

Luminosity function of quasars at $1.0 < z < 3.5$ from SDSS and DESI

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ABSTRACT

We present a study of the evolution of type 1 quasars at $1.0 < z < 3.5$, covering the peak epoch of quasar activity. The quasar evolution has been extensively explored by a variety of previous works and the derived quasar luminosity functions (QLFs) are not well consistent with each other, presumably due to the complexities introduced by different quasar selection techniques and associated completeness corrections. We use a new strategy to construct QLFs based on a library of all known quasars. We focus on a wide region of $\sim 1700 \text{ deg}^2$ and a deep field of $\sim 265 \text{ deg}^2$ that have rich spectroscopic data primarily from SDSS and DESI. We then apply traditional color cuts in the rest-frame UV/optical to select quasar candidates and use the quasar library to identify them. Our final sample consists of 62,426 quasars at $1.0 < z < 3.5$, with a high completeness ($\sim 96\%$) and a high purity ($\sim 93\%$) in the color selection. Simple color cuts can potentially minimize selection biases for the study of quasar evolution. We derive binned QLFs and characterize them using a double power-law model. Sample incompleteness and contamination are considered as part of the uncertainties in the calculation. Compared to previous results, our QLFs are slightly higher at the faint end, and also higher at the bright end at $2.5 < z < 3.5$. The QLFs suggest that the quasar evolution at $1.0 < z < 2.5$ can be well described by the pure luminosity evolution model, while at $2.5 < z < 3.5$, it can be described by either the pure luminosity evolution or the pure density evolution model.

Keywords: Quasars (1319); Redshift surveys (1378); Luminosity function (942)

1. INTRODUCTION

Quasars are among the brightest astrophysical objects and provide an important probe for studying the distant universe. They are powered by active supermassive black holes (SMBHs), and thus trace their formation and evolution (e.g., Kaspí et al. 2000; Wu et al. 2004; Di Matteo et al. 2005; Springel et al. 2005; Kormendy & Ho 2013) and shape the evolution of their host galaxies (e.g., Kauffmann et al. 2003; De Rosa et al. 2011; Valentini et al. 2021; Decarli et al. 2024; Onoue et al. 2025). Due to their extreme luminosity, quasars are often used as background sources to study the state of the intergalactic medium (IGM) (e.g., Fan et al. 2006; Carilli et al. 2010; McGreer et al. 2015; Jiang et al. 2022; Matsuoka et al. 2023). Large samples of quasars are also used to study the large-scale structure of the universe (e.g., Dawson et al. 2013; Font-Ribera et al. 2014; Delubac et al. 2015; Alam et al. 2021). Therefore,

quasars play an important role in our understanding of SMBHs, galaxy evolution, IGM, and large-scale structure of the universe.

In the past three decades, large sky surveys have produced more than one million quasars with spectra. The 2dF Project was initiated in 1990 (Lewis et al. 1998). Based on a sample of over 6000 quasars identified from the initial observations of the 2dF QSO Redshift Survey (2QZ), Boyle et al. (2000) reported the quasar luminosity function (QLF) and its redshift evolution. Croom et al. (2004) presented the final catalogue of the 2QZ that contains 23,338 quasars. The Sloan Digital Sky Survey (SDSS) quasar survey is one of the most widely used quasar surveys. Its initial goal was to obtain spectra for 100,000 quasars (York et al. 2000). As SDSS continued to operate, the number of observed quasar spectra increased significantly. The Baryon Oscillation Spectroscopic Survey (BOSS) aimed to observe more

than 150,000 quasars with $g < 22$ mag (Dawson et al. 2013). Moreover, the SDSS-IV quasar catalog from the SDSS Data Release 16 contains 750,414 quasars (Lyke et al. 2020). The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) can obtain up to 4000 spectra in a single exposure, reaching a limiting magnitude of $r \approx 19$ mag at a resolution of $R = 1800$. The LAMOST Data Releases 4 and 5 quasar catalog contains a total of 19,253 quasars, primarily in the redshift range of $0 < z < 4$ (Yao et al. 2019). The Dark Energy Spectroscopic Instrument (DESI) offers a substantial advance over previous wide-area spectroscopic surveys in quasar detection and redshift coverage (DESI Collaboration et al. 2016, 2022, 2025; Miller et al. 2024; Poppett et al. 2024; Anand et al. 2024; Green et al. 2025). Recently, the DESI survey is producing a large number of quasars (Chaussidon et al. 2023). Its quasar target selection was based on a random forest algorithm and color selection that identifies quasars in a magnitude range of $16.5 < r < 23.0$ mag. This selection process enables DESI to target over 200 deg^{-2} quasars, including 60 deg^{-2} quasars at $z > 2.1$.

There are many methods to select quasars. The color selection method has been widely used (e.g., Richards et al. 2002, 2006; Dawson et al. 2013; Myers et al. 2015; Wang et al. 2016; Pan et al. 2022; Chaussidon et al. 2023). This is because quasars with power-law spectra and stars with blackbody spectra have different distributions in the color space. Quasars are variable objects with different variability timescales ranging from hours to years (e.g., MacLeod et al. 2011; Palanque-Delabrouille et al. 2016), so the method based on variability is efficient to select quasars. Quasars can also be selected by their strong X-ray and radio emission (e.g., Hasinger et al. 2005; McGreer et al. 2009; Zeimann et al. 2011; Vito et al. 2014; Georgakakis et al. 2015; Bañados et al. 2015). With Gaia’s advancements in measuring proper motions with greater accuracy, the proper motion method has been applied to quasar selection in recent years (e.g., Heintz et al. 2020; Fu et al. 2021; Storey-Fisher et al. 2023). Recently, machine-learning techniques have become a powerful tool for quasar selection. Supervised classifiers, such as support vector machines (SVMs) and gradient-boosted decision trees (e.g., XGBoost), have been widely used in this field. These methods have been applied to time-domain variability features (Kim et al. 2011) and optical–infrared colors from large-area surveys (Jin et al. 2019; Zhu et al. 2026). They have also been extended to transfer-learning frameworks, which can help address data-set shifts in dense stellar regions such as the Galactic plane (Fu et al. 2021). Although many methods have been de-

veloped to select quasars, no single method is complete. Each method has its own selection biases and can miss certain types of quasars. For example, not all quasars show strong variability over short timescales. Color selection can also be incomplete in redshift ranges where quasar colors overlap with the stellar locus.

At present, more than one million quasars have been identified (Lyke et al. 2020; Chaussidon et al. 2023), with an increasing number of quasar candidates discovered, such as CatNorth (Fu et al. 2024). Different selection methods were used to find these quasars. This largely increases the selection efficiency, but makes it complicated to derive QLFs because of the mix of different selections. It consequently leads to discrepancies in the QLF measurements. For example, in the redshift range of $1.0 < z < 2.0$, the faint end of the QLFs from Palanque-Delabrouille et al. (2016) are significantly higher than the results of Ross et al. (2013) and Yang et al. (2018).

In our work, we make use of the SDSS DR16 (Ahumada et al. 2020) and DESI Year 3 quasars as an existing library, regardless of how they were selected. We then apply a straightforward color selection method to select quasars and estimate sample completeness using this library. We introduce the data and target selection in Section 2. In Section 3, we present our completeness corrections, model fitting, and derive QLFs. In Section 4, we compare our results with previous studies and discuss the evolution of the QLFs. We summarize the paper in Section 5. For SDSS, we use the point-spread function (PSF) magnitudes in the AB system. For the UKIRT Infrared Deep Sky Survey (UKIDSS) and Visible and Infrared Survey Telescope for Astronomy (VISTA), we use aperture magnitudes in the Vega system. The Wide-field Infrared Survey Explorer (WISE) PSF magnitudes are also expressed in the Vega system. We adopt a Λ -dominated flat cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. DATA AND TARGET SELECTION

We study the quasar evolution of type 1 quasars at $1.0 < z < 3.5$. There are two main reasons for selecting this intermediate redshift range. The first one is that the density peak of luminous quasars occurs between $z = 2$ and $z = 3$. The other reason is that the colors of quasars at $2 < z < 3$ are similar to those of type A and type F stars, making it difficult to select these quasars (e.g., Fan 1999; Richards et al. 2002, 2006). Therefore, our goal is to improve the QLF measurement at this redshift range.

