INFRARED IMAGING OF SLOAN DIGITAL SKY SURVEY QUASARS: IMPLICATIONS FOR THE QUasar $K$ CORRECTION

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Received 2007 July 6; accepted 2008 August 12; published 2008 September 26

ABSTRACT

We have imaged 45 quasars from the Sloan Digital Sky Survey (SDSS) with redshifts $1.85 < z < 4.26$ in $JHK_s$, with the Kitt Peak National Observatory simultaneous quad infrared imaging device imager. By combining these data with optical magnitudes from the SDSS we have computed the rest-frame optical spectral indices of this sample and investigate their relation with quasar redshift. We find a mean spectral index of $\langle \alpha_o \rangle = -0.55 \pm 0.42$ with a large spread in values. We also find possible evolution of the form $\alpha_o = (0.148 \pm 0.068)z - (0.964 \pm 0.200)$ in the luminosity range $-28.0 < M_B < -26.5$. Such evolution suggests changes in the accretion process in quasars with time and is shown to have an effect on computed quasar luminosity functions.

Key words: galaxies: active – galaxies: evolution – quasars: general

Online-only material: color figures

1. INTRODUCTION

The recent publication of large samples of quasars from the Sloan Digital Sky Survey (SDSS; Schneider et al. 2007) and the Two Degree Field QSO Redshift Survey (2QZ; Croom et al. 2004) allows the study of the evolution of the quasar population spanning long lookback times with large, homogenous catalogs of objects and the characterization of the quasar luminosity function (QLF). The Richards et al. (2006a) QLF formed from the SDSS Third Data Release Quasar Catalog (DR3QLF) is defined from 15,343 quasars over 1622 deg$^2$, spanning redshifts from $z = 0$ to 5 and reaching luminosities down to $M_i < -23$ in their lowest redshift bins. They find a peak in type 1 quasar activity between $z = 2.2$ and 2.8 and a general flattening of the slope of the bright-end QLF with increasing redshift. Hopkins et al. (2007) compute a bolometric QLF, combining many quasar surveys, including the DR3QLF and the 2QZ. They find a peak in the quasar luminosity density at $z = 2.15$ and an evolving QLF bright-end slope that becomes flatter at redshifts $z > 3$.

One major difficulty in characterizing the evolution in quasar space densities is finding an appropriate way to calculate the absolute magnitudes of a survey sample and compare these magnitudes with other surveys, or even to objects within the same survey if it spans a large redshift range, i.e., how to calculate the appropriate $K$ correction. Traditionally, absolute magnitudes were corrected back to the rest-frame $B$ band (Schmidt & Green 1983; Boyle et al. 1987), as most early surveys for quasars included the measurement of flux around 4400 Å, by assuming a power-law form for quasar spectra redward of Ly$\alpha$ of the form $f_\nu \propto \nu^{-\alpha}$ and assuming an average spectral index, $\alpha$, for the survey sample. As surveys move to higher redshifts, beyond $z = 3$, the observed $B$ band ceases to sample the quasar continuum effectively, as the Ly$\alpha$ line moves into and redward of that filter. In the recent past, research groups have adopted several methods for computing absolute magnitudes and have referenced their magnitudes to different rest-frame wavelengths. For instance, Schmidt et al. (1995) and Kennefick et al. (1995) adopt an average spectral index of $\alpha = -0.5$ in their computations of $M_B$, while Warren et al. (1994) avoid the adoption of a spectral index by computing the QLF as a function of $M_C(1215)$, the flux in the continuum under the Ly$\alpha$ line, from their direct measurements of the flux at that point in their survey spectra. More recently, Croom et al. (2004) present their QLF from the 2QZ at $0.4 < z < 2.1$ in terms of $M_B$, and Richards et al. (2006a) assume an average spectral index, but correct $i$-band magnitudes to $z = 2$. The correction to $z = 2$ is prompted by the desire to minimize the effects of extrapolating the assumed quasar power law over large wavelengths, as suggested by Wisotzki (2000).

Such differences in the methods for computing absolute magnitudes has led to some discrepancies in computed quasar space densities in past surveys (Kennefick et al. 1997). The initial goals of this near-infrared (NIR) imaging program were to measure the rest-frame $B$-band flux for a set of quasars in several redshift ranges, to compare the differences in the absolute magnitudes ($M_B$) as computed from extrapolations of flux values at lower wavelengths to flux values measured directly, and to see how this changed with redshift. This is equivalent to measuring the rest-frame optical spectral index of the quasars from optical and NIR photometry. In this paper, we report the initial results of a program to measure the rest-frame optical spectral index, $\alpha_o$, of a subset of SDSS quasars at $1.85 < z < 4.26$ using their reported optical magnitudes and NIR photometry obtained at the Kitt Peak National Observatory (KPNO) 2.1 m telescope using the simultaneous quad infrared imaging device (SQIID). In Section 2 we present the program design. The data used in the project, both archived and new observations, are described in Section 3. In Section 4 we give the program results, including computations of spectral indices and the implications for the resulting absolute magnitudes. We discuss our results further in Section 5.

