each Mg II doublet line is assumed to have the same profile with flux ratio set to be between 2:1 and 1:1 (Laor et al. 1997). The same assumption is applied to the narrow component of each Mg II doublet line. Figure 6 shows an example of Mg II fit.

4.4. C IV

C IV is measured when the quasar redshift is larger than 1.58. The fitting regions for the pseudo-continuum are 1145–1465 Å
One Gaussian and one Gaussian–Hermite are used to fit the C IV emission. There is no upper limit set for the FWHM of the Gaussian function, because the existence of a strong narrow component for C IV is still debatable. An example of C IV fitting is presented in Figure 7.

Figure 4. Example of Hα measurement for J104427.74+271806.2, z = 0.076. The top panel shows the pseudo-continuum fit. The red line is the power law, the blue line is the power law plus Fe II template. The bottom panel shows the Hα emission line and [N II] fitting. The black line is the continuum subtracted spectrum. Each blue line represents one component. The red line is the combined emission line profile.

Figure 5. Example of Hβ measurement for J133700.83+181029.6, z = 0.076. The top panel shows the pseudo-continuum fit. The red line is the power law, the blue line is the power law plus Fe II template. The bottom panel shows the Hβ emission line and [O III]. The black line is the continuum subtracted spectrum. Each blue line represents one component. The red line is the combined emission line profile.

4.5. The Reliability of the Emission Line Fitting

As mentioned in Paper I, the core routines of the emission line fitting are adopted from Dong et al. (2008) and Wang et al. and 1700–1705 Å. One Gaussian and one Gaussian–Hermite are used to fit the C IV emission. There is no upper limit set for the FWHM of the Gaussian function, because the existence of a strong narrow component for C IV is still debatable. An example of C IV fitting is presented in Figure 7.

The distributions of the FWHM of Hα, Hβ, Mg II, and C IV are shown in Figure 8. After spectra measurements, each fitting result is inspected visually. Flags are added based on the quality of the fit.
who used the MPFIT package (Markwardt 2009) to perform χ²-minimization using the Levenberg–Marquardt technique. One may find the detailed discussion of the measurement uncertainties and justifications in Dong et al. (2008, Section 2.5) and Wang et al. (2009, Section 2.2). Shen et al. (2011, Section 3.3, hereafter Shen11) also provides a detailed discussion regarding the different measurements of Mg II. To justify the fitting results of this set of data, we provide simple comparisons between LAMOST DR2&3 and that of Shen11. Histograms on the left side of Figure 9 compare the FWHMs of Hβ, Mg II, and C IV, while histograms on the right side compare their EWs. It appears that our measurements of FWHM and EW for Hβ and C IV are smaller than those of Shen11, with a mean difference of $-0.079 \pm 0.19$ dex and $-0.16 \pm 0.21$ dex for Hβ, and $-0.043 \pm 0.35$ dex and $-0.10 \pm 1.6$. The FWHM of Mg II is larger than that
of Shen11 and the EW is smaller, with a mean difference of 0.048 $\pm$ 0.18 dex and $-0.061 \pm 0.28$ dex, respectively. As mentioned in previous sections, four Gaussians are used to fit the broad component of $H\beta$, and one Gaussian and one Gaussian–Hermite function are used to fit the CIV emission line in our work. In Shen11, a single or a maximum number of three Gaussians are used to fit the broad component of $H\beta$ and CIV. For MgII, we used doublets with one narrow and one broad component, while Shen11 used one or a maximum number of three Gaussians. Shen11 states that these two fitting procedures yield consistent results in FWHM of MgII after applying both methods on the SDSS spectra. It is plausible that the small differences showed in Figure 9 are due to the differences in the fitting procedures and/or the different SNRs of LAMOST/SDSS spectra.