2.1. Data

We select type 1 quasars using their optical-infrared colors. From a morphological perspective, both quasars and stars appear as point sources in ground-based images, making it challenging to distinguish quasars based solely on morphology. To efficiently select quasars and achieve higher completeness, we use the SDSS optical data, UKIDSS and VISTA near-IR data, and WISE $W1$ - and $W2$ -band mid-IR data. These bands cover a large wavelength range for an efficient selection of quasars from point-like sources.

Our targets are first selected from the SDSS imaging data. We exclude objects with the SDSS processing flags ‘BRIGHT’, ‘EDGE’, ‘SATUR’, and ‘BLENDED’. The extinction data are obtained from SDSS DR16, and we correct the optical magnitudes for Galactic extinction before applying the color selection. We identify point-like objects using the SDSS photometric morphological classification. In the SDSS imaging pipeline, sources are classified as point-like (type = 6) when the difference between the PSF magnitude and the cmodel magnitude satisfies $\text{psfMag} - \text{cmodelMag} < 0.145$ mag (SDSS documentation). In the following analysis, the color selection is applied only to these point-like sources.

The near-IR imaging data are from UKIDSS and the VISTA Hemisphere Survey (VHS). UKIDSS is a near-IR survey carried out with the Wide Field Camera (WFCAM) on UKIRT (Lawrence et al. 2007). We use their photometric data from the UKIDSS Large Area Survey (LAS). VHS is a near-IR survey designed to reach a depth 30 times fainter than the Two Micron All Sky Survey in at least two wavebands J and K_s (McMahon et al. 2013). When performing cross-matching between SDSS and UKIDSS/VISTA, the matching radius is $1''$.

WISE performed an all-sky survey in the 3.4, 4.6, 12, and 22 μm bands (Wright et al. 2010). We use the unWISE Catalog and the matching radius is $1''.5$ (Lang 2014; Lang et al. 2016). The unWISE Catalog offers two key advantages over the existing WISE catalog (AllWISE): it is built on substantially deeper imaging data and provides enhanced modeling for densely crowded regions (Schlafly et al. 2019).

In addition to the photometric data mentioned above, we also use spectral data from SDSS and DESI. The SDSS DR16 SpecObj table provides redshifts and spectral classifications of galaxies, stars, and quasars, including 1,362,512 quasar spectra (Ahumada et al. 2020). For DESI, we use the spectral data from a version of the Year 3 dataset (DESI Jura dataset), which contains information for 3,372,691 quasar spectra.

To achieve a high sample completeness, we target sky regions where a large fraction of the candi-

date quasars have already been spectroscopically confirmed by SDSS and DESI. We define two distinct sky zones. The first is a deep region that covers $20^{\text{h}}40^{\text{m}} < \text{R.A.} < 3^{\text{h}}40^{\text{m}}$, $-1^{\circ}26' < \text{decl.} < 1^{\circ}26'$. It is located in SDSS Stripe 82 and its area is 264.6 deg^2 . The second region is a wide region that encompasses two areas: $22^{\text{h}}40^{\text{m}} < \text{R.A.} < 2^{\text{h}}0^{\text{m}}$, $1^{\circ}26' < \text{decl.} < 10^{\circ}00'$ and $8^{\text{h}}50^{\text{m}} < \text{R.A.} < 15^{\text{h}}50^{\text{m}}$, $-2^{\circ}00' < \text{decl.} < 10^{\circ}00'$. The total area is 1689.1 deg^2 .

2.2. Color selection

To ensure a uniform quasar selection over a wide redshift range, we develop a selection method that balances sample completeness with selection efficiency and construct two sets of color-color selection criteria, optimized separately for low-redshift ($1.0 < z < 2.5$) and high-redshift ($2.5 < z < 3.5$) quasars. We examine the distributions of stars and quasars in different color-color diagrams and find that in the redshift range of $1.0 < z < 2.5$, the $u - r$ vs. $r - K$ color-color diagram (Figure 1(a), 1(b)) is effective to separate quasars from stars. This is because quasars at $1.0 < z < 2.5$ exhibit a significantly bluer $u - r$ color compared with late-type stars, while their $r - K$ color appears slightly redder than that of early-type stars. Therefore, we apply the following color selection criteria:

$$\begin{cases} u - r < 1.5, \\ 1.1 < r - K < 3.5, \\ r - K > 0.8(u - r) + 1.1. \end{cases}$$

The magnitude range for target selection is $15.0 < r < 21.5$ mag in the deep region, and is $15.0 < r < 20.5$ mag in the wide region.

We summarize sample completeness and purity in Table 1. We define color-selection completeness as the ratio of color-selected quasars to all quasars within a redshift range. We define purity as the ratio of color-selected quasars to all color-selected sources with spectra (including quasars, stars, and galaxies). We also define spectral completeness as the ratio of color-selected sources with spectral observations to all color-selected sources. In the deep region, we find 11,611 quasars at $1.0 < z < 2.5$. Similarly, in the wide region we find 42,119 quasars in the same redshift range. The color-selection completeness of the sample is 95% (97%) in the deep (wide) region, in all magnitude ranges that we consider. Only a small number of quasars at $1.0 < z < 2.5$ are excluded by our selection method, and this is mainly due to two factors. First, the u -band magnitude errors for some quasars are large, which results in large color errors. Second, there are a small number of very red

