PARTIALLY OBSCURED QUASARS IN THE SLOAN DIGITAL SKY SURVEY EARLY DATA RELEASE

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Received 2003 January 28; accepted 2004 November 1

ABSTRACT

We have compiled a sample of 21 low-redshift ($z \leq 0.3$), luminous active galactic nuclei (AGNs) with large Balmer decrements ($H_\alpha/H_\beta > 7$) using the galaxy and QSO catalogs of the Sloan Digital Sky Survey Early Data Release. Using this sample we attempt to determine the fraction of quasars with large internal absorption. We find that these AGNs have strong $[O \, iii]$ $\lambda 5007$ and broad $H_\alpha$ emission, and that starlight dominates the spectra in the blue band, suggesting that these objects are heavily reddened. Their narrow emission line ratios are similar to those of Seyfert 2 galaxies, yet the average $[O \, iii]$ $\lambda 5007$ emission is $\sim 10$ times more luminous. Applying the empirical relation between the optical continuum and the Balmer line luminosity for blue quasars, we find that the intrinsic luminosities of these 21 objects are in the range for quasars. We propose that they are obscured, intermediate-type quasars analogous to type 1.8 and 1.9 Seyfert galaxies. The ratio of these optically selected, intermediate-type quasars to type 1 quasars is found to be around 1, similar to that for local Seyfert galaxies. Preliminary study indicates that most of these quasars are hosted in early-type galaxies. 

Subject headings: galaxies: active — galaxies: nuclei — quasars: general

1. INTRODUCTION

The unified model for Seyfert galaxies is now well supported (see Antonucci 1993 for a review). The model postulates that Seyfert 1 and Seyfert 2 galaxies are physically the same, except that the broad-line region (BLR) in Seyfert 2 galaxies is obscured from our line of sight by dust in the nucleus or in the host galaxy, and that quasars are luminous versions of Seyfert galaxies. Obscuration by dust should also play an important role in quasars. However, the evidence supporting such unification for quasars is substantially weaker than for Seyfert galaxies. Whether or not the difference between Seyfert galaxies and QSOs is simply a matter of luminosity is still a hotly debated issue; for instance, some researchers argue that a dusty torus in QSOs may not even exist or that, if one exists, its opening angle for quasars is substantially weaker than for Seyfert galaxies. Results for quasars analogous to type 1.8 and 1.9 Seyfert galaxies. The ratio of these optically selected, intermediate-type quasars to type 1 quasars is found to be around 1, similar to that for local Seyfert galaxies. Preliminary study indicates that most of these quasars are hosted in early-type galaxies. 

Some of these objects may not follow the strict definition of the “type 2” AGN, since they sometimes reveal weak broad $H_\alpha$ lines in deeper, high-S/N spectra (e.g., 1E 0449.4+1823, Boyle et al. 1998; AX J0849+4454, Akiyama et al. 2002). They are, however, heavily obscured AGNs.
ambiguous results on the morphology, stellar velocity dispersion, and star formation history in these host galaxies.

This paper is organized as follows: In § 2 we present the details of our analysis of the SDSS spectra and describe our selection criteria for intermediate-type QSOs. Section 3 presents the main properties of our sample, as well as discussion of some interesting individual objects. Section 4 is a short summary. Throughout the paper, we assume a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. SAMPLE CONSTRUCTION AND DATA ANALYSIS

2.1. Construction of the Parent Sample

The parent sample of our partially obscured QSOs is the low-redshift AGNs (QSOs and Seyfert galaxies) with reliable broad H$\alpha$ lines selected from the spectral data set of the SDSS EDR. We construct the parent sample in four stages.

First, we select all the objects classified by the SDSS spectroscopic pipeline as galaxies (SPEC_GALAXY, specClass = 2) or quasars (SPEC_QSO, specClass = 3) with $z \leq 0.3$. This yields 38,223 objects in total (37,657 as SPEC_GALAXYs, 566 as SPEC_QSOs). We limit $z \leq 0.3$ so that the centroid of H$\alpha$ lies at $\leq 8500 \text{ Å}$, allowing us to reliably measure the H$\alpha$ flux. In this first step we do not limit the signal-to-noise ratio (S/N), because some objects may have a reliable broad H$\alpha$ line yet a rather weak continuum with a very low S/N. For any object with multiple spectroscopic observations, we retain only the spectrum with the highest S/N.