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The initial goal of this observing program was to measure the rest-frame B-band flux for a sample of quasars at a range of redshifts in order to essentially bypass the need to extrapolate a power law over large wavelength ranges when applying a K correction in the computation of quasar absolute magnitudes, \(M_B\).

The central wavelength of the \(J\) band is 1.27 \(\mu\)m, which corresponds to the rest-frame \(B\) band (central wavelength of 4400 Å) at \(z = 1.88\). Likewise, \(H\) band corresponds to the rest-frame \(B\) band at \(z = 2.80\), and \(K_s\) band at \(z = 4.06\). Figure 1 shows the NIR \(JHK_s\) filter curves, along with the “redshifted” Johnson \(B\) band at these redshifts, that is, the portion of the spectrum measured to sample the rest-frame \(B\) band at the given redshift.

For this project, we targeted 45 quasars chosen from the SDSS quasar catalogs for NIR imaging centered around the above redshift ranges. We combine this NIR photometry with reported optical magnitudes to compute rest-frame optical spectral indices for the sample. Programmatically, this can be achieved by fitting the photometric data to measure the slope of the spectral energy distribution, \(\alpha\), as discussed further below.

Richards et al. (2006a) has reported the DR3QLF computed from SDSS quasars as a function of \(M_i\) corrected to a redshift of \(z = 2\), and the selection of the \(B\) band for computations of the QLF has become less common as quasar surveys move to higher redshift. Here, we compute the optical spectral index, \(\alpha_o\), for a subset of the SDSS quasars using optical and NIR photometry. We then explore possible correlations of \(\alpha_o\) with redshift or luminosity and how that might affect the characterization of the QLF and its evolution.

3. OBSERVATIONS AND DATA REDUCTIONS

3.1. SQIID Near-Infrared Imaging

Forty-five quasars from the SDSS Third Data Release Quasar Catalog (DR3Q; Schneider et al. 2005) were imaged with SQIID on the KPNO 2.1 m telescope during 2005 March 22–23. The SQIID infrared camera uses individual 512 × 512 pixel quadrants of ALADDIN InSb arrays, with a pixel scale of 0.69 pixel^{-1} at the KPNO 2.1 m. The effective field of view is 304" × 317".

The observing strategy involved imaging each target quasar for a total of 600 s, with five pointings of 120 s, each the sum of fifteen 8 s coadds, offset by roughly 45" between pointings to improve background subtraction. Conditions were nonphotometric, with light cirrus over the course of the run. Seeing ranged from 1.3 to 1.9 over two nights of the observing run.

The images were processed using the IRAF\(^5\) package. Dark frames were acquired for each combination of coadd and exposure time utilized during the run. A global flat field for each night and each filter was constructed from the object frames using the USQFLAT routine, configured to subtract the dark current and then to perform a median combine of the frames. Image processing was performed using the MOVCORE routine to generate and subtract a moving sky image created from the six frames obtained closest to the object frame in time and to correct for pixel-to-pixel sensitivity differences by dividing by the appropriate flat field. The final image of each quasar in each band was constructed by registering the five pointings using the USQMOS routines and combining the frames using the NIRCOMBINE routine.

Object detection and measurement was carried out using the Source Extractor\(^7\) software. The observations were made under fair but nonphotometric conditions. Calibration was performed through the use of stellar Two Micron All Sky Survey (2MASS; Cutri et al. 2003) sources in the object frames. The 2MASS images and catalogs were accessed through the National Virtual Observatory\(^8\) (NVO) Open SkyQuery and DataScope Query tools and manipulated using the Aladdin multiview tool (Bonnarels et al. 2000). The \(JHK_s\) magnitudes reported in Table 1 and used in the following analysis were derived from the flux inside circular apertures of radius 3.5. The photometric zero points for the frames were calculated using stellar 2MASS sources in the frame of the quasar with measured \(JHK_s\) aperture magnitudes. Typically five to seven calibration stars were used with magnitudes ranging from 14 to 16 in \(J\) and \(H\), and from 14 to 15 in \(K_s\). The 2MASS aperture magnitudes were measured in a 4" radius and “curve-of-growth” corrected out to an “infinite” aperture.\(^9\) Therefore, the magnitudes given in Table 1 are effectively aperture corrected by using these corrected 2MASS sources as standards. NIR magnitudes, uncorrected for Galactic extinction, for the quasars are given in Table 1 and Figure 2, along with their associated errors, which include both measured photometric errors for the quasars and the errors introduced by the calibration process. The quasars in the subsample observed with SQIID are 1–2 magnitudes fainter than the SDSS quasars detected by 2MASS. The relatively few number of quasars in the highest redshift bin (∼4.06) meant that we had to choose fainter objects over a slightly wider redshift range than in the two lower redshift bins.

