Properties of Spectrally Defined Red QSOs at $z = 0.3–1.2$

A.-L. Tsai and C.-Y. Hwang

Institute of Astronomy, National Central University, No. 300, Jhongda Rd., Jhongli, Taoyuan 32001, Taiwan; altsai@astro.ncu.edu.tw, hwangcy@astro.ncu.edu.tw

Received 2015 July 26; revised 2017 May 8; accepted 2017 May 17; published 2017 June 14

Abstract

We investigated the properties of a sample of red Quasi-stellar Objects (QSOs) using optical, radio, and infrared data. These QSOs were selected from the Sloan Digital Sky Survey Data Release 7 quasar catalog. We only selected sources with sky coverage in the Very Large Array Faint Images of the Radio Sky at Twenty-centimeters survey, and searched for sources with Wide-field Infrared Survey Explorer counterparts. We defined the spectral color of the QSOs based on the flux ratio of the rest-frame 4000 to 3000 Å continuum emission to select red QSOs and typical QSOs. In accordance with this criterion, only QSOs with redshifts between 0.3 and 1.2 could be selected. We found that red QSOs have stronger infrared emission than typical QSOs. We noted that the number ratios of red QSOs to typical QSOs decrease with increasing redshifts, although the number of typical QSOs increase with redshifts. Furthermore, at high redshifts, the luminosity distributions of typical QSOs and red QSOs seem to have similar peaks; however, at low redshifts, the luminosities of red QSOs seem to be lower than those of typical QSOs. These findings suggest that there might be at least two types of red QSOs in our QSO samples.

Key words: catalogs – quasars: general – surveys

1. Introduction

Quasi-stellar Objects (QSOs) are one type of active galactic nucleus (AGN) and are among the most luminous objects in the universe. The energy of AGNs is believed to be powered by surrounding accretion disks feeding matter into a supermassive black hole (SMBH) at the center of the host galaxy. The accretion disk and SMBH are surrounded by a dusty torus that can obscure the line of sight in certain directions. Some AGNs also have strong radio emission with relativistic jets perpendicular to the accretion disk (Urry & Padovani 1995).

A typical QSO spectrum shows a non-stellar continuum with strong broadband emission and narrow-line emission. In the rest frame, the continuum spectrum usually peaks at ultraviolet (UV) to soft X-ray wavebands. However, recent observations have discovered a new population of QSOs, which show redder optical or infrared (IR) colors than typical QSOs (Webster et al. 1995; Richards et al. 2003; Glikman et al. 2007). No standard definition for these red QSOs currently exists.

The nature of these red QSOs is still unclear. The redness could be attributed to several different effects, such as dust reddening (Glikman et al. 2004; Urrutia et al. 2009), an intrinsically red continuum of these QSOs (Richards et al. 2003), contamination from stars in host elliptical galaxies (Masci et al. 1998), or additional red synchrotron emission (Whiting et al. 2001). The majority of the red QSOs discovered are considered to be reddened by dust (Cutri et al. 2002; Glikman et al. 2004; Canalizo et al. 2006). The origins of the red color could be explained by one of the following two scenarios: (1) the lines of sight to the dust-reddened QSOs pass through the AGN torus, or (2) the dust is produced during starburst activities which follow the galaxy mergers that trigger QSOs. The second scenario is likely related to an early evolutionary stage of QSOs. However, although dust might be a crucial effect of reddening, we do not know whether the reddening is caused entirely by dust. Therefore, using various methods to test the potential effects involved in reddening is essential.

The existence of dust in QSOs can significantly affect the observational properties of QSOs and their host galaxies (Rudy 1984). In optical observations, a population of dust-obscured QSOs would be missed by magnitude-limited surveys. The percentage of the missing QSOs might be from a few percent to ~30% (Whiting et al. 2001). However, the optically obscured photons re-emerge as emission at the infrared band. Therefore, the infrared emission might reveal the properties of dust-obscured QSOs. In addition, we noted that radio emission is barely affected by dust absorption, and that radio emission of QSOs should be independent of the amount of dust in the sources. To investigate the origins of the red color of the QSOs, we used optical, infrared, and radio data to study the properties of selected QSO samples.

Most selection methods for finding red QSOs rely on photometric selection. For example, the parent QSO samples were selected from either optical (Richards et al. 2003), infrared-infrared matching (Banerji et al. 2013), optical–infrared matching (Cutri et al. 2001; Georgakakis et al. 2009; Fynbo et al. 2013; Ross et al. 2015), or optical–infrared–radio matching sources (Glikman et al. 2007, 2012; Urrutia et al. 2009). The criteria for selecting red QSOs were mainly based on their photometric colors, such as optical–optical (e.g., $r - i$, $g - r$; Fynbo et al. 2013), optical–infrared (e.g., $R - K$, $g - J$, $i - K$, $r - W_4$; Cutri et al. 2001; Glikman et al. 2007, 2012; Georgakakis et al. 2009; Urrutia et al. 2009; Fynbo et al. 2013; Ross et al. 2015), and infrared–infrared colors (e.g., $J - K_s$, $J - K$, $W_1 - W_2$; Cutri et al. 2001; Glikman et al. 2007, 2012; Georgakakis et al. 2009; Urrutia et al. 2009; Banerji et al. 2013; Fynbo et al. 2013). However, even for the same photometric colors, red QSOs could be defined by different color criteria in different surveys; for example, the red QSOs were selected with $J - K > 2$ and $R - K > 5$ from the 2MASS-SDSS samples by Georgakakis et al. (2009), $J - K > 1.7$ and $R - K > 4$ from the FIRST-2MASS samples by Glikman et al. (2007, 2012), and $J - K > 1.3$ and $R - K > 5$ from the FIRST-2MASS samples by Urrutia et al. (2009). This implies that the red QSOs discussed in various studies might not be uniform. Furthermore, other
The Astrophysical Journal, 842:57 (11pp), 2017 June 10