Second, the 566 SPEC_QSOs are visually examined to remove (1) objects with too many bad pixels or too low S/N in the H$\alpha$ region, and (2) objects obviously without broad emission lines. This stage cuts the sample to 459 SPEC_QSOs. Using these we build a subsample of normal type 1 AGNs (QSOs and luminous Seyfert 1.0 galaxies, hereafter called “blue AGNs”) to use as a reference in the next stages. These blue AGNs are selected according to the following criteria: (1) $D_{4000} \leq 1$ (the definition of the 4000 Å break index $D_{4000}$ introduced by Balogh et al. [1999] is adopted here, using bands 3850–3890 and 4000–4100 Å), and (2) blue color ($u' - g' < 0.6$, corresponding to the conventional criterion of $U - B \approx 0.4$). These criteria produce a subsample of 94 objects. For these objects, we fit the continua using a single power law or broken power law. For some objects with apparent Fe $\nu$ multiplets, we fit the continua employing the empirical optical Fe $\nu$ template of Boroson & Green (1992, hereafter BG92) broadened by convolving a Gaussian of various widths. The continuum (and Fe $\nu$ multiplets if present) was then subtracted and the remaining emission lines were fitted with an appropriate line profile (the details of the emission-line fitting are described in § 2.3). These emission-line fits yield the equivalent widths (EWs) of the broad H$\alpha$ component of the 94 objects. These range from 134.4 to 726.2 Å with a mean value of 335.4. These EWs will be used later to roughly evaluate the relative contribution of the stellar and nuclear components.

In the third stage, nuclear continuum and/or starlight subtraction is performed for the remaining 365 SPEC_QSOs and the 37,657 SPEC_GALAXYs. For 41 SPEC_QSOs without prominent stellar features, power-law continua (and Fe $\nu$ templates if necessary) were fitted in the same way as for the blue AGNs. For the other SPEC_QSOs, where the stellar contribution cannot be neglected, the nuclear continuum and the stellar component are fitted simultaneously (see § 2.2).

For the 37,657 SPEC_GALAXYs, we initially perform starlight subtraction by fitting the emission-line–free regions of the spectrum with nine synthesized templates, which are discussed in detail in § 2.2. Then the emission lines of these 37,657 objects are measured assuming Gaussian profiles. This is a preparatory fitting for subsequent reductions. More than a thousand candidates were selected using the criterion that the broad component of H$\alpha$ (FWHM $> 1000 \text{ km s}^{-1}$) is significant (>5σ). Then we visually examined these candidates to exclude the objects with a false broad component of H$\alpha$ caused by poor nuclear contribution. After these culled, the number of the candidates is reduced to 867. However, for some of them, the nuclear contribution is not negligible. Those 126 objects with EW(H$\alpha$) $> 30$ Å (~0.2 times the minimum EW(H$\alpha$) of blue AGNs and ~0.1 times the mean value) are picked up for more precise starlight and nuclear continuum subtraction, as described in § 2.2.

The main task of the fourth stage in our analysis is to fit the emission lines precisely using several schemes (see § 2.3) for all the selected 1232 objects (459 SPEC_QSOs and 867 SPEC_GALAXYs). Based on the emission-line parameters, we select out 583 objects (including the 94 blue AGNs) as our parent sample. The criterion is $f_{\text{H}\alpha} \geq 5 s_{\text{H}\alpha, \text{fit}}$, where $s_{\text{H}\alpha, \text{fit}}$ is the total flux error of the broad H$\alpha$ component synthesized from two parts: (1) $s_{\text{H}, \text{sub}}$, the error given by the spectral line fitting procedure, and (2) $s_{\text{H}, \text{sub}}$, the error introduced by template subtraction because of the mismatch between the object’s spectrum and the model spectrum. The latter are discussed in § 2.2.