\(^5\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^6\) http://www.noao.edu/kpno/sqid/

\(^7\) http://terapix.iap.fr/

\(^8\) http://www.us-vo.org/

\(^9\) http://www.ipac.caltech.edu/2mass/releases/allsky/doc/
3.2. The SDSS Third Data Release Quasar Catalog

The SDSS uses a multicolor technique to select quasar candidates in the optical $ugriz$ bands over the redshift range $0.08 < z < 5.41$. The DR3 contains 46,420 quasars with luminosities $M_i > -22$. Initially, we chose 60 quasars from the SDSS Early Data Release (EDR) quasar catalog (Schneider et al. 2002) for NIR imaging. Quasars were selected from the EDR catalog randomly from those objects with R.A.s close to the local sidereal time during the observations. All of the imaged quasars are contained in the SDSS DR3 catalog, and the optical photometry reported in Table 1 and used in the data analysis were taken from this later catalog.

The SDSS DR3 has been matched to the 2MASS All-Sky Data Release Point Source Catalog (Cutri et al. 2003) and the 2MASS $JHK_s$ magnitudes and errors are reported for those SDSS quasars with 2MASS detections (Columns 25–30 of the DR3Q). We have used the 6192 quasars with 2MASS detections as a bright comparison sample to our fainter (1 mag to 1.5 mag) SQUIID sample (Figures 2 and 3).

![Table 1: SQUIID Sample Quasar NIR Photometry](image_url)
4. RESULTS

4.1. Colors

The magnitudes were corrected for Galactic extinction using the value of $A_u$ for each object reported in the SDSS DR3Q catalog. Column 15 (Schneider et al. 2005). These values were taken from the maps of Schlegel et al. (1998) which assume an extinction-to-reddening ratio $RV = 3.1$. Extinctions in the Sloan griz bands are then 0.736, 0.534, 0.405, and 0.287 times $A_u$, respectively. The value of $A/E(B-V)$ for the Sloan $u$ band is 5.155; consulting Schlegel et al. (1998) for the UKIRT $JHK$ values gives 0.902, 0.576, and 0.367, respectively. This gives values for the extinction in these bands of $AJ = 0.175A_u$, $AH = 0.112A_u$, and $AK = 0.071A_u$. Colors computed from these extinction-corrected magnitudes for the SQIID sample and the SDSS quasars detected by 2MASS are shown in Figure 3. The SQIID sample spans the same range in quasar colors as do the 2MASS-detected quasars.

Also shown in Figure 3 are expected colors for quasars computed using synthetic quasar spectra generated with power-law spectral indices and averaged over several different realizations of the Lyα forest. The colors were computed by passing the quasar spectra through SDSS and SQIID filters and calibrated with a comparison Vega spectrum from the Space Telescope Science Institute CALSPEC10 site. The ugriz Vega-based magnitudes were then converted to the SDSS AB system using the formula for the AB magnitude (Oke & Gunn 1983)

$$AB = -2.5 \log_{10} f_\nu - 48.6,$$

in the following form:

$$AB = -2.5 \alpha_o \log_{10} \nu - 48.6,$$

4.2. Optical Spectral Indices

In order to compute the rest-frame optical continuum slopes of the quasar spectral energy distributions, we have converted our NIR, Vega-based photometry to the AB system. To accomplish this, we first constructed an NIR spectrum for Vega based on the absolute flux calibrations for Vega reported by Mégevand (1995) (see their Table 4), constraining the blue end to have $f_\nu = 2446$ Jy at $\lambda = 9000 \text{ Å}$, as given in their formula for the blackbody fit to Vega (see their page 776). We then compared the flux from this spectrum with a flat source with $f_\nu = 3631$ Jy, the zero point of the AB system (Oke & Gunn 1983), for each 2MASS and SQIID $JHK_s$ filter. The offsets for the 2MASS filter set are: $J_{AB} = J + 0.84$, $H_{AB} = H + 1.33$, and $K_{AB} = K_s + 1.79$. For the SQIID filter set they are: $J_{AB} = J + 0.88$, $H_{AB} = H + 1.35$, and $K_{AB} = K_s + 1.75$.

If we assume that the optical flux for a quasar is given by $f_\nu = \nu^{\alpha_o}$, then we can rewrite the formula for the AB magnitude (Oke & Gunn 1983)

$$AB = -2.5 \log_{10} f_\nu - 48.6$$

as

$$AB = -2.5 \alpha_o \log_{10} \nu - 48.6,$$

Holberg & Bergeron (2006). The dotted line in Figure 3 represents quasars with $\alpha = -0.5$. While the quasar colors do cluster around this line, the colors span a considerable range, larger than the errors in their colors. This is consistent with results found by Pentericci et al. (2003), who found a similar spread in optical/NIR colors in a sample of 45 SDSS quasars at $3.6 < z < 5.03$. 

10 http://www.stsci.edu/hst/cdbs/calspec.html

Figure 2. SQIID $JHK_s$ magnitudes for the subsample of SDSS quasars given in Table 1 (blue triangles) along with their associated errors. Also shown are the $JHK_s$ magnitudes of the 6192 quasars from the SDSS Third Data Release Quasar Catalog with measurable 2MASS detections (black dots). The SQIID data reach about 1 mag to 2 mag fainter than the 2MASS data.

(A color version of this figure is available in the online journal.)