5. Continuum Luminosity and the Virial Black Hole Mass

The LAMOST survey is not equipped with a photometry telescope (Song et al. 2012). Its large field of view makes it...
difficult in some cases to find a suitable flux standard star for each spectrograph, especially for those relatively faint extragalactic objects. Therefore, the released LAMOST quasar spectra either are not flux-calibrated or have poor flux calibrations. To estimate continuum luminosity, we use the five-band SDSS photometry instead. The PSF magnitudes of each quasar are retrieved from SDSS photometry database. Before the photometry fit, these magnitudes are corrected with Galactic extinction and converted to flux density, \(F_\lambda\), where \(\lambda\) is the effective wavelength of each filter. Two components are used to fit the photometry, i.e., a continuum spectrum and an emission line template. As described in Vanden Berk et al. (2001), hereafter VB01, the continuum spectrum can be represented by two power laws with a break at 4661 Å. The spectral indices given by VB01 are \(\alpha_\lambda = -1.54\) at the blueward of 4661 Å and \(\alpha_\lambda = -0.42\) at the redward of 4661 Å. The emission line template is generated by removing the continuum spectrum from the composite median quasar spectrum. The normalizations of the continuum spectrum and emission line template are free parameters. The other two free parameters are the spectral indices of the two power laws, with \(\alpha_\lambda = -1.54\) and \(\alpha_\lambda = -0.42\) as their initial values, respectively. The fitting uses Python PYTOOLS.NMPFIT\(^7\) to perform \(\chi^2\)-minimization with the Levenberg–Marquardt algorithm. Figure 10 presents two luminosity fitting examples. The results are well matched with the composite spectrum (Vanden Berk et al. 2001), with an average spectral index of \(-1.52\) blueward of 4661 Å and \(-0.33\) redward of 4661 Å. The monochromatic continuum luminosities at 1350, 3000, and 5000 Å are calculated from the power-law continuum spectra. We compared the monochromatic continuum luminosities to Shen et al. (2011) and drew the histograms on the left side of Figure 11. It is clear that our results agree very well with those of Shen et al. (2011).

\[^7\]http://cars.uchicago.edu/software/python/index.html

We calculate virial black hole mass using H\(\beta\), Mg II, and C IV based on the Shen et al. (2011) scheme as follows:

1. \(M_{\text{BH}}(\text{H}\beta)\),

\[
\log_{10}\left(\frac{M_{\text{BH, vir}}}{M_\odot}\right) = 0.910 + 0.50\log_{10}\left(\frac{L_{5100}}{10^{44} \text{ erg s}^{-1}}\right) + 2\log_{10}\left(\frac{\text{FWHM}(\text{H}\beta)}{\text{km s}^{-1}}\right)
\]

(Vestergaard & Peterson 2006)

2. \(M_{\text{BH}}(\text{Mg II})\),

\[
\log_{10}\left(\frac{M_{\text{BH, vir}}}{M_\odot}\right) = 0.740 + 0.62\log_{10}\left(\frac{L_{3000}}{10^{44} \text{ erg s}^{-1}}\right) + 2\log_{10}\left(\frac{\text{FWHM}(\text{Mg II})}{\text{km s}^{-1}}\right)
\]

(Vestergaard & Osmer 2009).

3. \(M_{\text{BH}}(\text{C IV})\),

\[
\log_{10}\left(\frac{M_{\text{BH, vir}}}{M_\odot}\right) = 0.660 + 0.53\log_{10}\left(\frac{L_{1350}}{10^{44} \text{ erg s}^{-1}}\right) + 2\log_{10}\left(\frac{\text{FWHM}(\text{C IV})}{\text{km s}^{-1}}\right)
\]

(Shen & Kelly 2010).