Tsai & Hwang

concerns with photometric selection include redshifted strong emission lines that could contaminate the photometric colors and photometric data of the same emission lines that could contaminate the photometric colors. Concerns with photometric selection include redshifted strong emission lines at different redshifts. To avoid these problems with photometric selection of red QSOs, Richards et al. (2003) defined red QSOs based on “relative photometric colors,” which are the differences between the measured photometric colors and the median colors of QSOs at the redshift of the QSO. In this study, we developed a new method for classifying red QSOs with a statistical definition based on “relative spectral flux” to not only facilitate avoidance of the inconsistency caused by photometric cutoffs, but also enable the selection of statistically defined red QSOs to study the origins of their redness. Since the redness of our QSOs was uniformly defined at the same rest-frame wavelengths over the entire redshift range we considered, conducting follow-up confirmations for the reality of the redness is not necessary.

In this study, we selected the parent QSOs from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7) Quasar Catalog based on their spectra at the rest frame. The SDSS DR7 QSOs included both photometrically selected and FIRST-matched QSO samples (Richards et al. 2002). We chose QSOs with radio counterparts from the Very Large Array Faint Images of the Radio Sky at Twenty-centimeters (VLA FIRST) radio survey, as well as infrared counterparts from the Wide-field Infrared Survey Explorer (WISE). We defined QSO colors based on the relative flux ratio from the spectrum. Through this method, we could select red QSOs without the contamination of strong emission lines, thereby enabling us to include a wide range of red QSOs to study their general properties. The details of the data selection are described in Section 2. We present our results in Section 3, and discuss the implication of our results in Section 4. The cosmology parameters we are using in this paper are $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.30$, and $\Omega_{\Lambda} = 0.70$.

2. Sample Selection

2.1. Optical Data and Definition of QSO Color

Our QSOs were selected from the SDSS DR7 Quasar Catalog (Schneider et al. 2010). We limited our sample to $i$-band magnitudes brighter than the PSF magnitude of 19.1.$^1$ We downloaded the spectra$^2$ of these QSOs and defined the QSO color with the flux ratio of the two continuum bands at the rest-frame $\lambda = 4000 \pm 50$ Å to $\lambda = 3000 \pm 50$ Å (see Figure 1). The flux ratio $r$ is defined as

$$r = \frac{\bar{f}_{\lambda}}{\bar{f}_{3000}} = \frac{\int^{4050} \lambda \bar{f}_\lambda d\lambda}{\int^{3950} \lambda \bar{f}_\lambda d\lambda},$$  \hspace{1cm} (1)$$

where $\bar{f}_\lambda$ is the mean flux density within a range of wavelengths, $f_\lambda$ is the flux density per unit wavelength, and $\lambda$ is in units of Å. These two bands were selected to avoid strong narrow lines (e.g., Mg II, O II, and H$\gamma$) and broad emission lines (e.g., Fe II). Because of the wavelength range of SDSS spectra, only QSOs with redshifts from 0.3 to 1.2 could be selected.

1. http://www.sdss2.org/dr7/; PSF mag. $i < 19.1$ for $z < 2.3$.

2. The spectra were downloaded using the interface of the 10th SDSS Data Release. We note that the spectra are actually from DR7, which mainly includes QSOs at $z < 2.3$. For DR10, the QSOs are at $z > 2.2$. 

---

**Figure 1.** Example of the spectrum of an SDSS QSO at the rest frame. The two gray bars indicate the wavebands of the stacked flux at $\lambda = 3000 \pm 50$ Å and $4000 \pm 50$ Å.

**Figure 2.** Flux ratio of the QSO samples at different redshifts.

**Figure 3.** Number distributions of the QSO samples vs. the continuum flux ratios of 4000 to 3000 Å within the FIRST sky coverage. The number bin width is 0.02. The black curve is a Gaussian fitting with peak center at flux ratio $r_{\text{peak}} = 0.52$, and $\sigma \approx 0.042$. We select QSOs with flux ratio $r \pm 2\sigma$, i.e., $0.50 \leq r \leq 0.54$, as rQSOs (blue color), and QSOs with flux ratio $r \geq 0.66$ as rQSOs (red color). The other QSOs are shown in gray color.
Figure 4 shows the flux ratios at different redshifts. We found that the mode values of flux ratios at different redshifts are all located within the 0.5–0.6 bin and were independent of redshift. Notably, the flux ratios at low redshifts are more scattered than those at high redshifts. The number distribution of the flux ratios look like a Gaussian distribution with an extended right tail (Figure 3). Therefore, we fitted the left wing of the distribution with a Gaussian function and folded the result to the right wing. The distribution peaked at $r_{\text{peak}} = 0.52$ with $\sigma \approx 0.042$. The 3$\sigma$ at the right wing was at $r \approx 0.65$. Therefore, for comparison, we defined our QSO samples with $r \geq 0.66$ as red QSOs (hereafter rQSOs), and the QSOs with $0.50 \leq r \leq 0.54$ ($r_{\text{peak}} \pm 3\sigma$) as typical QSOs (hereafter tQSOs). Notably, the tQSOs only represented the sources with the most likely color in the SDSS QSO samples. Section 4 offers further discussion regarding the distribution of the QSO samples. We noted that the color ratio difference between the rQSOs and the tQSOs roughly corresponded to an absorption of 0.26 mag at 4000 Å when the colors were caused by dust absorption, assuming that the SMC dust-extinction law (Pei 1992) was in effect. Notably, the effective $E(B-V)$ of 0.26 was similar to the definition of red QSOs in Lacy et al. (2015, 2015).