Figure 3. SDSS optical and SQIID $JHK_s$ colors for the subsample of SDSS quasars observed with SQIID given in Table 1 (blue triangles) along with their associated errors. Also shown are the colors of the 6192 quasars from the SDSS Third Data Release Quasar Catalog with measurable 2MASS detections (black dots). The dashed line shows the expected colors of quasars with spectral indices of $\alpha = -0.5$, including emission lines and Lyα forest continuum depression.

(A color version of this figure is available in the online journal.)
allowing us to compute $\alpha_o$ as the slope of a fit to straight line in AB magnitude versus log $v$. This was accomplished by using the Numerical Recipes routine FIT (Press et al. 1992). Spectral indices for each quasar observed with SQUIID are given in Table 2. The mean spectral index for the sample is $(\alpha_o) = -0.55 \pm 0.42$. However, there appears to be a change in the mean slope with redshift in the SQUIID sample, with quasars at lower redshifts having a steeper slope. In Figure 4, AB magnitudes transformed to the quasar rest-frame and normalized to 20.0 in the bluest band completely redward of Ly$\alpha$ are given along with a line showing the mean slope for that redshift range. The mean spectral index for each of the redshift bins is: $(\alpha_o)_{1.88} = -0.71 \pm 0.43$, $(\alpha_o)_{2.82} = -0.49 \pm 0.40$, $(\alpha_o)_{4.03} = -0.40 \pm 0.39$ (see also Table 3). These spectral indices were calculated using all available passbands. For consistency, if we only use those passbands available in all three redshift bins (from rest-frame $\sim 1500$ Å out to $\sim 4500$ Å), the computed spectral indices change very little, with means of: $(\alpha_o)_{1.88} = -0.68$, $(\alpha_o)_{2.82} = -0.50$, $(\alpha_o)_{4.03} = -0.40$.

### 4.3. $K$ Corrections and Absolute Magnitudes

In order to compute a luminosity function for quasars, the absolute magnitude of each discovered object must be calculated. This can be a bolometric luminosity, the luminosity at a point in the continuum, or the flux in a passband. However, since the spectra of quasars are redshifted and even an individual survey can span a large range in redshift, the calculation must include a conversion from an observed band to an emitted band. This conversion from observed flux to rest-frame flux is referred to as the $K$ correction (Humason et al. 1956), defined as the “technical effect that occurs when a continuous energy distribution $F(\lambda)$ is redshifted through fixed spectral-response bands of a detector” (Oke & Sandage 1968 p. 22). If the spectral energy distribution (SED) is not flat, this will include both the effect of detecting light from a region of the emitted spectrum shifted from the effective wavelength of the detector and the effective squeezing of the detector bandpass in the emitted frame.

Following the formalism of Hogg et al. (2002), the $K$ correction is defined as

$$M_{\text{emitted}} = m_{\text{observed}} - DM - K(z),$$

where DM is the distance modulus, given as

$$DM = 5 \log_{10} \left[ \frac{D_L}{10 \text{pc}} \right].$$

$K(z)$ is the $K$ correction, which depends on the SED of the observed object (see Hogg et al. 2002, Equation 8), and $D_L$ is the luminosity distance. Following Hogg (2000) and assuming $\Omega_M + \Omega_\Lambda = 1$, the luminosity distance is given by

$$d_L(z; \Omega_M, \Omega_\Lambda, H_0) = \frac{c(1+z)}{H_0} \int_0^z \left[ (1+z')^2(1+\Omega_M z') - z'(2+z')\Omega_\Lambda \right]^{-1/2} dz'.$$

We assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ throughout (Spergel et al. 2007).

For a power-law SED of the form $f_\nu \propto \nu^\alpha$ we can write

$$K(z) = -2.5 \alpha \log(1+z) - 2.5 \log(1+z),$$

where the first term transforms from the emitted band to the observed band at $z = 0$ and the second term corrects for the effective narrowing of the passband when observing redshifted objects. Quasar spectra also contain various broad emission lines, and their contribution to the $K$ correction will be addressed below.

Table 2 (Column 4) lists the absolute magnitude, $M_{i(z=0)}$, for each quasar as reported in the SDSS DR3Q catalog. These values were computed by correcting the SDSS $i$ magnitudes for Galactic extinction, assuming $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, and applying a standard continuum correction by assuming a spectral index of $\alpha = -0.5$ and correcting to $z = 0$.

The DR3QLF is computed as a function of $M_i$, but $K$ corrected to $z = 2$, near the peak in the quasar distribution. They also correct for emission lines by convolving a composite spectrum created from 16,713 SDSS quasars with the continuum subtracted with the SDSS filters. Their values are reported in Table 2 (Column 5) as $M_{i(z=2)}$. They compute a combined $K$ correction, assuming a spectral index of $\alpha = -0.5$ (see their Table 4), which we will refer to here as $K_2$. We adopt the Richards et al. (2006a) methodology but employ the spectral index computed for our SQUIID subsample in computing the $M_i$.