In principle, the virial black hole mass should be estimated using single-epoch spectra, which is not possible for LAMOST quasars. Because the time difference between SDSS photometry and the LAMOST observation, the variations of quasar luminosity might be 0.1–0.2 mag (Vanden Berk et al. 2004; Zuo et al. 2012; Ai et al. 2013). We compared our estimated BH masses to Shen et al. (2011) and plot the results on the right side of Figure 11. On average, the LAMOST DR2&3 H\(\beta\)
The estimated BH mass is $0.23 \pm 0.37$ dex smaller than Shen et al. (2011), the Mg II estimated BH mass is $0.12 \pm 0.38$ dex smaller, and the C IV estimated BH mass is $0.020 \pm 0.35$ dex smaller. Comparing to the FWHM differences in Figure 9, the difference between BH mass estimate is mostly due to the difference between the FWHM measurements. We drew the BH mass distributions of LAMOST DR2&3 and Shen et al. (2011) along the redshift in Figure 12. It is clear that even with a slightly different BH mass estimate, the LAMOST quasars still occupy the same BH mass space as Shen et al. (2011). The BH mass given in this work can be considered as a good approximation.
Table 1  
The LAMOST Quasar Survey Data Release Two and Three Quasar Catalog: Table Description

| Column | Name                          | Format   | Description                                                                 |
|--------|-------------------------------|----------|----------------------------------------------------------------------------|
| 1      | OBSID                         | STRING   | unique object id in LAMOST database                                        |
| 2      | DESIGNATION                   | STRING   | hhmms.s±ddmms.s (J2000.0)                                                  |
| 3      | RA                            | DOUBLE   | R.A. in decimal degrees (J2000.)                                           |
| 4      | DEC                           | DOUBLE   | Decl. in decimal degrees (J2000.0)                                         |
| 5      | PLANID                        | STRING   | spectroscopic plan identification                                         |
| 6      | SPID                          | STRING   | spectrograph identification                                                |
| 7      | FIBERID                       | STRING   | fiber number of the spectrum                                                |
| 8      | MJD                           | STRING   | MJD of the spectroscopic observation                                       |
| 9      | SOURCE_FLAG                   | LONG     | sources of quasar candidates                                               |
| 10     | M_i                          | DOUBLE   | absolute i-band magnitude with K-correction to z = 2 follows Richards et al. (2006) |
| 11     | CLASS_VI                      | STRING   | classification given by visual inspection                                  |
| 12     | CLASS_FLAG                    | SHORT    | classification flag                                                        |
| 13     | Z_PIPELINE                    | DOUBLE   | redshift given by LAMOST pipeline                                           |
| 14     | Z_VI                          | DOUBLE   | redshift given by visual inspection                                         |
| 15     | Z_PIPELINE                    | DOUBLE   | redshift quality flag                                                      |
| 16     | SNR_SPEC                      | DOUBLE   | Median S/N per pixel of the spectrum                                       |
| 17     | FWHM_BROAD_HA                 | DOUBLE   | FWHM of broad Hα in km s⁻¹                                                  |
| 18     | EW_BROAD_HA                   | DOUBLE   | rest-frame equivalent width of broad Hα in Å                               |
| 19     | FWHM_NARROW_HA                | DOUBLE   | FWHM of narrow Hα in km s⁻¹                                                 |
| 20     | EW_NARROW_HA                  | DOUBLE   | rest-frame equivalent width of narrow Hα in Å                              |
| 21     | EW_NII_6585                   | DOUBLE   | rest-frame equivalent width of [N II]6584 in Å                             |
| 22     | EW_SII_6718                   | DOUBLE   | rest-frame equivalent width of [S II]6718 in Å                             |
| 23     | EW_SII_6732                   | DOUBLE   | rest-frame equivalent width of [S II]6732 in Å                             |
| 24     | EW_FE_HA                      | DOUBLE   | rest-frame equivalent width of Fe within 6000–6500 Å in Å                 |
| 25     | LINE_NPIX_HA                  | LONG     | number of good pixels at the rest-frame 6400–6765 Å                       |