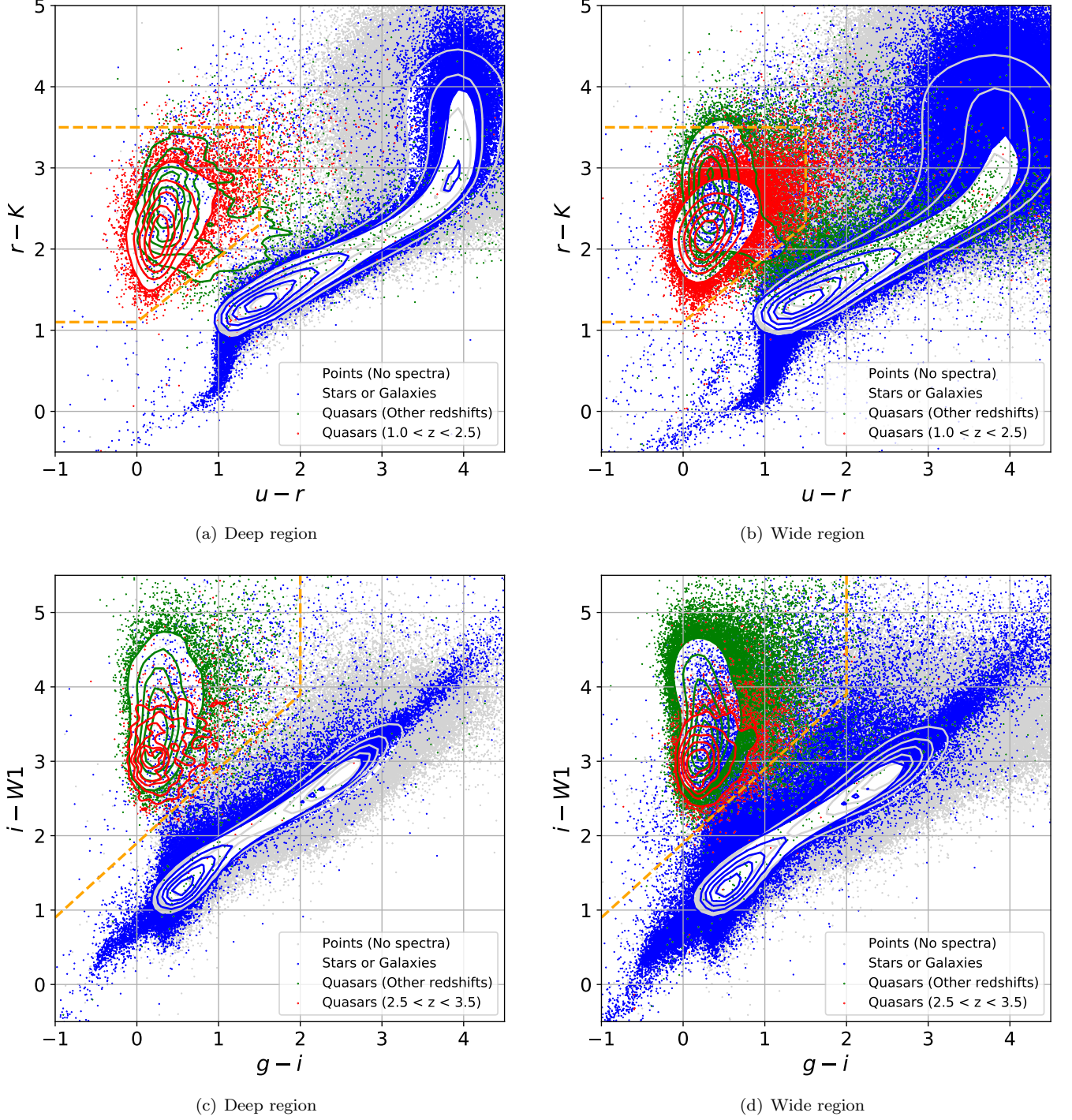


Figure 1. Our color selection criteria. Panels (a) and (b) show the selection of quasars at $1.0 < z < 2.5$ in the deep region and wide region, respectively. The magnitude range of the objects is $15.0 < r < 21.5$ mag in (a) and $15.0 < r < 20.5$ mag in (b). The light grey dots represent point sources without spectra. Quasars at $1.0 < z < 2.5$ are marked by the red dots, and other quasars are represented by the green dots. Stars and galaxies are indicated by the blue dots. The orange dashed line denotes our color selection criteria. Panels (c) and (d) show the selection of quasars at $2.5 < z < 3.5$ in the deep region and wide region, respectively. The magnitude range of the objects is $15.0 < i < 21.5$ mag in (c) and $15.0 < i < 20.5$ mag in (d). The red dots indicate quasars at $2.5 < z < 3.5$, and the orange dashed line represents our color selection criteria. We adopt the AB magnitude system for SDSS photometry, and the Vega system for VISTA, UKIDSS, and WISE data. Zero-point corrections are not applied in this work.

quasars that cannot be identified by our current color selection method. The purity of the sample is 97% (95%) in the deep (wide) region, in all magnitude ranges that we consider. Some contaminants are white dwarfs that typically exhibit a very blue color. Other contaminants include stars with large photometric errors. When we computed sample completeness and purity in the next section, their associated uncertainties are estimated in a straightforward way that the fraction of missed quasars or the fraction of contaminants correspond to a 2σ uncertainty. For example, if a completeness is 96%, then its associated 2σ uncertainty is 4%, or 1σ uncertainty is 2%.

In the redshift range of $2.5 < z < 3.5$, quasars appear much fainter in the rest-frame UV continuum due to the IGM absorption. This results in the quasar's $u-r$ color being very similar to that of low-temperature stars. We find that the $g-i$ and $i-W1$ color-color diagram (Figure 1(c), 1(d)) works well in distinguishing quasars from stars. This is because quasars in this redshift range have a notably bluer $g-i$ color than that of late-type stars, while their $i-W1$ color is slightly redder than that of early-type stars. Therefore, we apply the following color selection criteria:

$$\begin{cases} g-i < 2.0, \\ i-W1 < (g-i) + 1.9. \end{cases}$$

The magnitude range for target selection is $15.0 < i < 21.5$ mag in the deep region, and is $15.0 < i < 20.5$ mag in the wide region.

With the above selection criteria, we find 1768 quasars in the deep region and 6928 quasars in the wide region. Table 1 shows that we maintain a reasonable balance between completeness and purity. Our selection only excludes a small number of real quasars, mainly due to large $W1$ -band magnitude errors for some quasars. The color-based selection inevitably includes certain contaminants, such as intrinsically blue white dwarfs and galaxies that are occasionally misclassified as point sources. Additionally, some stars have positional offsets between their WISE coordinates and SDSS coordinates, which results in cross-matching errors. Currently, our cross-matching radius with the UnWISE Catalog is $1''.5$. Although reducing it to $1''$ could help mitigate this interference, it may also prevent some sources from successfully matching with the WISE data.

2.3. Simulation

To further test the effectiveness of our color selection method, we performed a simulation using the `simqso` package (McGreer et al. 2021). `Simqso` is a collection of tools designed to generate simulated quasar

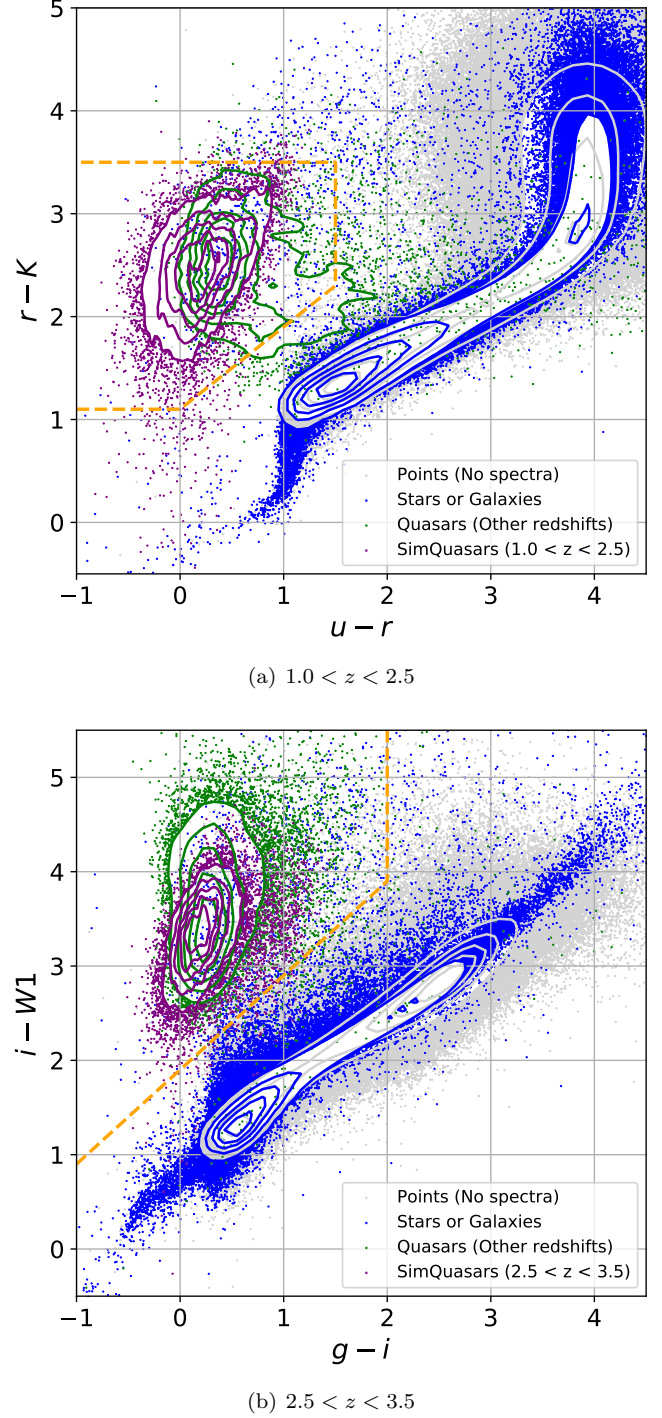


Figure 2. Color-color diagrams of our simulated quasars. Panel (a) displays the redshift range of $1.0 < z < 2.5$ and covers a magnitude range of $15.0 < r < 21.5$. Panel (b) shows the redshift range of $2.5 < z < 3.5$ and covers a magnitude range of $15.0 < i < 21.5$. The purple dots represent the simulated quasars. For the convenience of comparison, we also plot the true distributions of point-like stars and galaxies with the blue dots. The orange dashed line represents our color selection criteria.