This gives an expression for $K(z)$:

$$K(z) = K_2 - 2.5(\alpha_o - \alpha_{\text{fix}}) \log_{10}(1+z),$$

where $\alpha_{\text{fix}} = -0.5$. Therefore, $M_{i(\alpha_o)}$ is given as

$$M_{i(\alpha_o)} = m_i - 5 \log_{10} \left[ \frac{D_L}{10 \text{pc}} \right] - K_2 + 2.5(\alpha_o + 0.5) \log_{10}(1+z).$$

The values of $\alpha_o$ and $M_{i(\alpha_o)}$ for the SQUIID sample are listed in Table 2 (Columns 6 and 8), and the $M_{i(\alpha_o)}$ are plotted versus redshift in Figure 5. Because our imaged $z \sim 4$ quasars are fainter than those in the two lower redshift ranges, the program samples quasars of similar luminosity at all three redshifts, unlike the 2MASS crossmatches, which have a distinct dependence of luminosity on redshift, as would be expected for a flux-limited survey.

### 4.4. Correlations

In order to investigate possible correlations of $\alpha_o$ with redshift or luminosity, we used the Astronomy SURVival Analysis tools (ASURV; LaValley et al. 1992), accessed through the IRAF STSDAS package. Linear regressions were performed using both the EM (estimate and maximize; Dempster et al. 1977) and the Buckley–James (Buckley & James 1979) algorithms resulting in the following expressions for $\alpha_o$ in terms of $z$ and $M_{i(\alpha_o)}$:

$$\alpha_o(z) = (0.148 \pm 0.068)z - (0.964 \pm 0.200),$$

$$\alpha_o(M_{i(\alpha_o)}) = (0.168 \pm 0.083)M_{i(\alpha_o)} + (4.084 \pm 2.305),$$

$$\alpha_o(z, M_{i(\alpha_o)}) = (0.249 \pm 0.065)z + (0.295 \pm 0.080)M_{i(\alpha_o)} + (6.891 \pm 2.137).$$

The expressions for $\alpha_o(z)$ and $\alpha_o(M_{i(\alpha_o)})$ are plotted along with the data in Figure 6. We have also computed the generalized Kendall’s tau correlation coefficient between these variables using the BHK method (LaValley et al. 1992). For the
\[ \varepsilon \] and \( z \) relation, we find \( \tau = 0.40 \) with a 95% probability of a correlation. For \( \varepsilon \) and \( M_{i(z)} \), we find \( \tau = 0.30 \) with an 85% probability of a correlation. We note, however, that the SQIID sample was not chosen to sample a broad range of absolute magnitude. Instead fainter sources were necessarily chosen at higher redshifts because fewer bright quasars are present at these very high redshifts in the SDSS sample due to the relatively fewer number of quasars at these epochs. We have also included an expression for \( \varepsilon(z, M_{i(z)}) \) and show the projections of the residuals of this fit along with the residuals from the expressions for \( \varepsilon(z) \) and \( \varepsilon(M_{i(z)}) \) in Figure 7. The residuals in the two-dimensional expressions (top panels) are similar to those for the three-dimensional expression (lower panels).

The distributions of the spectral indices for the SQIID and 2MASS-detected samples are shown in Figure 8 (left panel). Also shown are the separate distributions of the SQIID subsamples at \( z \approx 1.88, 2.82, \) and 4.03 (right panel). The \( \varepsilon \) distribution of the 2MASS-detected SDSS quasars were computed using the

### Table 2

SQIID Sample Spectral Indices

| SDSS DR3 Designation (1) | Redshift (2) | \( \varepsilon \) (3) | \( M_{i(z=0)} \) (4) | \( M_{i(z=2)} \) (5) | \( \varepsilon(z) \) (6) | \( \sigma_{\varepsilon(z)} \) (7) | \( M_{i(z=2)} \) (8) |
|-------------------------|-------------|----------------|------------------|----------------|----------------|----------------|----------------|
| SDSS 095048.48−000177.7 | 1.8802      | 0.298          | −25.777          | −26.068        | −1.77          | 0.12           | −27.527        |
| SDSS 095908.28−003508.0 | 1.8753      | 0.183          | −26.694          | −26.983        | −0.34          | 0.09           | −26.798        |
| SDSS 101119.94−004145.3 | 1.8879      | 0.234          | −26.225          | −26.519        | −0.88          | 0.07           | −26.952        |
| SDSS 102517.58+003422.0 | 1.8879      | 0.257          | −27.241          | −27.535        | −0.28          | 0.05           | −27.281        |
| SDSS 103204.74−011191.1 | 1.8715      | 0.330          | −26.651          | −26.940        | −0.39          | 0.07           | −26.808        |
| SDSS 103427.57−002233.9 | 1.8698      | 0.375          | −26.205          | −26.493        | −0.59          | 0.10           | −26.596        |
| SDSS 110725.70+003353.8 | 1.8732      | 0.181          | −26.702          | −26.990        | −0.61          | 0.07           | −27.111        |
| SDSS 115153.38+003826.9 | 1.8805      | 0.114          | −27.672          | −27.963        | −0.45          | 0.04           | −27.902        |
| SDSS 121655.39+001415.3 | 1.8706      | 0.130          | −27.026          | −27.315        | −0.21          | 0.06           | −26.985        |
| SDSS 123505.91−003022.3 | 1.8804      | 0.121          | −26.684          | −26.975        | −0.49          | 0.05           | −26.967        |
| SDSS 123514.94+004740.7 | 1.8747      | 0.126          | −26.263          | −26.552        | −0.90          | 0.08           | −27.007        |
| SDSS 123947.60+002516.2 | 1.8483      | 0.087          | −25.629          | −25.912        | −1.62          | 0.14           | −27.185        |
| SDSS 132742.92+003532.6 | 1.8736      | 0.134          | −26.928          | −27.216        | −0.90          | 0.05           | −27.677        |
| SDSS 135605.41−010024.4 | 1.8860      | 0.264          | −26.521          | −26.815        | −0.75          | 0.06           | −27.098        |
| SDSS 141015.36−001418.9 | 1.8758      | 0.222          | −26.630          | −26.920        | −0.87          | 0.07           | −27.343        |
| SDSS 143614.24+001558.9 | 1.8659      | 0.208          | −26.884          | −27.171        | −0.67          | 0.06           | −27.365        |
| SDSS 145838.04+004217.9 | 1.8847      | 0.251          | −26.806          | −27.098        | −0.40          | 0.06           | −26.987        |