2.2. Starlight/Continuum Subtraction

Accurate starlight subtraction for the measurement of nuclear emission lines is important. Usually it is implemented by fitting the non–emission-line regions of the spectrum with a model spectrum composed of galaxy templates that are derived from either observed star spectra (e.g., Kauffmann et al. 2003) or observed galaxy spectra (e.g., Ho et al. 1997a). In this work we develop a “two-step” method to build the galaxy templates described in detail in Li et al. (2005). Here we provide a brief summary of this approach.

First, principal component analysis (PCA) is applied to an observed stellar library newly available (STELIB; Le Borgne et al. 2003). The resultant star eigenspectra broadened to various velocity dispersions are then used to fit the high-quality spectra of more than a thousand galaxies selected from the SDSS spectral data set according to six color–color diagrams using 18 synthesized magnitudes, which constitute a uniform library with a full spectral-type coverage. Based on the fitting result, we construct model spectra of the 1016 representative galaxies with a zero velocity dispersion. Again PCA is applied to these model spectra, and the galaxy eigenspectra with a zero velocity dispersion are obtained. After testing with SDSS galaxies using an F-test, the first nine galaxy eigenspectra are picked up as our galaxy templates. Our galaxy templates have three advantages in addition to the merits of the PCA technique itself: (1) they do not include any light from the AGN, since they are derived from the model spectra generated from pure star eigenspectra; (2) they represent the most prominent features of the SDSS galaxies since they are based on representative galaxy spectra from the SDSS; (3) they can be used to fit the stellar velocity dispersion of the galaxies since they themselves are not velocity-broadened.

When used to fit the host galaxy component of the objects, these nine templates are broadened by convolving with a Gaussian to match the stellar velocity dispersion of the host galaxy. The host galaxy component is thus modeled as the linear combination of the nine best-fitting broadened spectra.

In our sample, many objects appear to have both a host galaxy component and a nuclear component. In such cases, we
fit the (almost) emission-line–free regions of the spectrum with the nine broadened template spectra + a reddened power law with $E_{B-V}$ varying between 0 and 2.5. The latter represents the nuclear component. Here the power law is $f(\lambda) = C\lambda^{-1.7}$, taken as the unreddened nuclear continuum according to Francis (1996). Some objects have visible Fe II emission that must also be removed before spectral line fitting. For those objects, we first subtract the starlight/continuum component without taking account of the Fe II emission and fit the spectral lines. Then we broaden BG92’s optical Fe II template to the width of the broad Hβ, and fit the pseudocontinuum (wavelength ranges of prominent emission lines other than Fe II multiplets were masked out) again with the nine broadened template spectra + the reddened power law + the broadened BG92 template.

In order to estimate the mismatch of this subtraction, we fit $\sim 1000$ high-quality spectra of absorption-line galaxies and obtain the standard deviation of the relative error of the subtraction $\sigma_r(=0.027)$. Using this we estimate the error of the flux of a broad line caused by the subtraction as the flux of the underlying continuum within the region of 4 FWHMs of the line multiplied by $\sigma_r$.

### 2.3. Emission-Line Fitting

We developed a systematic code to fit the emission lines. With this code, we can fit each spectrum using several different fitting schemes. For example, for narrow Hα, we can tie its width to that of another line, such as [S II] $\lambda 6731$, while fitting the spectra with an extremely broad Hα component; or we can just fix it to a designated value, such as the fitted width of [O III] $\lambda 5007$ when [O II] $\lambda 5007$ is the only reliable narrow line. The results of the different fitting schemes are compared with each other, and the one with minimum $\chi^2$ is chosen. In this work, the primary goal of the line fitting is to obtain accurate measurements of broad Hα and broad Hβ, with an emphasis on the former. To achieve this goal, we must accurately separate the Balmer lines from the nearby narrow lines. In general, our fitting strategies are as follows:

1. Initially, lines are fitted with Gaussians, one Gaussian for each narrow or broad component of the lines. For example, four Gaussians are used to fit the Hα+[N II] lines. The flux ratio of the [N II] doublet $\lambda 6583/\lambda 6548$ is fixed to the theoretical value of 2.96, and their profiles are assumed to be identical. Likewise the [O III] doublet is similarly constrained. Usually we also require the profiles of the narrow Hα and [N II] to be the same.