Table 1. Completeness and Purity for the Quasar Selection

Regions	Morphology	Cross-matching	Redshift	Color	Purity	Spectral
Deep region	$86.9 \pm 6.5\%$	$71.7 \pm 14.1\%$	$1.0 < z < 2.5$	$95.2 \pm 2.4\%$	$96.8 \pm 1.6\%$	$98.4 \pm 0.8\%$
			$2.5 < z < 3.5$	$96.4 \pm 1.8\%$	$93.3 \pm 3.3\%$	$91.0 \pm 4.5\%$
Wide region	$99.2 \pm 0.4\%$	$85.7 \pm 7.1\%$	$1.0 < z < 2.5$	$97.0 \pm 1.5\%$	$95.4 \pm 2.3\%$	$96.4 \pm 1.8\%$
			$2.5 < z < 3.5$	$96.8 \pm 1.6\%$	$91.4 \pm 4.3\%$	$87.1 \pm 6.4\%$

Note: Morphology, cross-matching, color, and spectral refer to morphology completeness, cross-matching completeness, color completeness, and spectral completeness, respectively.

spectra and photometric data. The quasar evolution model we use for simulation is the pure luminosity evolution (PLE) model at $1.0 < z < 2.5$ and the luminosity evolution density evolution (LEDE) model at $2.5 < z < 3.5$ of BOSS DR9 (Ross et al. 2013). The power-law slopes follow a Gaussian distribution, and the continuum is modeled as a series of broken power laws. We use the default values for these parameters. For each quasar, we simulate a spectral range from 3000-300,000 Å. We set the spectral resolution as $R = 1000$. We simulate about 100,000 quasars for each of the two redshift ranges.

We use the SDSS, UKIDSS, and WISE photometric systems to calculate object magnitudes. Magnitude errors are also added so that these errors follow the magnitude-error distributions of real objects in each band. We randomly draw 10,000 quasars from the simulated samples and plot them in the color-color diagram (Figure 2). For comparison, we also plot real stars, galaxies, and point sources without spectral data from the deep region. It shows that our color selection method is robust. For the simulated quasars, our color selection completeness is 97.8% for $1.0 < z < 2.5$ and 98.9% for $2.5 < z < 3.5$. Our color selection method effectively recovers the vast majority of quasars.

3. RESULTS

3.1. Completeness corrections

In this subsection, we applied four major completeness corrections—morphology, cross-matching, color selection, and spectroscopic coverage—to derive the QLFs. The first incompleteness comes from morphology. In order to quickly exclude galaxies, we only selected point sources (SDSS type = 6) when selecting quasars. Distant quasars with strong detections are typically point sources. However, very faint point sources may be misclassified by the SDSS photometric pipeline as extended sources. We cross-match the quasar catalog with the SDSS photometric data to obtain the morphological classification of quasars and calculate the proportion of point-source quasars among all quasars. The calculated

completeness is $99.2\% \pm 0.4\%$ in the wide region, and is $86.9\% \pm 6.5\%$ in the deep region.

The second incompleteness is from the cross-matching procedure. To obtain multi-band photometric data, we cross-matched SDSS photometry data with the UKIDSS catalog (VISTA catalog) and the UnWISE catalog in the wide region (deep region). However, some sources are faint in the infrared bands, resulting in a lack of corresponding UKIDSS, VISTA, or WISE data, which leads to missing matches in the cross-matching process. In the wide region, our average completeness in this procedure is $85.7\% \pm 7.1\%$, and in the deep region, the average completeness is $71.7\% \pm 14.1\%$. In addition, fainter quasars have lower completeness. The uncertainties of the completeness are calculated using the same approach as we did earlier. All these uncertainties will be propagated to the final calculation of QLFs.

The third incompleteness comes from the color selection method. Figure 1 shows that a small fraction of quasars are outside of our selection criteria. We calculate the completeness based on this fraction. In the wide region, our completeness of the color selection is over 96%, and in the deep region, our completeness of the color selection is about 95%.

The final sample incompleteness comes from the incompleteness of spectral observations. Not all sources have spectral data. We assume that sources without spectra have the same fraction of quasars as those with spectra. In both wide and deep regions, our spectral completeness is over 87%.

By combining these completeness corrections together, we obtain the final completeness correction, or sample selection function $p(M, z)$. This function gives the probability that a quasar with a given absolute magnitude M_{1450} and redshift z can be selected by our method. We adopt the method described in Richards et al. (2006) to compute the absolute magnitude M_{1450} from the observed i -band apparent magnitude. We choose M_{1450} as the reference magnitude because the rest-frame 1450 Å lies in a relatively line-free region of the quasar ultraviolet spectrum, and thus provides

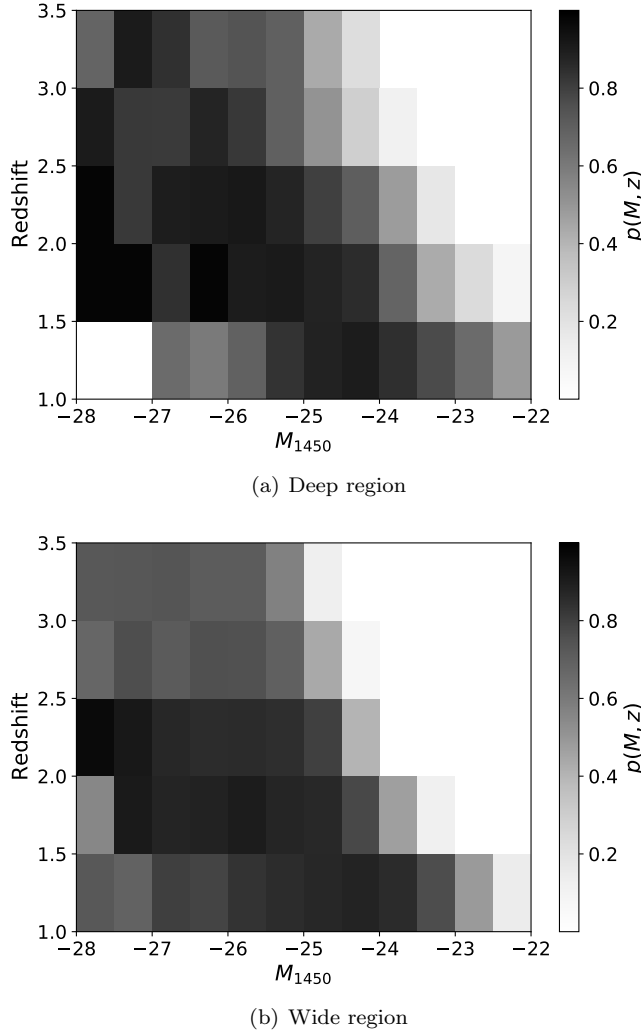


Figure 3. Distribution of the quasar selection function $p(M, z)$. Panel (a) shows the distribution of $p(M, z)$ in the deep region. A magnitude limit of $15.0 < r < 21.5$ mag is adopted for $1.0 < z < 2.5$, while a magnitude limit of $15.0 < i < 21.5$ mag is adopted for $2.5 < z < 3.5$. Panel (b) shows the distribution of $p(M, z)$ in the wide region. A magnitude limit of $15.0 < r < 20.5$ mag is adopted for $1.0 < z < 2.5$, while a magnitude limit of $15.0 < i < 20.5$ mag is adopted for $2.5 < z < 3.5$.

a robust tracer of the intrinsic AGN continuum with minimal contamination from strong emission lines. Figure 3 shows the quasar selection function in the deep region and the wide region. The low-completeness regions at the faint end is mainly caused by the apparent-magnitude limit. In these regions, the sources are too faint to be detected, rather than being missed by our selection.

3.2. QLFs

We derive binned QLFs first. We set $p(M, z)$ as the quasar selection function, and the available volume

(Avni & Bahcall 1980) for a quasar with absolute magnitude M and redshift z in a magnitude bin ΔM and redshift bin Δz is given by

$$V_a = \iint_{\Delta M \Delta z} p(M, z) \frac{dV}{dz} dz dM. \quad (1)$$

The binned QLF and its statistical uncertainties can be expressed as follows:

$$\Phi(M, z) = \sum \frac{1}{V_a^i}, \quad (2)$$

$$\sigma(\Phi) = \left[\sum \left(\frac{1}{V_a^i} \right)^2 \right]^{\frac{1}{2}}, \quad (3)$$

where V_a^i is the available volume in each bin, and the sum is over all quasars in each bin.

We divide the redshift range of $1.0 < z < 3.5$ into 5 bins with a bin size of 0.5. In each redshift bin, we further divide the luminosity into several magnitude bins with a bin size of 0.5 magnitudes.

The K -correction is applied following the prescription given in Richards et al. (2006). The calculated results are shown in Table 2. The final errors $\Delta\Phi$ are obtained by adding the errors from each step of the completeness corrections to the statistical uncertainties $\sigma(\Phi)$. We plot the binned QLFs in Figure 4.