| 26     | LINE_MED_SN_HA                | DOUBLE   | median S/N per pixel at the rest-frame 6400–6765 Å                       |
| 27     | LINE_REDCH2_HA                | DOUBLE   | reduced χ² of Hα emission line fit                                         |
| 28     | LINE_FLAG_HA                  | SHORT    | quality flag of Hα fitting                                                 |
| 29     | FWHM_BROAD_HB                 | DOUBLE   | FWHM of broad Hβ in km s⁻¹                                                  |
| 30     | EW_BROAD_HB                   | DOUBLE   | rest-frame equivalent width of broad Hβ in Å                               |
| 31     | FWHM_NARROW_HB                | DOUBLE   | FWHM of narrow Hβ in km s⁻¹                                                 |
| 32     | EW_NARROW_HB                  | DOUBLE   | rest-frame equivalent width of narrow Hβ in Å                              |
| 33     | EW_OIII_4959                  | DOUBLE   | rest-frame equivalent width of [O III]4959 in Å                             |
| 34     | EW_OIII_5007                  | DOUBLE   | rest-frame equivalent width of [O III]5007 in Å                             |
| 35     | EW_FE_HB                      | DOUBLE   | rest-frame equivalent width of Fe within 4435–4685 Å in Å                  |
| 36     | LINE_NPIX_HB                  | LONG     | number of good pixels at the rest-frame 4750–4950 Å                       |
| 37     | LINE_MED_SN_HB                | DOUBLE   | median S/N per pixel at the rest-frame 4750–4950 Å                       |
| 38     | LINE_REDCH2_HB                | DOUBLE   | reduced χ² of Hβ emission line fit                                         |
| 39     | LINE_FLAG_HB                  | SHORT    | quality flag of Hβ fitting                                                 |
| 40     | FWHM_BROAD_MGII_2796          | DOUBLE   | FWHM of the broad Mg II 2796 in km s⁻¹                                     |
| 41     | EW_BROAD_MGII_2796             | DOUBLE   | rest-frame equivalent width of the broad Mg II 2796 in Å                   |
| 42     | FWHM_NARROW_MGII_2796         | DOUBLE   | FWHM of the narrow Mg II 2796 in km s⁻¹                                     |
| 43     | EW_NARROW_MGII_2796           | DOUBLE   | rest-frame equivalent width of the narrow Mg II 2796 in Å                  |
| 44     | FWHM_BROAD_MGII_2796          | DOUBLE   | FWHM of the whole broad Mg II in km s⁻¹                                    |
| 45     | EW_BROAD_MGII                 | DOUBLE   | rest-frame equivalent width of the whole broad Mg II in Å                  |
| 46     | FWHM_MGII                     | DOUBLE   | FWHM of the whole Mg II emission line in km s⁻¹                            |
| 47     | EW_MGII                       | DOUBLE   | rest-frame equivalent width of the whole Mg II in Å                        |
| 48     | EW_FE_MGII                    | DOUBLE   | rest-frame equivalent width of Fe within 2200–3090 Å                      |
| 49     | LINE_NPIX_MGII                | LONG     | number of good pixels at the rest-frame 2700–2900 Å                       |
| 50     | LINE_MED_SN_MGII              | DOUBLE   | median S/N per pixel at the rest-frame 2700–2900 Å                       |
| 51     | LINE_REDCH2_MGII              | DOUBLE   | reduced χ² of Mg II emission line fit                                     |
| 52     | LINE_FLAG_MGII                | SHORT    | quality flag of Mg II fitting                                             |
| 53     | FWHM_BROAD_CIV                | DOUBLE   | FWHM of the broad C IV in km s⁻¹                                           |
| 54     | EW_BROAD_CIV                  | DOUBLE   | rest frame equivalent width of the broad C IV in Å                         |
| 55     | FWHM_NARROW_CIV               | DOUBLE   | FWHM of the narrow C IV in km s⁻¹                                           |
| 56     | EW_NARROW_CIV                 | DOUBLE   | rest frame equivalent width of the narrow C IV in Å                        |
| 57     | FWHM_CIV                      | DOUBLE   | FWHM of the whole C IV in km s⁻¹                                           |
| 58     | EW_CIV                        | DOUBLE   | rest-frame equivalent width of the whole C IV in Å                         |
| 59     | LINE_NPIX_CIV                 | LONG     | number of good pixels at the rest-frame 1500–1600 Å                       |
| 60     | LINE_MED_SN_CIV               | DOUBLE   | median S/N per pixel at the rest-frame 1500–1600 Å                       |
6. Catalog Parameters

We provide a compiled catalog for all quasars observed in LAMOST DR2 and DR3. Parameters included in the quasar catalog is list in Table 1. We describe each parameter in detail below.