2.2. Radio Data and Definition of Radio-loud QSOs and Radio-quiet QSOs

We looked for the radio counterparts of the QSOs in the sky coverage of the VLA FIRST radio survey (Becker et al. 1997) within a 2″ radius, which can match 98% of the sources with a real association (e.g., McMahon et al. 2002). For QSOs with a radio detection, we used their radio-to-optical ratios to classify a group of radio-loud QSOs (RLQs; Kellermann et al. 1989; Ivezić et al. 2002). The radio-to-optical ratio $R_g$ is defined as

$$R_g = \log \left( \frac{f_{\text{radio}}}{f_{\text{optical}}} \right) = 0.4(g - t),$$

where $f_{\text{radio}}$ is the radio flux, $f_{\text{optical}}$ is the optical flux, $g$ is the SDSS $g$-band magnitude, and $t$ is the radio magnitude defined as

$$t = -2.5 \log \left( \frac{f_{\text{FIRST}}}{3631 \text{ Jy}} \right),$$

where $f_{\text{FIRST}}$ is the integrated flux density of FIRST (Oke & Gunn 1983; Ivezić et al. 2002). We defined QSOs with $R_g > 1$ as RLQs (Kellermann et al. 1989; Ivezić et al. 2002). The QSOs without radio detection and those with radio detection but with $R_g \leq 1$ were both classified as radio-quiet QSOs (RQQs).

2.3. Infrared Data

In order to investigate the dust properties at the infrared band, we searched for the infrared counterpart of the QSOs within the FIRST sky coverage using the data from WISE, which performed an all-sky survey at four different wavebands, W1 (3.4 μm), W2 (4.6 μm), W3 (12 μm), and W4 (22 μm), where W1 and W2 are narrow bands, and W3 and W4 are broad bands (Wright et al. 2010). The infrared counterparts were identified by matching the All-Sky WISE Source Catalog objects within a 2″ radius, which is the pixel scale of the WISE detectors. We found a counterpart in WISE within a 2″ radius search for all SDSS QSOs, except for 22 sources. In the
following analysis, we considered only these WISE-detected sources.

### 3. Results

#### 3.1. Distributions of the rQSOs

Our sample included 22,429 QSOs, of which 5585 were tQSOs with $0.50 < r < 0.54$ ($\approx$25% of the total QSOs) and 2932 were rQSOs with $r \geq 0.66$ ($\approx$13% of the total QSOs). In order to compare the luminosities of different types of QSOs, we chose the luminosity at the rest-frame 4000 Å to represent the luminosity of each source. The luminosity per unit wavelength can be derived from the flux density per unit wavelength (Hogg 1999),

\[ f_\lambda = \frac{1}{1+z} \frac{L_\lambda/(1+z)}{4\pi D_L^2}, \]

where $z$ is the redshift, $L_\lambda/(1+z)$ is the luminosity per unit wavelength at the rest frame, $L_\lambda$ is the luminosity per unit wavelength in the observed frame, and $D_L$ is the luminosity distance. Therefore, we defined the luminosity $L_{4000}$ at the rest frame as

\[ L_{4000} = (1+z) 4\pi (D_L(z))^2 \bar{f}_{4000(1+z)}, \]

where $z$ is the SDSS redshift, $\bar{f}_{4000(1+z)}$ is the mean flux at 4000 $(1+z)$ Å in the observer frame, and $D_L(z)$ is the luminosity distance. The $L_{4000}$ luminosity distribution of these QSOs is shown in Figure 4(a). The luminosity distribution of the tQSOs is similar to that of the whole QSO sample: both peak at log $(L_{4000}) \approx 42.1$. However, the distribution of the rQSOs peaks at log$(L_{4000}) \approx 41.1$. Notably, dust absorption might have led to an underestimation of the luminosity; therefore, if the redness of these QSOs was caused by dust, the QSOs might have lower luminosities.

The luminosity distributions of the radio-loud and the radio-quiet sources within the rQSOs and the tQSOs are shown in Figures 4(b) and (c), respectively. For the tQSOs (Figure 4(b)), the overall luminosity distribution was dominated by radio-quiet tQSOs (hereafter tRQQs). The luminosity distributions of the rQQs and the radio-loud tQSOs (hereafter rRLQs) were similar; the distribution peaks of both were at log$(L_{4000}) \approx 42.1$ and 41.9, respectively. For the rQSOs (Figure 4(c)), the overall luminosity distribution was also dominated by radio-quiet rQSOs (hereafter rRQQs). The distribution peaks for radio-loud rQSOs (hereafter rRLQs) and rRQQs were both at log$(L_{4000}) \approx 41.1$. However, the rRLQs showed a flat distribution, which was different from that of the rRQQs.

We showed the number fractions of the rQSOs and the tQSOs at different luminosities (Figure 5(a) and Table 1) and at different redshifts (Figure 5(b) and Table 2). We found that the rQSOs and the tQSOs had different trends along redshifts and luminosities. The number fractions of the rQSOs decreased with increasing redshifts and luminosities, whereas the number fractions of the tQSOs increased with redshifts and luminosities.