3.3. Model fitting

In order to characterize the QLFs at $1.0 < z < 3.5$, we adopt a double power-law model (Boyle et al. 2000) as the parametric form for the QLFs,

$$\Phi_{par}(M, z) = \frac{\Phi^*}{10^{0.4(\alpha+1)(M-M^*)} + 10^{0.4(\beta+1)(M-M^*)}}, \quad (4)$$

where α and β represent the slopes of the faint and bright ends of the function, respectively, M^* is the characteristic magnitude, and Φ^* is the normalization of the density.

We apply the maximum likelihood method (Marshall et al. 1983) to fit the derived luminosity function. The likelihood function is expressed as follows:

$$S = -2 \sum \ln[\Phi(M_i, z_i) p(M_i, z_i)] + 2 \int_{\Delta M} \int_{\Delta z} \Phi(M, z) p(M, z) \frac{dV}{dz} dz dM, \quad (5)$$

Table 2. Binned QLFs

M_{1450}	N	$\log(\Phi)$	$\Delta\Phi/10^{-9}$	Regions
$1.0 < z < 1.5$				
-26.75	4	-8.02	6.52	Deep region
-26.25	11	-7.54	15.94	Deep region
-25.75	24	-7.26	20.52	Deep region
-25.25	67	-6.9	26.97	Deep region
-24.75	162	-6.54	39.49	Deep region
-24.25	386	-6.17	68.49	Deep region
-23.75	563	-5.98	133.55	Deep region
-23.25	765	-5.8	264.14	Deep region
-22.75	951	-5.64	543.0	Deep region
-22.25	894	-5.54	1047.3	Deep region
-27.75	3	-8.99	0.74	Wide region
-27.25	5	-8.74	1.1	Wide region
-26.75	20	-8.21	2.04	Wide region
-26.25	57	-7.74	4.53	Wide region
-25.75	172	-7.29	8.49	Wide region
-25.25	435	-6.9	15.56	Wide region
-24.75	1002	-6.54	29.04	Wide region
-24.25	2084	-6.23	48.91	Wide region
-23.75	3488	-6.0	93.0	Wide region
-23.25	4838	-5.8	199.84	Wide region
-22.75	4382	-5.65	453.17	Wide region
-22.25	1715	-5.55	953.36	Wide region
$1.5 < z < 2.0$				
-27.75	2	-8.57	1.94	Deep region
-27.25	4	-8.27	2.75	Deep region
-26.75	6	-8.02	4.63	Deep region
-26.25	32	-7.36	8.0	Deep region
-25.75	91	-6.87	20.76	Deep region
-25.25	222	-6.49	37.11	Deep region
-24.75	410	-6.21	70.63	Deep region
-24.25	709	-5.96	128.96	Deep region
-23.75	875	-5.77	363.15	Deep region
-23.25	777	-5.62	923.19	Deep region
-22.75	544	-5.52	1646.65	Deep region
-22.25	235	-5.45	2756.83	Deep region
-27.75	4	-8.82	1.11	Wide region
-27.25	17	-8.41	1.12	Wide region
-26.75	49	-7.93	2.45	Wide region
-26.25	203	-7.32	6.21	Wide region
-25.75	542	-6.9	11.61	Wide region
-25.25	1345	-6.49	30.12	Wide region
-24.75	2604	-6.2	57.14	Wide region
-24.25	4047	-5.96	146.19	Wide region
-23.75	3848	-5.77	392.25	Wide region
-23.25	1405	-5.63	882.37	Wide region
$2.0 < z < 2.5$				
-27.75	1	-8.89	1.29	Deep region
-27.25	5	-8.11	4.15	Deep region
-26.75	21	-7.53	7.97	Deep region
-26.25	61	-7.07	14.88	Deep region
-25.75	160	-6.66	27.22	Deep region

M_{1450}	N	$\log(\Phi)$	$\Delta\Phi/10^9$	Regions
-25.25	329	-6.32	57.11	Deep region
-24.75	491	-6.11	120.95	Deep region
-24.25	682	-5.91	253.19	Deep region
-23.75	654	-5.77	620.74	Deep region
-23.25	303	-5.66	1456.5	Deep region
-27.75	5	-8.99	0.48	Wide region
-27.25	38	-8.09	1.69	Wide region
-26.75	138	-7.5	4.84	Wide region
-26.25	386	-7.05	11.72	Wide region
-25.75	890	-6.69	22.8	Wide region
-25.25	1930	-6.35	46.54	Wide region
-24.75	3212	-6.1	99.41	Wide region
-24.25	2416	-5.93	283.37	Wide region
$2.5 < z < 3.0$				
-27.75	4	-8.25	3.03	Deep region
-27.25	19	-7.53	9.59	Deep region
-26.75	26	-7.39	11.98	Deep region
-26.25	81	-6.93	20.46	Deep region
-25.75	163	-6.6	44.01	Deep region
-25.25	229	-6.38	100.33	Deep region
-24.75	263	-6.19	237.74	Deep region
-24.25	227	-6.01	503.53	Deep region
-23.75	111	-5.92	950.11	Deep region
-27.75	18	-8.28	2.29	Wide region
-27.25	69	-7.74	4.59	Wide region
-26.75	191	-7.28	12.47	Wide region
-26.25	434	-6.94	20.87	Wide region
-25.75	912	-6.62	41.33	Wide region
-25.25	1483	-6.38	83.24	Wide region
-24.75	1469	-6.18	219.73	Wide region
-24.25	347	-6.04	468.58	Wide region
$3.0 < z < 3.5$				
-27.75	4	-8.12	5.16	Deep region
-27.25	9	-7.89	4.87	Deep region
-26.75	26	-7.39	11.34	Deep region
-26.25	52	-7.03	28.46	Deep region
-25.75	94	-6.78	42.02	Deep region
-25.25	169	-6.5	81.08	Deep region
-24.75	140	-6.38	198.06	Deep region
-24.25	101	-6.24	364.78	Deep region
-27.75	10	-8.55	1.32	Wide region
-27.25	37	-7.98	3.33	Wide region
-26.75	149	-7.38	9.7	Wide region
-26.25	277	-7.1	18.16	Wide region
-25.75	546	-6.81	32.97	Wide region
-25.25	782	-6.56	81.57	Wide region
-24.75	249	-6.41	203.65	Wide region

Note: Φ and $\Delta\Phi$ is in units of $\text{Mpc}^{-3}\text{mag}^{-1}$.

where $p(M, z)$ is the selection function of quasars. We apply the MCMC method to obtain the best-fit results and estimate the associated uncertainties. The best-fit results are presented in Table 3. We also plot the parametric QLFs with the orange dashed line in Figure 4. The results show that as the universe evolves, there is no clear evolutionary trend in the bright- and faint-end slopes of the QLFs, while the characteristic luminosity continues to decrease and the density normalization increases.

4. DISCUSSION

4.1. Evolution models

Most previous works suggested that QLFs follow the pure luminosity evolution (PLE) model at $z \lesssim 2.2$ and the luminosity evolution density evolution (LEDE) model at $z \gtrsim 2.2$ (Croom et al. 2009; Ross et al. 2013; Palanque-Delabrouille et al. 2013, 2016; Yang et al. 2018). However, some studies suggest that for QLFs with $z \gtrsim 2.0$, the pure density evolution (PDE) model is sufficient to describe the quasar evolution (Kim & Im 2021; Pan et al. 2022). We test the PLE model, PDE model, and LEDE model separately. For the PLE model, we use the following definition (Croom et al. 2009):

$$M^*(z) = M^*(0) - 2.5(k_1 z + k_2 z^2). \quad (6)$$

The PDE model follows the formula by Kim & Im (2021):

$$\log[\Phi^*(z)] = \log[\Phi^*(z = z_p)] + k_1(z - z_p), \quad (7)$$

we set $z_p = 1.0$ and 2.5 for the two redshift ranges $1.0 < z < 2.5$ and $z > 2.5$, respectively. The LEDE model follows the formula by Ross et al. (2013):

$$\log[\Phi^*(z)] = \log[\Phi^*(z = z_p)] + k_1(z - z_p), \quad (8)$$

$$M^*(z) = M^*(z = z_p) + k_2(z - z_p). \quad (9)$$

In addition to the three models mentioned above, we also explore the model in which all parameters evolve, referred to as a “free case”:

$$X(z) = X_0 + k_i(z - z_p), \quad (10)$$

where $X \in \{\log \Phi^*, M^*, \alpha, \beta\}$, and the coefficient $k_i \in \{k_{\log \Phi^*}, k_{M^*}, k_\alpha, k_\beta\}$.