2. If the FWHM of the broad Hα line is less than 3000 km s$^{-1}$, we also try a Lorentzian profile to fit the broad lines.

3. If [O III] or [S II] doublets show a complex profile (e.g., with faint, extended wings), double Gaussians are employed to fit each narrow line.

4. If the broad and narrow Hα components cannot be separated by the fit, the narrow lines in the Hα+[N II] region will be given the same profile as the narrow Hβ line if available, or [S II], or [O III], in this order.

5. Likewise, if the broad and narrow Hβ components cannot be separated by the fit, the narrow Hβ line will be given the same profile as the narrow Hα, or [O III], or [S II], in this order.

6. If the broad Hβ line is weak or unavailable, we constrain its profile to be that of the broad Hα line.

Following the above steps, we have measured the lines of most objects. But exceptions always exist since, as we know, the profiles of emission lines may be formed in quite different regions. For example, in several spectra the broad Hα component shows two or more velocity peaks, while in some others it even has an asymmetric or irregular shape. In these cases we adopt multiple Gaussians to constrain the fit if the data quality is high enough (e.g., 2 Gaussians for the broad Hα component of SDSS J101405.89+000620.3, as plotted in Fig. 1). In fact, all the spectra are fitted interactively and then inspected visually. The fitting of the Hα+[N II] region for all the 21 partially obscured QSOs is displayed in Figure 1 (right).

### 2.4. The Sample of Intermediate-Type Quasars

It is well established that the Balmer line luminosity is tightly correlated with the nuclear continuum luminosity for both quasars and Seyfert galaxies (Yee 1980; Shuder 1981; Ho & Peng 2001). We plot in Figure 2 the Hα luminosity versus the absolute magnitude for our blue AGNs. A linear fit shows

$$\log L_{H\alpha} = -(0.340 \pm 0.018)M_g + (35.17 \pm 0.40) \text{ (ergs s}^{-1}),$$  

which is perfectly consistent with the result of Ho & Peng (2001), who got

$$\log L_{H\alpha} = -(0.340 \pm 0.012)M_g^{pec} + (35.11 \pm 0.25)$$  

for a sample of PG quasars and Seyfert galaxies. According to equation (1), an Hα luminosity of $\log L_{H\alpha} (\text{ergs s}$^{-1}) $\approx 42.82$ mag gives $M_g = -22.5$ mag as the quasar selection limit in this paper.

Figure 3 shows the distribution of broad Hα/Hβ for the 94 blue AGNs we selected. It can be seen that the scattering of the Hα/Hβ ratios is rather small, with an average Hα/Hβ of 2.97 ± 0.36. Assuming that all the objects in the parent sample have the same intrinsic Balmer decrement, Hα/Hβ = 2.97, we calculate the internal extinction as well as the intrinsic luminosity of Hα for the reddened objects. The Galactic extinction curve in Fitzpatrick (1999) with $R_V = 3.1$ is utilized, and the intrinsic luminosity of the broad Hα component is estimated as

$$\log L_{H\alpha}^{int} = \log L_{H\alpha}^{obs} + 1.87[\log (H\alpha/H\beta) - \log (2.97)].$$  

Figure 4 shows the observed luminosity of the broad Hα component versus the Hα/Hβ ratio for all the 583 objects in the parent sample. The tilted line corresponds to our quasar selection limit, i.e., $M_g^{pec} \approx -22.5$ mag or log $L_{H\alpha}^{int} \approx 42.82$ ergs s$^{-1}$. Out of the 80 objects above the tilted line, we compile a partially obscured QSO sample of 21 objects with Hα/Hβ > 7 (listed in Table 1). The Hα/Hβ > 7 criterion is set to select those objects with relatively severe obscuration, in analogy with type 1.8/1.9 Seyfert galaxies. By this criterion, the sample satisfies the requirement of the intrinsic nuclear luminosity 10 times greater than the observed one or $E(B - V) \approx 0.75$, which is reddened more severely than the dust-reddened quasars $[E(B - V) \leq 0.5]$ compiled by Richards et al. (2003) from the SDSS QSO catalog. The SDSS spectra of the 21 objects are shown in Figure 1 (left).