#### Table 1

| Luminosity | $n_{tQSO}$ | $n_{rQSO}$ | $\xi_{tQSO}$ | $n_{tQSO}$ | $\xi_{rQSO}$ |
|-----------|-----------|-----------|------------|-----------|------------|
| $40 < \log L_{4000} < 41$ | 499 | 1218 | 18.9% | 839 | 47% |
| $41 < \log L_{4000} < 42$ | 836 | 2217 | 22.0% | 1636 | 71% |
| $42 < \log L_{4000} < 43$ | 723 | 1544 | 21.3% | 1073 | 69% |
| $43 < \log L_{4000} < 44$ | 699 | 1392 | 20.6% | 1014 | 66% |

#### Table 2

| Redshift | $n_{tQSO}$ | $n_{rQSO}$ | $\xi_{tQSO}$ | $n_{tQSO}$ | $\xi_{rQSO}$ |
|----------|-----------|-----------|------------|-----------|------------|
| $0.3 < z < 0.4$ | 2464 | 365 | 14.92% | 845 | 34.55% |
| $0.4 < z < 0.5$ | 2397 | 426 | 17.77% | 622 | 25.95% |
| $0.5 < z < 0.6$ | 2389 | 479 | 20.05% | 455 | 19.05% |
| $0.6 < z < 0.7$ | 2264 | 548 | 24.20% | 282 | 12.46% |
| $0.7 < z < 0.8$ | 2143 | 594 | 27.72% | 160 | 7.47% |
| $0.8 < z < 0.9$ | 2286 | 636 | 27.82% | 158 | 6.91% |
| $0.9 < z < 1.0$ | 2502 | 700 | 27.98% | 140 | 5.60% |
| $1.0 < z < 1.1$ | 2880 | 841 | 29.20% | 144 | 5.00% |
| $1.1 < z < 1.2$ | 3122 | 996 | 31.90% | 126 | 4.04% |

Note. The symbols are the same as those in Table 1.
We also listed the number fractions of the tRLQs and the rRLQs at different luminosities (Table 3) and at different redshifts (Table 4). The results shows that at all ranges of luminosities and redshifts, the RRLQs had a higher number fraction that is red than those of tRLQs. However, Figure 6 shows that the radio-loud fractions of rRLQs and tRLQs increased with luminosity. Furthermore, rRLQs showed higher radio-loud fractions than tRLQs did. To investigate whether the red color increased with redshifts, although the radio-loud fractions of rRLQs increased with luminosity faster than those of tRLQs. Nevertheless, the radio-loud fractions of RRLQs were higher than those of tRLQs at all redshifts. The radio-loud fractions increased with redshifts at low redshifts (z = 0.3−0.7), but showed almost no change (or slightly decreased) at high redshifts (z = 0.8−1.1). The overall radio-loud fraction of RRLQs (ξ_{rRLQ}(RLQ) = 16.75%) was approximately three times that of tRLQs (ξ_{tRLQ}(RLQ) = 6.27%).

Figure 7 shows the number distribution of rRLQs and tRLQs at different redshifts. We found that the number ratios of rRLQs to tRLQs decreased with increasing redshifts, although the number of tRLQs increased with redshift. In addition, at high redshifts, the rRLQs and the tRLQs seemed to have similar luminosity distribution peaks, yet at the lowest redshifts (z = 0.3−0.4), the rRLQs had a lower luminosity distribution peak than the tRLQs did. To investigate whether the red color was due to dust obscuration, we separated the rRLQs into two different color ranges with 0.66 ≤ r < 0.80 and r ≥ 0.80. We found that at all redshifts, the distributions of these two rRLQ groups were not significantly different from each other, indicating that the rRLQ luminosity is independent of color.

### 3.2. Dust–Luminosity Relation

To investigate the differences in dust properties between rQLs and tQSOs, we compared the dust continuum emission at the rest frame of 10 µm between these two groups. Since our QSO samples were at redshifts between 0.3 and 1.2, the 10 µm continuum emission was redshifted to 13–22 µm. Therefore, we used the $M_{10\,\mu m}$ versus log($L_{4000}$) diagram (Figure 8(a)) to present the dust–luminosity relation for the QSOs, where $M_{10\,\mu m}$ is the absolute magnitude at the rest-frame 10 µm derived from the WISE magnitudes and the SDSS redshifts:

$$M_{10\,\mu m} = m_{10\,\mu m} - (5 \log(D_L) - 5),$$

where $m_{10\,\mu m}$ is the apparent magnitude of the source at 10(1 + z) µm in the observer frame, which can be derived from the interpolation from W3 and W4 magnitudes.

Figure 8(a) shows that $M_{10\,\mu m}$ is proportional to log($L_{4000}$). The fitted lines for the rQSOs and the tQSOs show a small separation. The confidence intervals in Figures 8(a) and (b) are too small to be easily visible, but they are still visible in Figure 8(c). Since the confidence intervals did not overlap between the rQSO and the tQSO fittings, the small separation was highly significant.

To determine whether radio activity is related to dust properties, we also present the relation for RQQs and RLQs in Figures 8(b) and (c), respectively. The results shows that the red samples were more luminous at 10 µm than the typical samples for both RQQs and RLQs. Notably, the infrared magnitude difference between the rRLQs and the tRLQs was substantially larger than the difference between the rRQQs and the tRQQs.