We use the four models to fit the QLFs, and then use the reduced χ^2_ν to evaluate the goodness of fit:

$$\chi^2_\nu = \frac{\sum [(\Phi_{obs} - \Phi_{th})/\sigma]^2}{n - \nu}, \quad (11)$$

where Φ_{obs} is the binned QLF obtained from the calculation, Φ_{th} is the binned QLF derived using the quasar

evolution model, n is the number of data points, and ν is the number of free parameters.

The results are listed in Table 4. The limited number of data points leads to overfitting, so we consider both the χ^2 values and the degrees of freedom (dof) when evaluating the goodness of fit. In the redshift range of $1.0 < z < 2.5$, the PLE model has the best fitting performance, which is consistent with previous results (Ross et al. 2013; Palanque-Delabrouille et al. 2016; Yang et al. 2018). This indicates that during this stage, the number density of quasars remains approximately constant, while their average luminosity evolves systematically over time. Therefore, the PLE model provides a better description of the observational data. In the redshift range of $2.5 < z < 3.5$, the χ^2_ν values of the three models show no significant differences, mainly because only two redshift bins are included. However, since the PDE model has one fewer parameter compared to the PLE and LEDE models, we consider that the PDE model is enough to describe quasar evolution within this redshift range. This conclusion is consistent with the results of Kim & Im (2021).

4.2. Comparison with previous results

In Figure 5, we compare our QLFs with those from previous studies (Ross et al. 2013; Palanque-Delabrouille et al. 2016; Yang et al. 2018). For the results from Ross et al. (2013), we use their PLE model for $z < 2$ and the LEDE model for the deep region when $z > 2$. For the results from Palanque-Delabrouille et al. (2016), we use their PLE+LEDE model for comparison. For the results from Yang et al. (2018), we apply the PLE model for $z < 2.5$ and the LEDE model for $z > 2.5$. To facilitate a direct comparison with previous studies, we convert the magnitudes used in their QLFs into M_{1450} .

Compared with Ross et al. (2013), our QLFs show higher number densities at the faint end in most redshift bins. At $z \sim 2.7$, our bright-end QLF is also higher. These differences are mainly related to the different quasar selections and completeness estimates. To make a direct comparison, we select a common sky region and focus on a redshift range $2.5 < z < 3.0$. In this region, nearly all quasars in the statistical sample of Ross et al. (2013) are recovered by our optical-infrared color selection. In addition, our selection identifies about 1.5 times more spectroscopically confirmed quasars than those included in the sample of Ross et al. (2013). These additional quasars are systematically redder than those in the sample of Ross et al. (2013). This is because the quasar selection in Ross et al. (2013) was based on the BOSS XDQSO color selection without infrared data. As a result, the completeness is relatively

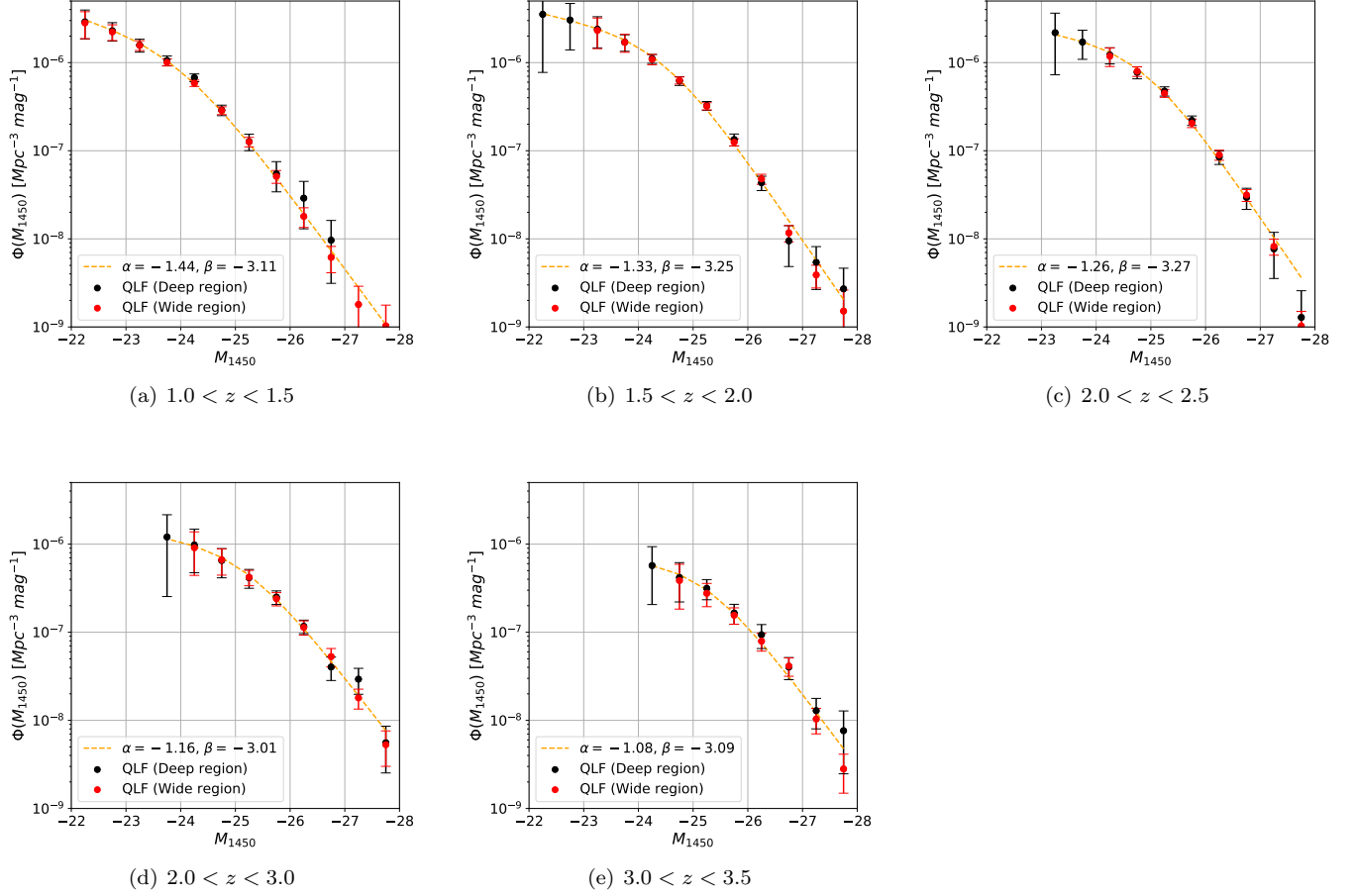


Figure 4. QLFs at $1.0 < z < 3.5$. The black solid dots represent the binned QLFs in the deep region, and the red solid dots represent the binned QLFs in the wide region. The orange dashed line represents the result of fitting the parameterized luminosity function using the maximum likelihood method, derived by combining the deep region data with the wide region data.

Table 3. Parameters of the Best Fits

redshift	α	β	M^*	$\log \Phi^*$
$1.0 < z < 1.5$	$-1.44^{+0.04}_{-0.05}$	$-3.11^{+0.05}_{-0.06}$	$-23.98^{+0.09}_{-0.10}$	$-5.79^{+0.04}_{-0.05}$
$1.5 < z < 2.0$	$-1.33^{+0.04}_{-0.04}$	$-3.25^{+0.04}_{-0.04}$	$-24.46^{+0.06}_{-0.06}$	$-5.73^{+0.03}_{-0.03}$
$2.0 < z < 2.5$	$-1.26^{+0.07}_{-0.07}$	$-3.27^{+0.06}_{-0.06}$	$-24.89^{+0.10}_{-0.09}$	$-5.83^{+0.05}_{-0.05}$
$2.5 < z < 3.0$	$-1.16^{+0.15}_{-0.14}$	$-3.01^{+0.08}_{-0.09}$	$-25.12^{+0.18}_{-0.19}$	$-5.99^{+0.08}_{-0.09}$
$3.0 < z < 3.5$	$-1.08^{+0.06}_{-0.13}$	$-3.09^{+0.07}_{-0.07}$	$-25.23^{+0.10}_{-0.11}$	$-6.21^{+0.04}_{-0.05}$

low. Their Figure 7 shows that the selection efficiency is usually about 30%–75% in most bins, and the completeness is only $\sim 50\%$ even for bright quasars at $z \sim 2.7$. At this redshift, quasar colors are very similar to those of A/F stars in the optical. In contrast, our optical-infrared color selection reaches a higher completeness of $\sim 80\%$ for bright quasars at the same redshift. This allows us to recover quasars more effectively, and explains why our bright-end QLF is higher near $z \sim 2.7$.