![Image: Figure 13. Sources of the quasar candidates. The top two pie plots are results from cross-matching SDSS quasars with LAMOST quasars. The gray areas are quasars reported in SDSS and NED. The white region is for quasars not reported in SDSS nor in NED. Overall, about 40% of quasars are not reported by SDSS. It indicates that the LAMOST Quasar Survey provides a great supplement to low-to-moderate redshift quasar surveys. The bottom two pie plots are sources of LAMOST quasar candidates. The white region is for quasars selected by infrared-optical color. The light-gray area is for quasars selected by data-mining. The dark-gray area is for objects that not selected as quasar candidates, but are confirmed as quasars. It shows that infrared-optical color selection results in more quasars than any other selection methods.]

Table 1 (Continued)

| Column | Name                    | Format | Description                                                                 |
|--------|-------------------------|--------|-----------------------------------------------------------------------------|
| 61     | LINE_REDCHI2_CIV        | DOUBLE | reduced $\chi^2$ of C IV emission line fit                                  |
| 62     | LINE_FLAG_CIV           | SHORT  | quality flag of C IV fitting                                               |
| 63     | ALPHA1                  | DOUBLE | wavelength power-law index from 1300 to 4661 Å                              |
| 64     | ALPHA2                  | DOUBLE | wavelength power-law index from 4661 Å toward the red end of the spectrum  |
| 65     | MODEL_PHOT_CHI2         | DOUBLE | reduced chi-square of continuum fitting                                    |
| 66     | CONT_FLAG               | SHORT  | quality flag of continuum fitting                                          |
| 67     | LOGL1350                | DOUBEL | monochromatic luminosity at 1350 Å in units of erg s$^{-1}$                |
| 68     | LOGL1350_ERR            | DOUBEL | error of LOGL1350 in units of erg s$^{-1}$                                 |
| 69     | LOGL3000                | DOUBEL | monochromatic luminosity at 3000 Å in units of erg s$^{-1}$                |
| 70     | LOGL3000_ERR            | DOUBEL | error of LOGL3000 in units of erg s$^{-1}$                                 |
| 71     | LOGL5100                | DOUBEL | monochromatic luminosity at 5100 Å in units of erg s$^{-1}$                |
| 72     | LOGL5100_ERR            | DOUBEL | error of LOGL5100 in units of erg s$^{-1}$                                 |
| 73     | LOGMBH_HB               | DOUBEL | virial BH mass based on H$\beta$ in units of $M_\odot$                     |
| 74     | LOGMBH_ERR_HB           | DOUBEL | error of LOGMBH_HB in units of $M_\odot$                                  |
| 75     | LOGMBH_HB_FLAG          | SHORT  | reliability of LOGMBH_HB                                                   |
| 76     | LOGMBH_MGII             | DOUBEL | virial BH mass based on Mg II in units of $M_\odot$                         |
| 77     | LOGMBH_ERR_MGII         | DOUBEL | error of LOGMBH_MGII in units of $M_\odot$                                |
| 78     | LOGMBH_MGII_FLAG        | SHORT  | reliability of LOGMBH_MGII                                                 |
| 79     | LOGMBH_CIV              | DOUBEL | virial BH mass based on C IV in units of $M_\odot$                          |
| 80     | LOGMBH_ERR_CIV          | DOUBEL | error of LOGMBH_CIV in units of $M_\odot$                                 |
| 81     | LOGMBH_CIV_FLAG         | SHORT  | reliability of LOGMBH_CIV                                                  |

1. OBSID: unique object identification in LAMOST database.
2. Designation: LAMOST Jhmmss.s+ddmms.s (J2000).
3–4. R.A. and decl.
5–8. Spectral observation information. MJD: modified Julian data; PLANID: spectroscopic plan identification; SPID:
spectrograph identification; FIBERID: fiber number. A LAMOST spectrum is named as spec-MJD-PLANID-SPID-FIBERID.fits.