### 3. DISCUSSION

#### 3.1. Testing the Assumption of Large Internal Extinction

We have tentatively classified 21 objects as intermediate-type quasars according to their high intrinsic nuclear luminosities estimated by equation (3). The most remarkable property of these objects is their large Hα/Hβ ratios. Our basic assumption is that their intrinsic Hα/Hβ ratio is similar to that of the “normal” QSOs, i.e., 2.97, and that the large observed Hα/Hβ...
Fig. 1.—SDSS spectra of the intermediate-type quasars and the line fits. The vertical axis is flux in units of $10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and the horizontal is wavelength in Å. The left panels show the procedure of starlight/continuum subtraction: the original spectrum (top line), the stellar component (middle, solid line), the nuclear continuum (middle, dotted line), and the starlight/continuum subtracted residual (bottom line). For clarity, the residual is offset downward by an arbitrary constant. The right panels show the process of line parameter measurement. Top right: Original data and individual components of the fit (thin curves), and final fit (thick curve). Bottom right: The residual.
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ratio is due to relatively large internal extinction. This assumption is consistent with the fact that the optical continuum of almost all these objects is dominated by the stellar component of the host galaxy (see Fig. 1).

To test our assumption, we match the parent sample and 2MASS catalogs and find 286 objects having counterparts within 1″ in the 2MASS Point Source Catalog (PSC), without any extended “contamination” and with a reliable magnitude in the $K_s$ band. Of these objects, the bigger the $H\alpha/H\beta$ ratio, generally the redder the $u-K_s$ color. All sources with $H\alpha/H\beta > 7$ have $u-K_s > 4.5$ (Fig. 5), indicating that their $H\alpha/H\beta$ ratios and $u-K_s$ colors are consistent with our assumption. The absolute $K_s$ magnitudes are well correlated with the luminosities of the broad $H\alpha$ components of these objects (Fig. 6). To eliminate spurious correlations due to the redshift effect, we calculate the partial correlation coefficient for a redshift $z$ as

$$r_{xy,z} = \frac{r_{xy} - r_{xz} r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}},$$

where $x, y$ refer to the $H\alpha$ luminosity and the absolute $K_s$ magnitude, and $r_{xy}, r_{xz}$, and $r_{yz}$ refer to the correlation coefficients between $x$ and $y$, $x$ and $z$, and $y$ and $z$. The partial correlation coefficient is $-0.625$ with a chance probability of $<0.0001$ for $\log L_{H\alpha}$ and $M_{K_s}$, and goes up in absolute value to $-0.724$ for $\log L_{H\alpha}$ and $M_{K_s}$ estimated according to our assumption. Again, this favors our assumption of large internal extinction.