Compared with [Palanque-Delabrouille et al. \(2016\)](#), our QLF is higher at the bright end at $2.5 < z < 3.5$. This difference is related to the survey area and the limited number of very bright quasars in their sample. Their analysis is mainly based on the Stripe 82 region, which covers only about 94.5 deg^2 . Indeed, their sample contains no quasars brighter than $g < 18 \text{ mag}$. We further test this effect using our deep-field data. For quasars at $2.5 < z < 3.5$ and $-28 < M_{1450} < -27$, about half of them have apparent magnitudes brighter

than $g = 18$ mag. Therefore, a non-negligible fraction of the most luminous quasars in this redshift and luminosity range would not be represented in their sample. The absence of these very bright quasars explains why their bright-end QLF is lower than our result.

The Yang et al. (2018) QLF was derived from a deep survey covering only $\sim 2 \text{ deg}^2$, which is much smaller than the area used in our study. This leads to large statistical uncertainties, and thus a direct comparison is not reasonable.

We also investigated the cumulative spatial density evolution of quasars within the redshift range $1.0 < z < 3.5$. The spatial density of quasars brighter than a specified magnitude M is determined by integrating the QLF,

$$\rho(< M, z) = \int_{-\infty}^M \Phi(M, z) dM, \quad (12)$$

where we apply the PLE model for the redshift range $1.0 < z < 2.5$ and the PDE model for $2.5 < z < 3.5$. We set the specified magnitude M to $-24, -25$, and -26 , respectively. Figure 6 shows the cumulative spatial density evolution based on our model. Overall, our results are consistent with those from previous studies. However, a slight difference is observed in the range of $1.0 < z < 2.5$, where our evolution is shallower compared with results from Ross et al. (2013).

Since our results are based on the DESI Jura dataset, which will not be publicly released, we further examined the differences between the Jura and Loa datasets. The Jura dataset is derived from a version of Year 3 data that closely corresponds to, but is not identical with, DESI Data Release 2, due to differences in both the number of observed targets and the data processing pipeline (Guy et al. 2023). The Loa dataset will be included with DR2. By cross-matching the spectra from Loa and Jura, we found that approximately 3.5% of the spectra are included in Loa but absent in Jura. Given that the quasar luminosity function is calculated in logarithmic space, this small difference has a negligible impact and does not affect our final results.

5. SUMMARY

In this paper, we have used the quasar catalogs from SDSS and DESI as a library to study the evolution of type 1 quasars at $1.0 < z < 3.5$. We defined two sky regions, including a deep region of $\sim 265 \text{ deg}^2$ with a depth reaching 21.5 mag, and a wide region of $\sim 1700 \text{ deg}^2$ with a depth of 20.5 mag. Using photometric data from SDSS, UKIDSS, VISTA, and WISE, and employing a straightforward color selection method, we built a quasar sample with high completeness and high purity.

We then measured the QLFs at $1.0 < z < 3.5$. We first assessed the completeness due to the morphologi-

cal classification, cross-matching, color selection methods, and incomplete spectra. Subsequently, we derived binned QLFs and fitted them using a double power-law model. Compared with previous studies, our QLF shows some differences. In most redshift bins, it has higher number densities at the faint end, and it is also higher at the bright end at $2.5 < z < 3.5$. These differences are mainly due to different quasar selection methods, completeness corrections, survey areas, and fitting methods. In our analysis, we apply a uniform color selection to a large spectroscopic quasar sample from SDSS and DESI, together with a consistent completeness correction. With a higher completeness and a larger survey area, our result gives a more uniform and self-consistent picture of quasar evolution over the redshift range of $1.0 < z < 3.5$.

We further examined the evolution of QLFs by evaluating the fit of three models: PLE, PDE, and LEDE. Our analysis found that the PLE model effectively describes the quasar evolution in the redshift range of $1.0 < z < 2.5$. It implies that the changes in the luminosity distribution of these quasars likely stem from systematic evolution in black hole accretion efficiency, rather than significant variations in their population size. For the higher redshift range of $2.5 < z < 3.5$, the PDE model is enough to characterize the quasar evolution in this redshift range. It suggests a continuous increase in the spatial number density of this quasar population during this epoch. This trend reflects the cosmological characteristics of their early formation and active phase. The transition between these two evolutionary modes reveals fundamental differences in the dominant physical mechanisms governing quasars across different cosmic epochs.

Looking ahead, with the upcoming deployment of a new generation of survey projects such as the Euclid Space Telescope (Euclid Collaboration et al. 2025) and the China Space Station Telescope (CSST) (CSST Collaboration et al. 2025), we will gain access to deeper and more systematic near-infrared data. These datasets will substantially improve constraints on the shape and evolution of QLFs at high redshifts, offering critical insights into the physical connection between quasar activity and the growth of SMBHs.

6. ACKNOWLEDGMENTS

We acknowledge support from the National Key R&D Program of China (2021YFA1600404) and the National Science Foundation of China (12225301).

This research used data obtained with the Sloan Digital Sky Survey (SDSS). Funding for SDSS IV has been provided by the Alfred P. Sloan Foundation, the