Notes: The redshift and galactic extinction data are taken from the SDSS DR3Q (Schneider et al. 2005).

a Absolute \( M_i \) from SDSS DR3Q, Column 32, \( K \) corrected to \( z = 0 \).

b Absolute \( M_i \) from Richards et al. (2006a) who \( K \) correct to \( z = 2 \).

c Absolute \( M_i \) computed using values from Richards et al. (2006a) who \( K \) correct to \( z = 2 \), but using the spectral index, \( \varepsilon(z) \), in Column (6).
**Figure 4.** AB magnitude vs. rest-frame wavelength for the SQIID sample. The $JHK$ magnitudes have been converted to the AB system (see text; the SDSS magnitudes are based on the AB system), and all magnitudes shifted to the rest-frame of the quasar. The magnitudes are also normalized to 20.0 in the bluest band completely redward of Ly$\alpha$, for the $\langle z \rangle = 1.88$ sample, $r$ for the $\langle z \rangle = 2.82$ sample, and $i$ for the $\langle z \rangle = 4.03$ sample. A power law is fit to each unnormalized quasar SED separately and given in Table 2. The broken lines show the SED of a power-law spectrum with a mean $\alpha_o$ for the sample.

Table 3
Sample Spectral Index Statistics

| Quasar Sample         | $N$ | $\langle z \rangle$ | $\langle M_{i(\alpha_o)} \rangle$ | $\alpha_o$ |
|-----------------------|-----|---------------------|-----------------------------------|-------------|
|                       |     |                     | Median               | Mean      | $\sigma$ |
| SDSS w/SQIID           | 45  | 2.81                | $-27.61$             | $-0.47$   | $-0.55$  | 0.42 |
| “J” subsample          | 17  | 1.88                | $-27.15$             | $-0.61$   | $-0.71$  | 0.43 |
| “H” subsample          | 15  | 2.82                | $-27.89$             | $-0.37$   | $-0.49$  | 0.40 |
| “K” subsample          | 13  | 4.03                | $-27.87$             | $-0.41$   | $-0.40$  | 0.39 |
| SDSS w/2MASS ($-28 < M_i < -26.5$) | 6192 | 0.98                | $-25.62$             | $-0.57$   | $-0.70$  | 0.53 |
| SDSS w/2MASS ($-28 < M_i < -26.5$) | 1336 | 1.44                | $-27.29$             | $-0.47$   | $-0.54$  | 0.37 |

same method as for the SQIID sample, using the optical bands completely redward of Ly$\alpha$ and the available 2MASS data from the DR3Q. Sample statistics are given in Table 3. The median of the complete SQIID sample distribution is flatter than the mean with a value of $-0.47$. The mean is shifted to steeper values by the presence of a red tail to the distribution. The median of the 2MASS sample distribution is $-0.57$. The mean is again shifted redward by a red tail to $\langle \alpha_o \rangle = -0.70 \pm 0.53$. The distributions of the two samples look very similar. However, performance of a Kolmogorov–Smirnov (K–S; Babu & Feigelson 1996; Press et al. 1992) test on the two data sets shows only a 38% probability that the two distributions are drawn from the same parent distribution. The differences could be due to the dependence of $\alpha$ on luminosity, as has been suggested by this work and others (e.g., Steffen et al. 2006), as the SQIID and 2MASS samples cover different areas of luminosity/redshift space (Figure 5). If we consider just those quasars from the 2MASS sample with $-28 < M_i(\alpha_o) < -26.5$ (where the bulk of the SQIID sample lies), then the mean of the distribution is $\langle \alpha_o \rangle = -0.54 \pm 0.37$ and the median is $-0.47$, almost identical to the SQIID sample, even though the bulk of these quasars are at redshifts between 0.5 and 2 (Table 3).