The extinction assumption is also substantiated by the relatively high $[O\ iii]$ luminosity. In addition to $H\alpha$ luminosity, there is observational evidence that $[O\ iii]$ luminosity can be used as a rough estimate of the intrinsic power of an AGN, even in type 2 objects (Véron-Cetty & Véron 2000 and references therein). Figure 7 plots the relation between $[O\ iii]$ luminosity and the estimated nuclear absolute magnitude for the objects with reliable $[O\ iii]$ $\lambda5007$ emission and reliable broad-line Balmer decrements in the parent sample. The $[O\ iii]$ luminosities are corrected for intrinsic extinction assuming an intrinsic Balmer decrement equal to 3.1 for the narrow components of $H\alpha$ and $H\beta$ (see Veilleux & Osterbrock 1987), and the intrinsic nuclear absolute magnitudes are estimated based on the intrinsic luminosity of the broad $H\alpha$ component according to equations (1) and (3). It is clear that the two are correlated, although the scatter in this relation is much larger than that for the correlation between the observed continuum and the $H\alpha$ luminosity for the blue AGNs (see Fig. 2). The derived partial correlation coefficient is $-0.578$ for $\log L_{[O\ iii]}$ and $M_{K_s}$ with a chance probability of $<0.001$. Hence, the correlation indicated in Figure 7 is not due to the redshift effect. The 87 QSOs/Seyfert 1s in the BQS sample (BG92) and all the intermediate-type quasars are both plotted for comparison. The $[O\ iii]$ luminosity of these intermediate quasars is comparable to that of luminous QSOs in the BQS sample and about 10 times more luminous than that of Seyfert galaxies, suggesting that they very possibly contain a quasar-like nucleus. However, from the relatively greater scatter of the relation between $\log L_{[O\ iii]}$ and $M_{K_s}$ for both the luminous PG QSOs and our intermediate-type QSOs, we may infer that the $[O\ iii]$ luminosity is not a good calibrator for higher nuclear luminosity.
The source of obscuration may be small-scale dusty material near the nucleus or a large-scale dust lane in the host galaxy. For the mean [O \text{ III}] luminosity of our intermediate quasars, the narrow-line region (NLR) size is typically of kiloparsec scale (Bennert et al. 2002). The kiloparsec-scale dust lane would also produce large reddening in the NLR, while small-scale dusty material would not. To see which of these probabilities is most likely, we plot in Figure 8 the H\alpha/H\beta ratio of the broad component versus that of the narrow component for 141 objects with reliably measured, narrow H\alpha, H\beta lines, including nine objects that are intermediate-type QSOs. First, it can be seen that our intermediate-type quasars, together with most of the other partly obscured AGNs, show no or moderate reddening in the NLR, as indicated by the narrow H\alpha/H\beta ratio in the range 2.0–5.5, while some of them show heavy reddening in the BLR with the broad H\alpha/H\beta ratio greater than 8 and up to \approx 20. Hence, the absorbing material could be the dusty torus similar to that seen in Seyfert galaxies, or some other small-scale obscuring material would not.

Notes.—Format for objects is hh:mm:ss.s/dd:mm:ss.s. Flux is in units of 10^{-17} ergs cm^{-2} s^{-1}. FWHM is in units of km s^{-1}. Col. (7) gives estimated absolute \text{g} magnitude based on the reddening-corrected luminosity of the broad H\alpha line. Col. (8) gives morphology of the host galaxy: E for early type (E, S0, Sa), and S for late type.

a Adopting the profile of broad H\alpha.
b Classified according to likelihoods and concentration index.
c Classified by visual inspection.

denoted by filled squares, type 1 QSOs by filled circles, and the remainder by open circles.

Fig. 5.—The $u' - K_s$ color vs. the H\alpha/H\beta ratio of the broad components for the 286 objects in the parent sample that have counterparts in the 2MASS PSC catalog without any extended source contamination. Intermediate-type QSOs are denoted by filled squares, type 1 QSOs by filled circles, and the remainder by open circles.
material in the nuclear region. However, a patchy, large-scale dust lane cannot be ruled out. Second, for a rather larger number of objects, however, both broad and narrow lines are comparably reddened to some considerable extent (with the narrow and broad Hα/Hβ ratios of ~5), indicating that the absorbing material might be a kiloparsec-scale dust lane or molecular disk in the host galaxy, which can play a major role in producing moderate, but not heavy, reddening.

3.2. Emission Lines and Continua

The broad Hα FWHMs of the 21 objects scatter widely from ~2100 km s⁻¹ (SDSS J165641.98+632307.7) to more than 20,000 km s⁻¹ (SDSS J101405.89+000620.3), with a median value of ~4500 km s⁻¹.

In the left and right panels of Figure 9 we plot [O iii] λ5007/Hβ versus [N ii]/Hα and [S ii]/Hα, respectively, for the 21 quasars. Most of the objects are located in the AGN region of the diagram (Veilleux & Osterbrock 1987) and the distribution is similar to that of Seyfert 2 galaxies, indicating that these objects are similar to normal Seyfert galaxies in the properties of the NLR. Thus quasars, even bona fide type 2 quasars, should also bear these properties. This result is consistent with the recent HST observations of the NLR of bright radio-quiet PG QSOs by Bennett et al. (2002), who also suggested that the NLR in quasars is a scaled-up version of that of Seyfert galaxies. However, there is one exception. SDSS J170601.87+601732.4 is located at the border between AGNs and LINERs, with [O ii] λ3727/[O iii] λ5007 > 1, yet [O ii] λ3727/[O iii] λ5007 < 1. It has an unusual spectrum and in fact is the only object in the parent sample that cannot be well fitted by our galaxy templates. We discuss this object in detail in § 3.5.