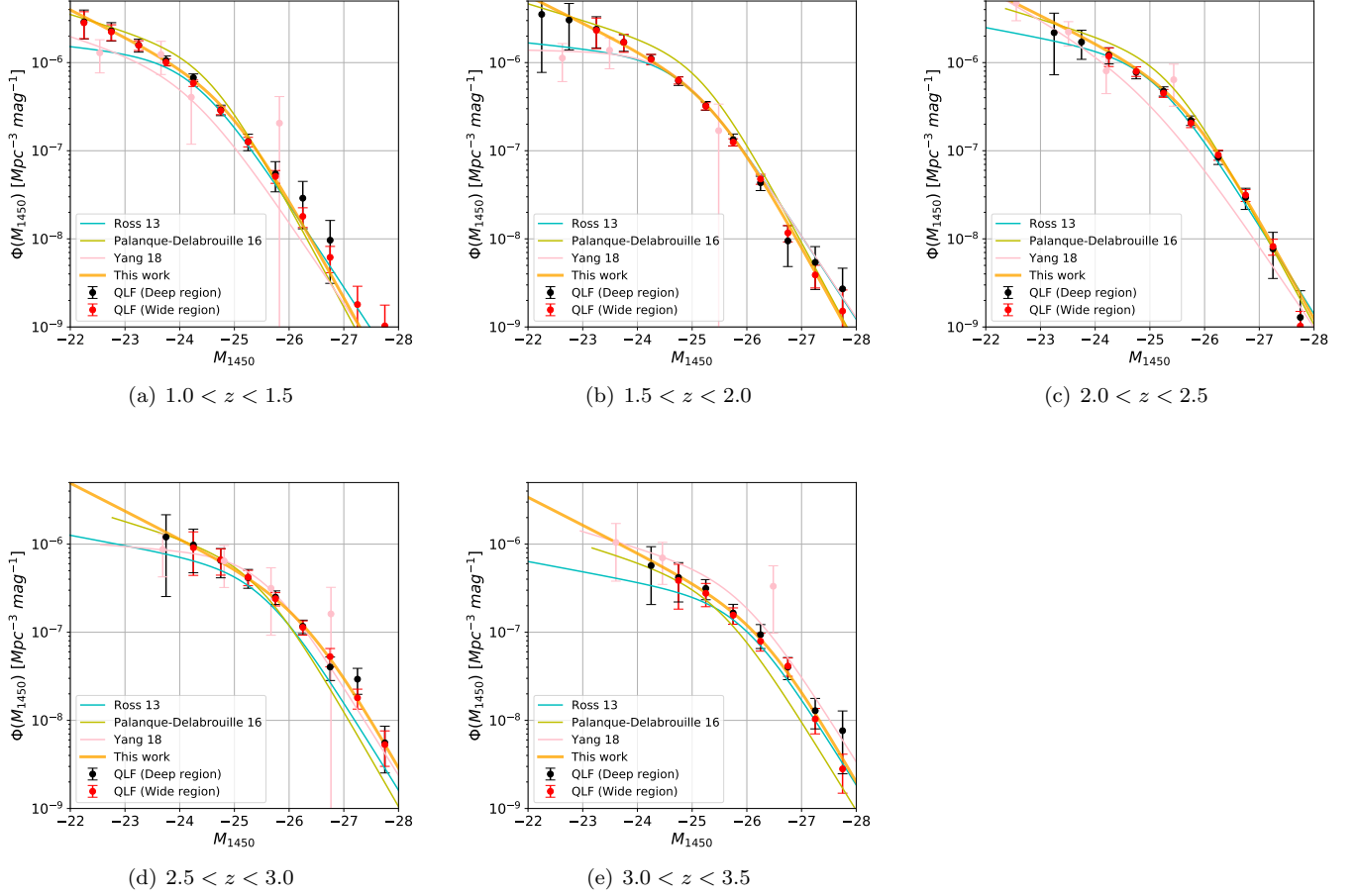


Figure 5. Comparison of QLFs with others. The solid orange line represents the QLFs using the PLE model for the redshift range $1.0 < z < 2.5$ and the PDE model for the redshift range $2.5 < z < 3.5$. For comparison, the solid cyan line represents the results from [Ross et al. \(2013\)](#), the solid yellow line shows the results from [Palanque-Delabrouille et al. \(2016\)](#), and the pink line indicates the results from [Yang et al. \(2018\)](#). The faint end of the results from [Palanque-Delabrouille et al. \(2016\)](#) and [Yang et al. \(2018\)](#) are truncated based on the limiting apparent magnitude of their quasar selection.

Table 4. Evolution Models

	α_0	β_0	M_s	$\Phi^*(z = z_p)$	k_1	k_2	k_3	k_4	$\chi^2_\nu(\chi^2/dof)$
$1.0 < z < 2.5$									
PLE	$-1.77^{+0.08}_{-0.07}$	$-3.84^{+0.12}_{-0.14}$	$-22.60^{+0.03}_{-0.03}$	$-6.30^{+0.02}_{-0.02}$	$0.98^{+0.01}_{-0.01}$	$-0.19^{+0.01}_{-0.01}$	...	...	0.41(22.73/56)
PDE	$-1.96^{+0.05}_{-0.04}$	$-3.82^{+0.12}_{-0.14}$	$-25.57^{+0.03}_{-0.03}$	$-6.84^{+0.02}_{-0.02}$	$0.47^{+0.02}_{-0.02}$	...	...	...	1.12(63.59/57)
LEDE	$-1.83^{+0.07}_{-0.06}$	$-3.89^{+0.13}_{-0.15}$	$-24.96^{+0.03}_{-0.03}$	$-6.44^{+0.02}_{-0.02}$	$0.08^{+0.02}_{-0.02}$	$-0.64^{+0.04}_{-0.03}$	...	...	0.70(39.34/56)
Free case	$-1.77^{+0.09}_{-0.08}$	$-3.39^{+0.14}_{-0.17}$	$-24.61^{+0.04}_{-0.04}$	$-6.23^{+0.02}_{-0.02}$	$-0.11^{+0.03}_{-0.03}$	$-0.96^{+0.04}_{-0.04}$	$0.00^{+0.13}_{-0.11}$	$-0.51^{+0.15}_{-0.19}$	0.60(32.64/54)
$2.5 < z < 3.5$									
PLE	$-1.87^{+0.20}_{-0.16}$	$-3.82^{+0.36}_{-0.49}$	$-21.37^{+0.09}_{-0.08}$	$-6.83^{+0.05}_{-0.06}$	$1.55^{+0.01}_{-0.01}$	$-0.29^{+0.01}_{-0.01}$	...	...	0.25(6.61/26)
PDE	$-1.79^{+0.21}_{-0.16}$	$-3.77^{+0.30}_{-0.39}$	$-26.34^{+0.08}_{-0.07}$	$-6.60^{+0.04}_{-0.05}$	$-0.32^{+0.09}_{-0.11}$	...	...	...	0.19(5.25/27)
LEDE	$-1.79^{+0.23}_{-0.18}$	$-3.77^{+0.32}_{-0.44}$	$-26.32^{+0.09}_{-0.08}$	$-6.59^{+0.05}_{-0.06}$	$-0.34^{+0.10}_{-0.12}$	$-0.03^{+0.18}_{-0.15}$	...	...	0.20(5.24/26)
Free case	$-1.49^{+0.27}_{-0.20}$	$-2.99^{+0.31}_{-0.46}$	$-25.59^{+0.10}_{-0.09}$	$-6.11^{+0.06}_{-0.07}$	$-1.34^{+0.11}_{-0.14}$	$-1.54^{+0.20}_{-0.16}$	$-0.59^{+0.45}_{-0.31}$	$-1.87^{+0.93}_{-1.37}$	0.18(4.33/24)

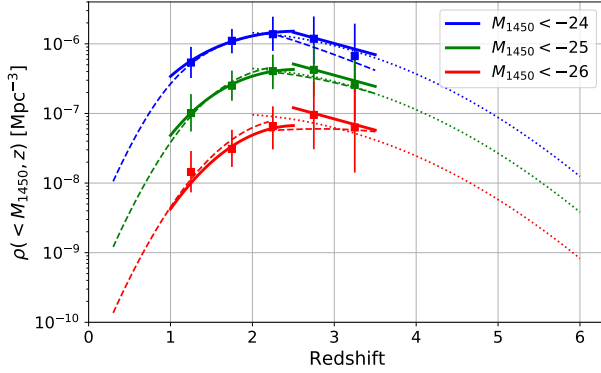


Figure 6. Cumulative density evolution of quasars at $1.0 < z < 3.5$. The blue, green, and red lines represent magnitude ranges $M_{1450} < -25$, -26 , and -27 mag, respectively. Square points and solid lines are our results. For comparison, the dashed line represents the results from Ross et al. (2013), and the dotted line shows the results from Kim & Im (2021).

U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High Performance Computing at the University of Utah. The SDSS website is www.sdss4.org.

This research used data obtained with the Dark Energy Spectroscopic Instrument (DESI). This material is based upon work supported by the U.S. Department of Energy (DOE), Office of Science, Office of High-Energy Physics, under Contract No. DE-AC02-05CH11231, and by the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility under the same contract. Additional support for DESI was provided by the U.S. National Science Foundation (NSF), Division of Astronomical Sciences un-

der Contract No. AST-0950945 to the NSF’s National Optical-Infrared Astronomy Research Laboratory; the Science and Technology Facilities Council of the United Kingdom; the Gordon and Betty Moore Foundation; the Heising-Simons Foundation; the French Alternative Energies and Atomic Energy Commission (CEA); the National Council of Humanities, Science and Technology of Mexico (CONAHCYT); the Ministry of Science, Innovation and Universities of Spain (MICTU/AEI/10.13039/501100011033), and by the DESI Member Institutions: <https://www.desi.lbl.gov/collaborating-institutions>. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U. S. National Science Foundation, the U. S. Department of Energy, or any of the listed funding agencies. The authors are honored to be permitted to conduct scientific research on I’oligam Du’ag (Kitt Peak), a mountain with particular significance to the Tohono O’odham Nation.

S.P. is supported by the international Gemini Observatory, a program of NSF NOIRLab, which is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the U.S. National Science Foundation, on behalf of the Gemini partnership of Argentina, Brazil, Canada, Chile, the Republic of Korea, and the United States of America.

Facilities: SDSS, DESI, UKIDSS, VISTA, WISE

Software: Astropy (Astropy Collaboration et al. 2013, 2018, 2022), Topcat (Taylor 2005), emcee (Foreman-Mackey et al. 2013).

All data records needed to reproduce the figures of this publication are available on Zenodo at [doi:10.5281/zenodo.21442096](https://doi.org/10.5281/zenodo.21442096).

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