### 4. Discussion and Conclusions

Notably, the red QSOs we selected might be different from the red QSOs selected in previous studies. Most red QSOs in previous studies have been selected by photometric color cuts with spectroscopic follow-ups (Cutri et al. 2001; Glikman et al. 2007, 2012; Georgakakis et al. 2009; Urrutia et al. 2009; Fynbo et al. 2013; Ross et al. 2015). Such selections might include different red QSOs depending on different selection...
The symbols are the same as those in Table 5.

0.3 1.1 0.9 0.8 0.7 0.6

Notes. Since our red QSOs were selected based on the flux ratio of the rest-frame 4000 Å continuum emission, our data excluded sources affected by strong emission lines. In addition, we selected the red QSOs based on the statistical definition. Therefore, we could also include slightly red QSOs, which cannot be found through photometric selection.

Since the SDSS QSOs contained both UVX-pre-selected and FIRST-pre-selected samples (Richards et al. 2002), the color distributions of these two groups of QSOs were expected to be different. The FIRST-pre-selected QSOs were expected to have a wider color distribution than the UVX-pre-selected QSOs, which were expected to be bluer than the FIRST-pre-selected QSOs. To know whether the properties of our selected red QSOs were affected by the selection bias of their FIRST counterparts, we plotted the number distribution for the radio-detected and the radio-undetected QSOs within the FIRST sky coverage (see Figure 9). Both distributions had the appearance of a Gaussian with an extended right tail. We fitted the left wing of the distributions with a Gaussian and folded the result to the right wing. Both distributions had peaks at $r_{\text{peak}} = 0.52$ and $\sigma \approx 0.041$, suggesting that the blue wings were similar for both distributions, indicating that our red QSO criterion was not affected by the FIRST-pre-selection. We could find red QSOs from the extended red tails whether or not the QSOs had FIRST detection.

However, the red wings were different; the red wing for the FIRST-detected QSOs extended farther than that for the FIRST-non-detected QSOs. This result might have been caused by the FIRST-pre-selected QSOs having a wider color distribution and more red QSOs. Notably, the FIRST QSOs were not UVX-pre-selected. In other words, a significant amount of red QSOs might have been missing in the UVX-pre-selected process. These red QSOs were not included in the SDSS catalog because of its photometric pre-selection. Comparing Figures 9(a) and (b), the results suggest that there should be many more red QSOs, which were not found by SDSS because of the photometric pre-selection used in SDSS. In addition, Figure 6(b) shows that the radio-loud fractions of the tQSOs did not change with different redshifts, but that the radio-loud fractions of the rQSOs at low redshifts ($z = 0.3–0.7$) increased with redshift and became almost constant at high redshifts ($z = 0.8–1.1$). Therefore, explaining the trends of the radio-loud fractions at different redshifts with radio selection bias is difficult. The red QSOs at low and high redshifts might have been caused by different types of reddening, or may be the result of selection effects.

Figures 5 and 7 also support this argument. Both figures show that the rQSOs with low luminosities were mainly present at low redshifts, but the rQSOs with high luminosities were mainly present at high redshifts. This could be explained by the fact that at low redshifts, most rQSOs are dust-obscured tQSOs. They become faint at high redshifts and are not detectable. However, the rQSOs at high redshifts with high luminosities might not be dust-obscured tQSOs, but instead might belong to another type of QSO.

**Table 5**

Radio-loud Fractions of tQSOs and rQSOs at Different Luminosities

| Luminosity | \(\xi(\text{RLQ})\) | \(\xi_{\text{tQSO}}(\text{RLQ})\) | \(\xi_{\text{rQSO}}(\text{RLQ})\) |
|------------|-----------------|-----------------|-----------------|
| 40 ≤ \(\log(L_{4000})\) < 41 | 7.02% | 2.75% | 10.21% |
| 41 ≤ \(\log(L_{4000})\) < 42 | 7.78% | 5.99% | 18.63% |
| 42 ≤ \(\log(L_{4000})\) < 43 | 9.13% | 7.02% | 26.02% |
| 43 ≤ \(\log(L_{4000})\) < 44 | 12.90% | 0.00% | 100.00% |
| 40 ≤ \(\log(L_{4000})\) < 44 | 8.15% | 6.27% | 16.75% |

Notes. (1) \(\xi(\text{RLQ}) = n_{\text{RLQ}}/n_{\text{QSO}}\). (2) \(\xi_{\text{QSO}}(\text{RLQ}) = n_{\text{RLQ}}/n_{\text{QSO}}\). (3) \(\xi_{\text{QSO}}(\text{RLQ}) = n_{\text{RLQ}}/n_{\text{QSO}}\).

**Table 6**

Radio-loud Fraction of tQSOs and rQSOs at Different Redshifts

| Redshift | \(\xi(\text{RLQ})\) | \(\xi_{\text{tQSO}}(\text{RLQ})\) | \(\xi_{\text{rQSO}}(\text{RLQ})\) |
|-----------|-----------------|-----------------|-----------------|
| 0.3 ≤ \(z\) < 0.4 | 7.81% | 4.66% | 11.83% |
| 0.4 ≤ \(z\) < 0.5 | 7.63% | 5.40% | 13.34% |
| 0.5 ≤ \(z\) < 0.6 | 8.83% | 7.10% | 17.14% |
| 0.6 ≤ \(z\) < 0.7 | 7.73% | 5.66% | 20.21% |
| 0.7 ≤ \(z\) < 0.8 | 9.19% | 6.90% | 25.62% |
| 0.8 ≤ \(z\) < 0.9 | 8.40% | 7.86% | 25.32% |
| 0.9 ≤ \(z\) < 1.0 | 8.11% | 6.71% | 25.00% |
| 1.0 ≤ \(z\) < 1.1 | 8.72% | 7.13% | 24.31% |
| 1.1 ≤ \(z\) < 1.2 | 7.24% | 4.72% | 17.46% |
| 0.3 ≤ \(z\) < 1.2 | 8.15% | 6.27% | 16.75% |

Note. The symbols are the same as those in Table 5.