As is clear from Figure 5, the 2MASS-detected sample has a strong correlation of luminosity with redshift. While this is
also true, to a lesser degree, for the SQIID sample, in order to select a statistically significant sample at high redshift and stay close to our desired redshift ranges, we had to observe fainter candidates at the higher redshift bins, as can be seen in Figure 2. This resulted in the SQIID subsamples having very similar mean luminosities of $M_{\alpha_o} = -27.15$, $-27.89$, and $-27.87$ at $z \sim 1.88$, $2.82$, and $4.03$, respectively. It is therefore not surprising that we see stronger evidence in favor of a correlation of $\alpha_o$ with $z$ than with luminosity, as our survey was designed to explore the relation with redshift. We do note, however, that if we limit the 2MASS-detected sample to have similar absolute magnitudes to our sample, then the statistics for $\alpha_o$ become very similar (Table 3), even though the mean redshifts are 1.44 and 2.81. What we conclude is that there is evidence for evolution of $\alpha_o$ with both $z$ and luminosity, but that more data at a broader range of luminosities is needed to fully characterize its form.

Computing the difference in the absolute magnitudes in Table 2, one computed with an average spectral index as in Richards et al. (2006a), $M_{\langle\alpha_o\rangle}$, and another where the value of $\alpha_o$ is used, $M_{\langle\alpha_o\rangle}$, we can see in Figure 9 that there is a trend with redshift, due to the suggested evolution of $\alpha_o$ with redshift. When using a spectral index computed from the quasar photometry, the quasars at $z \sim 2$ are brighter on average with respect to the luminosity computed with $\alpha = -0.5$, while the quasars at $z \sim 4$ are fainter. The difference in computed luminosities in the SQIID sample can be as much as $\pm 18$ mag.

4.5. The Quasar Luminosity Function

If there is evolution in $\alpha$ with redshift or luminosity, this will have a direct effect on the evolution of the QLF. For example, the DR3QLF is shown in Figure 10 (open symbols). If we recompute the absolute magnitudes of the bins (see Richards et al. 2006a, Table 6) by using the mean redshift of the quasars in the bin in Equation (9) to compute an average $\alpha_o$ at this mean redshift, the absolute magnitudes will shift by an amount $\Delta M_i = 2.5(\alpha_o + 0.5)\log_{10}(1 + z)$. This term will be zero where $\alpha_o = -0.5$, which corresponds to $z = 3.1$. For redshifts significantly below this, the quasar SED is steeper on average, and $M_i$ is correspondingly brighter. For redshifts above 3.1, the SEDs are on average flatter, and the $M_i$ are fainter.

This is shown graphically in Figure 10 where the DR3QLF is given along with points shifted in $M_i$ as described above. While the space density remains essentially unchanged near the peak of quasar activity at $z \sim 3$, the points shift towards brighter $M_i$ at lower redshift and towards fainter $M_i$ at higher redshifts. For cumulative space densities as a function of redshift, this would mean that at lower redshifts, more objects would have $M_i$ brighter than a given cutoff, increasing space densities, while at $z \sim 4$, fewer objects would make the cutoff, resulting in lower space densities. This would change the shape of the form in the number of quasars over time, giving rise to steeper growth at early times, with a more gradual decline locally.
Figure 7. (Top panels) Residuals in $\alpha_o$ of the linear expressions given in Equations (9) and (10) (bottom panels). Two-dimensional projections of the residuals in $\alpha_o$ of the expression given in Equation (11). The residuals average to $\sim 0$, but exhibit strong scatter, with residuals as large as $\sim 1$ in all cases.

Figure 8. Top-left: The distribution of rest-frame optical spectral indices, $\alpha_o$, for the SDSS quasars detected by 2MASS. The mean of the sample is $\langle \alpha \rangle = -0.70 \pm 0.53$ and the median is $-0.57$. Bottom-left: The distribution of $\alpha_o$ for the SQIID sample. The mean of the sample is $\langle \alpha \rangle = -0.55 \pm 0.42$ and the median is $-0.47$. Right: The distribution of $\alpha_o$ for the SQIID sample in each redshift bin. See Table 3 for sample statistics.
It has long been recognized that adopting an average spectral index for the power-law form of quasar spectral energy distributions can effect the evolution in the QLF (e.g. Giallongo & Vagnetti 1992; Francis 1996; Kennefick et al. 1997; Wisotzki 1998; Richards et al. 2006a). However, the adoption of an average spectral index persists in most studies of the QLF, with $\alpha = -0.5$ being the most common value used. Recent work in the X-ray region has led to a general consensus that there is a dependence of quasar SED on luminosity (see Tang et al. 2007, for an exception). As for dependence on $z$, some groups find no evidence for the evolution of X-ray spectral indices, $\alpha_{\text{ox}}$, with redshift (e.g., Steffen et al. 2006), while others do see a linear dependence of optical to X-ray spectral indices with $z$ (Kelly et al. 2007). X-ray emission in an active galactic nucleus (AGN) is generally taken to arise from a hot corona of optically thin gas heated by Compton scattering of thermal photons from a thick accretion disk, the likely source of the optical/UV emission. While emission from these two regions is likely related, there is little evidence for a direct link between the X-ray and optical/UV emission, and Kelly et al. (2007) find no evidence for a correlation between $\alpha_{\text{UV}}$ and $\alpha_{\text{ox}}$.