9: SOURCE_FLAG: SOURCE_FLAG is a 7-bit binary digit. The first three bits indicate whether the quasar is already reported by SDSS or NED (i.e., “011” in SDSS DR7, DR9 or DR10, “001” in DR12, “100” reported in DR14, “010” reported in NED but not in SDSS, and “000” neither reported by SDSS nor NED). The two bits in the middle indicate how the quasar candidate is selected (i.e., “00” infrared-optical color selected, “01” data-mining selected, “10” object not included in LAMOST LEGAS quasar survey sample but identified as quasar). The last two bits indicate whether the quasar is overlapped with M31/M33 field (“00” not overlapped, “01” object already reported in Huo et al. (2015), “10” object in M31/M33 field but not in Huo et al. 2015). For example SOURCE_FLAG = 64. “64” written in binary system is “1000000”. It means the quasar has already been reported by DR14, it was selected via infrared-optical color selection, and is not within M31/M33 field.

10: $M_{r}$ Absolute $r$-band magnitude with $K$-correction to $z = 2$ following Richards et al. (2006).

11–12: CLASS_VI and CLASS_FLAG. Visually inspected spectral type. If the spectral type is uncertain CLASS_FLAG = 1.

13–15: Redshift, Z_PIPELINE: redshift given by LAMOST pipeline; Z_VI: redshift confirmed by visual inspection. If the value of redshift is uncertain (e.g., only one emission line available), Z_FLAG = 1. If the spectrum is likely a quasar but too noisy to yield a redshift, Z_FLAG = 9.

16: SNR_SPEC. Median S/N per pixel in the wavelength regions of 4000–5700 Å and 6200–9000 Å.

17–23: FWHM and the rest-frame equivalent width of H$\alpha$, [N II] $\lambda$6584, and [S II] $\lambda$6718, 6732.

24: Rest-frame width of iron emission at 6000–6500 Å.

25–26: Number of good pixels and median S/N per pixel for the H$\alpha$ region in 6400–6755 Å.

27: LINE_REDCHI2_HA. Reduced $\chi^2$ of H$\alpha$ emission line fit.

28: LINE_FLAG_HA. Flag indicates the quality of H$\alpha$ fitting. As mentioned in Section 4.5, the MPFIT package (Markwardt 2009) is used to perform $\chi^2$-minimization using the Levenberg–Marquardt technique. The fitting automatically assigns “0” to those with converged results and “$-$1” without converged results. The un-converged fits are usually caused by low S/N, too few good pixels in the fitting region, or peculiar continuum and emission line properties. After fitting, we visually inspect each fitting result with LINE_FLAG_HA = 0. For those with clearly over-subtracted continuum, we changed their flag from 0 to 1 to flag an unreliable fit. If H$\alpha$ is outside the observational frame, LINE_FLAG_HA = $-$1.

29–34: FWHM and the rest-frame equivalent width of H$\beta$ and [O III] $\lambda$4959, 5007.

35: Rest-frame equivalent width of iron emission at 4435–4685 Å.

36–37: Number of good pixels and median S/N per pixel for the H$\beta$ region in 6400–6755 Å.

38: LINE_REDCHI2_HB. Reduced $\chi^2$ of H$\beta$ emission line fit.

39: LINE_FLAG_HB. Quality flag for H$\beta$ fitting. It is defined using the same scheme as LINE_FLAG_HA.

40–48: FWHM and the rest-frame equivalent width of Mg II.

49–50: Number of good pixels and median S/N per pixel for Mg II.

51: LINE_REDCHI2_MG. Reduced $\chi^2$ of Mg II emission line fit.