Figure 6. (a) Radio-loud fractions of tQSOs (open blue triangles) and rQSOs (open red squares) with different luminosities. The data points at \(\log(L_{4000}) > 43\) can be ignored due to meaningless statistics (small sample size). (b) Radio-loud fractions of tQSOs (open blue triangles) and rQSOs (open red squares) with different redshifts. The symbols are the same as those in the left panel.
To investigate whether the red color can be explained solely through dust obscuration (Cutri et al. 2002; Glikman et al. 2004; Canalizo et al. 2006), we created number distributions at different wavelength (Figure 10), including the luminosity distribution at 6000 Å continuum emission (Figure 10(a)), and the luminosity distribution of [O III]5007 Å (Figure 10(b)). We compared these two distributions with that in Figure 7. If dust obscuration were the main cause for the red color of the QSOs, then absorption would be different at different wavelengths following the dust-extinction curve.

Figure 10(a) shows the $L_{6000}$ luminosity distributions at low redshifts ($z = 0.3–0.6$) because of the limit of the spectrum coverage for high-redshift sources. In Figure 7 and Table 7, the 4000 Å luminosity distribution at $z = 0.3–0.4$ shows that the median for the rQSOs is $\log(L_{6000}) = 40.73$, and that for the tQSOs is $\log(L_{6000}) = 41.03$. The luminosity difference at 4000 Å is $\Delta \log(L_{6000}) = 0.3$, which would cause a luminosity difference at 6000 Å of $\Delta \log(L_{6000}) \approx 0.2$ if the difference were caused by the dust absorption assuming an SMC dust-extinction law (Pei 1992). Figure 10(a) and Table 7 show that the rQSOs and the tQSOs at $z = 0.3–0.4$ had a luminosity difference at 6000 Å of $\Delta \log(L_{6000}) \approx 0.1$. Furthermore, the rQSOs and the tQSOs at $z = 0.4–0.6$ had a luminosity difference at 6000 Å of $\Delta \log(L_{6000}) < 0.1$, indicating that dust absorption was not the only cause of redness.

Figure 10(b) shows the luminosity distribution of the collisionally excited lines [O III]5007 Å at redshifts of $z = 0.3–0.6$. The [O III]5007 Å is the strongest and least blended narrow emission line in the AGN (Baskin & Laor 2005). The luminosity distribution of [O III]5007 Å depends on AGN activity. Table 8 shows the $t$-test results between the rQSOs and the tQSOs at $z = 0.4–0.6$. It shows that the significance values are 0.3–0.6 (i.e., the mean values of these two groups are indistinguishable), indicating that both groups of QSOs at $z = 0.4–0.6$ might show similar AGN activity. However, the $t$-test results at $z = 0.3–0.4$ indicate that the rQSOs and the tQSOs have different AGN activities. The relatively faint luminosity of rQSOs at $z = 0.3–0.4$ (Figure 10(a)) might have been related to absorption, indicating that the redness of the rQSOs cannot be explained solely in terms of dust absorption. Therefore, dust obscuration is not the only cause of the red color of the QSOs.

Figure 8 also supports this argument. From the dust–luminosity relation, we found that the rQSOs had a stronger 10 μm emission than the tQSOs, implying that the rQSOs might have had more hot dust than the tQSOs. Furthermore, the infrared magnitude differences in the RLQs were substantially larger than those in the RQQs. Figure 8(c) shows that for a given absolute magnitude at 10 μm, the magnitude difference between the RLQs and the tRLQs was approximately 0.5 mag, which was larger than the magnitude difference subject to dust obscuration of <0.26 mag (see Section 2.1). In other words, the influence of the assumed dust extinction is not as major a cause as the results suggest.
Moreover, Figure 7 shows that the luminosity peaks between the rQSOs and the tQSOs showed no difference in most redshifts \((z = 0.4–1.1)\), except for the lowest redshifts \((z = 0.3–0.4)\) where they were significantly different. If the rQSOs were tQSOs with dust obscuration, then the rQSOs should have had a lower luminosity than the tQSOs at all redshifts. However, the luminosity distributions do not support the dust obscuration scenario. Furthermore, if a redder color represented more dust absorption, then the two groups of rQSOs (less red color with \(r < 0.66\) and more red color with \(r \geq 0.80\)) in Figure 7 should show different luminosity peaks. However, the result does not show a significant difference between these two red groups: the luminosities of the rQSOs were independent of their colors, which also reveal that most rQSOs in this study were not from dust-obscured sources.

On the other hand, the luminosity distributions of the rQSOs at low redshifts were different from those at high redshifts. At high redshifts \((z = 0.6–1.2)\), the number ratios of rQSOs to tQSOs were small, whereas at low redshifts \((z = 0.3–0.6)\), the number ratios of rQSOs to tQSOs were large. In addition, most rQSOs at low redshifts had relatively lower luminosities than the tQSOs. In other words, the observed rQSOs showed extremely different luminosity distributions at different redshifts, and might have had different origins.