Previous attempts to study the optical spectral energy distributions of quasars include Francis (1996) who found $\alpha = -0.46 \pm 0.30$ from a sample of LBQS quasars using optical and NIR photometry, Cristiani & Vio (1990) who computed $K$ corrections as a function of redshift in $UBV$ and found $\alpha \approx -0.7$ at 1000–5500 Å from their composite quasar spectra, Vanden Berk et al. (2001) who constructed a composite quasar spectrum from an SDSS quasar sample and found $\alpha = -0.46$ for the region $\text{Ly}\alpha$ to H$\beta$, and Pentericci et al. (2003) who found $\langle \alpha \rangle \approx -0.57 \pm 0.33$ from optical and NIR photometry of 45 $z > 3.60$ SDSS quasars. There is considerable spread in the values of $\alpha$ within each sample, and the distribution of $\alpha$ found here and by the groups using optical and NIR photometry (Francis 1996; Pentericci et al. 2003) are remarkably similar, each having a peak around $-0.5$ to $-0.3$ with a tail to the red that shifts the mean of the samples to steeper values. This could be consistent with the findings of Webster et al. (1995) in their comparison of optical to NIR colors of radio quiet and radio loud quasars, who predict quasars should have an SED with $\alpha = -0.3$ and that the distribution is caused by dust reddening in the host galaxies. Perhaps more important than the evolution of $\alpha_{\text{ox}}$ with $z$ is the distribution of the spectral index values, La Franca & Cristiani (1997) have pointed out that, if there is a spread in the spectral slope, there will be a corresponding slower luminosity evolution and steeper QLFs.

In general, the most desirable way to present the QLF is in terms of the bolometric luminosity. Richards et al. (2006b) demonstrate that computing bolometric luminosities from optical luminosities assuming a single mean quasar SED can lead to errors as large as 50%. Hopkins et al. (2007) have determined the bolometric QLF by combining the results of over two dozen quasar surveys from the hard X-ray to the mid-IR. They construct a model SED but allow for the distribution in the power-law components of the model, stressing that there is no “effective mean” SED. They also adopt the luminosity-
dependent value of $\alpha_{\text{obs}}$ of Steffen et al. (2006). However, they do not adopt a value of $\alpha_{\text{obs}}$ that depends on redshift as has been suggested by Kelly et al. (2007) and is supported by our findings in the rest-frame optical.

Given the brightness of our sample, we have not attempted to correct for the contribution of the host galaxy to the SED. The optical and NIR data were taken several years apart, and we have not considered variability in this sample. We have obtained NIR observations for $\sim 100$ more SDSS quasars in these redshift ranges, along with nearly simultaneous ($\sim 1$ month) optical imaging with the aim of adding to our survey sample and addressing the issue of variability. Richards et al. (2003) have stressed the need to correct for redshift-dependent color effects when computing photometric spectral indexes, as failing to do so can lead to effects systematic with redshift. We have neglected the presence of emission lines in our photometric passbands. However, due to the nature of the sample—each quasar is sampled at essentially the same points in their SEDs as is clearly seen in Figure 5—the apparent evolution would persist.

The generally accepted view of quasar activity is ascribed to the release of gravitational energy by accretion of matter onto a supermassive black hole. The UV/optical flux is seen as arising from a thin, optically thick accretion disk (see Koratkar & Blaes 1999, for a review), so a correlation between $\alpha$ and $\lambda$ implies evolution in the accretion process. More studies of the form and possible evolution of quasar SEDs are obviously still needed to constrain theoretical models of AGN structure and energy production mechanisms. While ever larger samples of quasars are discovered (e.g., Schneider et al. 2007), the form of the QLF cannot be fully characterized until we have a better understanding of quasar energy distributions and how they are affected by luminosity, redshift, and environment. Since we are now coming to understand how quasar activity might be related to galaxy formation and evolution, quantifying the shape of the QLF and its evolution remains a pressing problem. Here we have presented some evidence that quasar SEDs evolve with cosmic time and have shown that this has a direct effect on the evolution of their luminosity function.

J.K. and S.B. acknowledge the support of NSF ADVANCE grant AST-0340837 and National Virtual Observatory (NVO) Research Initiative Grant no. 000012. We thank the staff at KPNO for their assistance at the 2.1 m telescope, especially Mike Merrill for his assistance with the SQIID instrument and the UPSQIID package. We also thank our anonymous referee whose suggestions greatly improved the manuscript. This research has made use of data obtained from and software provided by the U.S. National Virtual Observatory, which is sponsored by the NSF. This publication makes use of data products from the 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the NSF. Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the participating institutions, NASA, the NSF, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/. The participating institutions are the University of Colorado, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Princeton University, the United States Naval Observatory, and the University of Washington.

Facilities: KPNO:2.1 m (SQIID), NVO, Sloan.

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