52: LINE_FLAG_MG. Quality flag for Mg II fitting. It is defined using the same scheme as LINE_FLAG_HA.

53–58: FWHM and the rest-frame equivalent width for C IV.

59–60: Number of good pixels and median S/N per pixel for C IV.

61: LINE_REDCHI2_CIV. Reduced $\chi^2$ of C IV emission line fit.

62: LINE_FLAG_CIV. Quality flag for C IV fitting. It is defined using the same scheme as LINE_FLAG_HA. For those BAL candidates, values of LINE_FLAG_CIV are also changed to 1.

63: ALPHA1. Continuum spectral index $\alpha$, where $1300 < \lambda < 4661$ Å.

64: ALPHA2. Continuum spectral index $\alpha$, where $\lambda > 4661$ Å.

65: MODEL_PHOT_CHI2. Reduced $\chi^2$ of continuum fit.

66: CONT_FLAG. Continuum fitting flag. As mentioned in Section 5, Python PYTOOLS.NMPFIT is used to perform $\chi^2$-minimization with the Levenberg–Marquardt algorithm. When the fitting converges, CONT_FLAG = 1. If the fitting cannot converge, CONT_FLAG = 0. The un-converged fitting usually happens when the SDSS 5-band magnitudes form a peculiar shape and, therefore, cannot be fitted with the composite spectrum.

67–72: Monochromatic luminosity calculated from the break power-law continuum. The relative errors are calculated via Monte-Carlo simulation.

73–81: Virial BH mass, error, and flags. The BH mass error is calculated using Monte-Carlo simulation. As BH mass is estimated using FWHM and monochromatic continuum luminosity, the flags of the BH mass are the combinations of the emission line fitting flags and the continuum fitting flags as shown in Table 2. When the LOGMBH_FLAG = $-$1, there is no available BH mass estimate. If the LOGMBH_FLAG = 1, the BH mass estimate should be used with caution.

7. Summary

In this work, we present LAMOST LEGAS Quasar Survey data releases two and three. There are 9024 confirmed quasars in DR2 and 10911 in DR3. Among them, 8100 quasars are not reported in either SDSS or NED. As mentioned before, our survey candidates were finalized before SDSS DR12; therefore, 2225 SDSS DR12 QSO catalog released quasars and 1810 DR14 QSOs should also be considered as independent discoveries. The bottom two pie plots in Figure 13 show the sources of the quasar candidates. In DR2, 44.8% quasars are from infrared-optical color selection, 41.4% are from
data-mining, and the remaining 13.8% are quasars that were not submitted as quasar candidates initially. In DR3, 52.0% quasars are from infrared-optical color selection, 44.0% are from data-mining, and the remaining 4% are not quasar candidates but are confirmed as quasars. This indicates that infrared-optical color selection is a promising method for selecting quasars. The top two pie plots are the cross-matching results between LAMOST quasars and SDSS quasars. In both DR2 and DR3, about 50% of LAMOST quasars are not reported by SDSS. This shows that LAMOST quasars provide a great supplement to low-to-moderate redshift quasars.

For each confirmed quasar, we applied emission line measurements of H\(\alpha\), H\(\beta\), Mg II, and C IV. We conducted a continuum fit using SDSS photometry data. We also estimated the black hole mass for each quasar. The results are compiled into one quasar catalog. Proper flags are added to indicate the liability of the fit or the estimate. Both LAMOST quasar spectra and the quasar catalog are available on-line. Follow-up studies based on LAMOST Quasar Survey, such as BAL study, are under way.

We acknowledge the support from the National Key Basic Research Program of China (grant 2014CB845700), the Ministry of Science and Technology of China under grant 2016YFA0400703, NSFC grants 11373008 and 11533001, and the Strategic Priority Research Program of China (No. XDB09000000) of National Astronomical Observatories, Chinese Academy of Sciences. The Guo Shou Jing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope, LAMOST) 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 National Astronomical Observatories, Chinese Academy of Sciences.

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