We also investigated whether the redness of the QSOs were caused by type II QSOs in the SDSS QSO samples. Some QSOs in the SDSS QSO catalog might have been from narrow-line sources (Schneider et al. 2010). We plotted the FWHM distribution of the H\(\beta\) \(4863\) Å emission for the rQSOs and the tQSOs (Figure 11), and found that most QSOs were broad-line sources; only a few were narrow-line sources, especially among the rQSOs at low redshifts with low luminosities. Approximately 3.6% of the rQSOs were narrow-line sources, and 0.14% of the tQSOs were narrow-line sources (see Table 9). These sources might have belonged to type II QSOs and been caused by dust absorption, or might be contaminated by the red light of stars in their host galaxies. However, the redness of the broad-line rQSOs might have different origins. These results support the fact that there were at least two types of rQSOs in our red sample.

Notably, the colors of our rQSOs were independent of redshift (Figure 2). Since our rQSOs were selected from the QSO samples with color deviation \(>3\sigma\), the number of rQSOs were \(<0.3\%\) of the QSO samples when the rQSOs followed a normal distribution. However, the fractions of rQSOs in the entire QSO sample at low redshifts (e.g., \(\xi(r\text{QSO}) = 25.95\%–34.55\%\) at \(z = 0.3–0.5\) as shown in Table 2) were...
samples have significantly different means.

The filled light-red histogram represents the rQSOs with flux ratios of 0.5 < \( r < 0.80 \). The filled red histogram represents the rQSOs with flux ratios 0.80. The values of the number, median, and standard deviation for the \( L_{4000} \) and \( L_{[\text{O} \text{III}]5007} \) distributions of the rQSOs and the tQSOs are listed in Table 7. The \( t \)-test results for the \( L_{4000} \) and \( L_{[\text{O} \text{III}]5007} \) distributions between the rQSOs and the tQSOs are listed in Table 8.

### Table 7

| Redshift | 4000 Å | 6000 Å | [O III]5007 Å |
|----------|--------|--------|--------------|
| \( 0.3 \leq z < 0.4 \) | 845 (40.73 ± 0.23) | 365 (41.03 ± 0.28) | 844 (40.69 ± 0.18) | 365 (40.80 ± 0.25) | 832 (42.02 ± 0.39) | 348 (42.21 ± 0.44) |
| \( 0.4 \leq z < 0.5 \) | 621 (41.04 ± 0.20) | 426 (41.23 ± 0.26) | 621 (40.90 ± 0.18) | 425 (40.97 ± 0.23) | 612 (42.38 ± 0.38) | 421 (42.39 ± 0.32) |
| \( 0.5 \leq z < 0.6 \) | 455 (41.26 ± 0.22) | 476 (41.42 ± 0.26) | 113 (41.00 ± 0.17) | 83 (41.07 ± 0.26) | 447 (42.63 ± 0.40) | 466 (42.61 ± 0.32) |
| \( 0.6 \leq z < 0.7 \) | 282 (41.48 ± 0.21) | 548 (41.59 ± 0.24) | 3 (41.39 ± 0.29) | 1 (41.61 ± 0.00) | 280 (42.79 ± 0.40) | 532 (42.78 ± 0.33) |
| \( 0.7 \leq z < 0.8 \) | 160 (41.71 ± 0.23) | 594 (41.78 ± 0.24) | 1 (41.81 ± 0.00) | - | 156 (43.04 ± 0.36) | 585 (43.00 ± 0.35) |
| \( 0.8 \leq z < 0.9 \) | 158 (41.85 ± 0.20) | 636 (41.89 ± 0.22) | - | - | 51 (43.27 ± 0.40) | 161 (43.20 ± 0.31) |
| \( 0.9 \leq z < 1.0 \) | 140 (42.02 ± 0.20) | 700 (42.00 ± 0.23) | - | - | - | - |
| \( 1.0 \leq z < 1.1 \) | 144 (42.14 ± 0.19) | 841 (42.09 ± 0.22) | - | - | - | 1 (43.43 ± 0.00) |
| \( 1.1 \leq z < 1.2 \) | 126 (42.25 ± 0.20) | 996 (42.18 ± 0.21) | - | - | - | - |

**Notes.** (1) The integer value is the number of different types of QSOs within the corresponding redshift range. (2) The values inside the parentheses are the median and the standard deviation of the logarithmic scale luminosity in different types of QSOs within the corresponding redshift range. (3) The unit of luminosity for both 4000 and 6000 Å is erg s\(^{-1}\) Å\(^{-1}\), and that for [O III]5007 Å is erg s\(^{-1}\). (4) The symbol "-" means there is no QSO found. (5) The standard deviation of ±0.00 means there is only one QSO found.

### Table 8

| Redshift | \( t \) | \( \) |
|----------|--------|--------|
| \( 0.3 \leq z < 0.4 \) | -7.9907 | 0.0000 |
| \( 0.4 \leq z < 0.5 \) | 0.5531 | 0.5803 |
| \( 0.5 \leq z < 0.6 \) | 0.9368 | 0.3491 |

**Notes.** (1) \( t \) is the \( t \)-test statistic. (2) \( \) is the significance. The significance is a value in the interval [0.0, 1.0]. A small value (\( \) < 0.01) indicates that the two samples have significantly different means.

The Astrophysical Journal, 842:57 (11pp), 2017 June 10  
Tsai & Hwang

The integer value is the number of different types of QSOs within the corresponding redshift range. The symbol "-" means there is no QSO found. The standard deviation of ±0.00 means there is only one QSO found.
The blue solid line represents the tQSOs with
emission line obtained from the SDSS database. The blue solid line represents the tQSOs with
range. The blue solid line represents the tQSOs with
emission line obtained from the SDSS database. The blue solid line represents the tQSOs with
range. The blue solid line represents the tQSOs with
emission line obtained from the SDSS database. The blue solid line represents the tQSOs with
range.

Figure 11. Number distributions of different types of QSOs vs. log(FWHM_{H\beta 4863}) at 0.3 < z < 0.9. Log(FWHM_{H\beta 4863}) is the Gaussian-fit FWHM of the H\beta
emission line obtained from the SDSS database. The blue solid line represents the tQSOs with
flux ratios of 0.50 < r < 0.54. The red solid line represents the rQSOs with
flux ratios >0.66. The filled light-red histogram represents the rQSOs with flux ratios of 0.66 < r < 0.80. The filled red histogram represents the rQSOs with
flux ratios >0.80. The dotted line represents the H\beta FWHM of 1000 km s\(^{-1}\). The number of QSOs with H\beta FWHM < 1000 km s\(^{-1}\) is listed in Table 9.

Table 9

| Redshift | QSOs | rQSOs | tQSOs |
|----------|------|-------|-------|
| 0.3 < z < 0.4 | 77 (3.15%) | 50 (5.92%) | 3 (0.82%) |
| 0.4 < z < 0.5 | 24 (1.00%) | 22 (3.54%) | 0 (0.00%) |
| 0.5 < z < 0.6 | 14 (0.59%) | 11 (2.43%) | 1 (0.21%) |
| 0.6 < z < 0.7 | 5 (0.22%) | 3 (1.07%) | 0 (0.00%) |
| 0.7 < z < 0.8 | 3 (0.14%) | 2 (1.25%) | 0 (0.00%) |
| 0.8 < z < 0.9 | 2 (0.11%) | 2 (1.64%) | 0 (0.00%) |
| 0.9 < z < 1.0 | 0 (0.00%) | 0 (0.00%) | 0 (0.00%) |
| 1.0 < z < 1.1 | 0 (0.00%) | 0 (0.00%) | 0 (0.00%) |
| 1.1 < z < 1.2 | 0 (0.00%) | 0 (0.00%) | 0 (0.00%) |
| 0.3 < z < 1.2 | 125 (0.93%) | 90 (3.63%) | 4 (0.14%) |

Notes. (1) The integer value is the number of different types of QSOs within the corresponding redshift range. (2) The value inside the parentheses is the
number fraction of different types of QSOs within the corresponding redshift range.

faint red QSOs, which have lower luminosities than tQSOs at
the same redshifts. Here the red color could be related to dust
obscuration. Notably, these faint red QSOs can easily be
detected at low redshifts, whereas at high redshifts they cannot
be detected because of the detection limit.

We are appreciative of Anthony Moraghan for English
corrections. We also thank the anonymous referee for very
useful comments.

This work is supported by the Ministry of Science and
Technology (MOST) of Taiwan, MOST 103-2119-M-008-
017-MY3.

This publication makes use of data products from the Wide-
field Infrared Survey Explorer, which is a joint project of the
University of California, Los Angeles, and the Jet Propulsion
Laboratory/California Institute of Technology, funded by the
National Aeronautics and Space Administration.

Funding for SDSS-III has been provided by the Alfred P.
Sloan Foundation, the Participating Institutions, the National
Science Foundation, and the U.S. Department of Energy Office
of Science. The SDSS-III web site is http://www.sdss3.org/.

SDSS-III is managed by the Astrophysical Research
Consortium for the Participating Institutions of the SDSS-III
Collaboration including the University of Arizona, the
Brazilian Participation Group, Brookhaven National Labora-
tory, Carnegie Mellon University, University of Florida, the
French Participation Group, the German Participation Group,
Harvard University, the Instituto de Astrofisica de Canarias,
the Michigan State/Notre Dame/JINA Participation Group,
Johns Hopkins University, Lawrence Berkeley National Labora-
tory, Max Planck Institute for Astrophysics, Max Planck Institute
for Extraterrestrial Physics, New Mexico State University,
New York University, Ohio State University, Pennsylvania State
University, University of Portsmouth, Princeton University, the
Spanish Participation Group, University of Tokyo, University of
Utah, Vanderbilt University, University of Virginia,
University of Washington, and Yale University.

References

Banerji, M., McMahon, R. G., Hewett, P. C., Gonzalez-Solares, E., &
Koposov, S. E. 2013, MNRAS, 429, L55
Baskin, A., & Luor, A. 2005, MNRAS, 358, 1043
Becker, R. H., Gregg, M. D., Hook, I. M., et al. 1997, ApJL, 479, L93
Canalizo, G., Stockton, A., Brotherton, M. S., et al. 2006, NewAR, 50, 650
Cutri, R. M., Nelson, B. O., Francis, P. J., & Smith, P. S. 2002, in ASP Conf. Ser.
284, AGN Surveys, ed. R. F. Green et al. (San Francisco, CA: ASP), 127
Cutri, R. M., Nelson, B. O., Kirkpatrick, J. D., Huchra, J. P., & Smith, P. S.
2001, in ASP Conf. Ser. 232, The New Era of Wide Field Astronomy, ed.
R. Clowes, A. Adamson, & G. Bromage (San Francisco, CA: ASP), 78
Fynbo, J. P. U., Krogager, J.-K., Venemans, B., et al. 2013, ApJS, 204, 6
Georgakakis, A., Clements, D. L., Bendo, G., et al. 2009, MNRAS, 394, 533

10