Our sample of intermediate-type quasars can be considered to be optically selected, since 19 of them are optical color-selected for SDSS spectroscopic follow-up, and only two of them are selected based on ROSAT detection. We find that 6 of the 21 intermediate-type quasars have FIRST/NVSS² counterparts within 5″, and the radio detection rate is about 28% ± 8%. This ratio is slightly higher than that of the 49 optically selected quasars (only 2 objects are selected based on ROSAT detection) at z < 0.3 in the SDSS Quasar Catalog (Schneider et al. 2002), which is 14%. Note that an even larger radio detection rate was reported by Richards et al. (2001), who found that nearly half of the reddened quasars are FIRST radio sources. There is only one radio-loud object in each sample (Schneider et al.’s and ours). Moreover, each is the only source resolved by FIRST.

3.3. The Fraction of Partially Obscured Quasars

In the same parent sample where we select our 21 intermediate-type quasars, we also select 44 type 1 QSOs. The selection criteria that we used are log L_Hα (ergs s⁻¹) ≥ 42.82 (i.e., M_g ≤ −22.5) and small Balmer decrements: 2.3 ≤ Hα/Hβ ≤ 4.1. The ratio of type 1 QSOs and the intermediate type 1s is 44:21 ≈ 2.1:1. It should be pointed out that the above two subsamples may not be complete and that the completeness of the samples is mainly affected by two factors: (1) the quality of the spectra that influenced our candidate selection and (2) the magnitude limit that SDSS used to select targets for spectroscopic observation. The spectral quality does not affect the selection of type 1 quasars, all of which have high-S/N spectra; however, it is not negligible for the selection of intermediate-type quasars. In Figure 4 we can see that the main incompleteness comes from the measurement of the broad Hβ component. For many objects, because of the limited spectra quality, we can only give upper limits to the broad Hβ flux. Thus our sample is conservative. A quick calculation shows that if we decrease the upper limits by 50%, 20 more sources would pass our selection criteria. We also check the possible incompleteness due to the requirement of at least a 5 σ detection of a broad Hα component. This potential selection effect is negligible, as discussed below. We note that over half (13 of 21) of the intermediate-type QSOs are from the SDSS galaxy catalog with a magnitude limit of 17.77 and that the typical S/N at this magnitude is 17.5. We can evaluate the limiting EW of the broad Hα line with this typical S/N and the median FWHM of the sample QSOs (4500 km s⁻¹) corresponding to our criterion for a reliable broad Hα line (f > 5 σ), which turns out to be 8 Å. Actually, the EWs of all the 21 objects are greater than 30 Å.

² Faint Images of the Radio Sky at Twenty cm, Becker et al. (1995); NRAO VLA Sky Survey, Condon et al. (1998).
In order to correct the bias caused by the magnitude limit imposed on the spectroscopic target selection, for each object we calculate $z_{\text{max}}^i$, where the object would reach the magnitude limit for SDSS spectroscopic follow-up. The corrected number of sources is estimated as $\sum V_{0.3}/V_{\text{max}}$, where $V_{0.3}$ is the comoving volume within $z = 0.3$ and $V_{\text{max}}$ is that within the smaller of $z_{\text{max}}^i$ and 0.3. After the bias correction for this imposed magnitude limit, the number of intermediate-type QSOs rises to 60.4 and the number of type 1 QSOs remains untouched. The bias-corrected ratio of type 1 QSOs to intermediate-type QSOs then becomes $44:60.4 \approx 1:1.4$. To compare this with Seyfert galaxies, we select 12 objects from our intermediate-type QSO sample that should be classified as type 1.8 or type 1.9 according to the quantitative classification introduced by Winkler (1992), and the bias-corrected number for these type 1.8 + 1.9 objects is 39.1. Thus the ratio of type 1 QSOs to the type 1.8+1.9 objects is 44:39.1, which is almost the same as that of Seyfert galaxies (cf. Sy1 vs. Sy1+Sy2; Forster 1999). But we must note that these above ratios rely on the intrinsic Hα/Hβ ratio and the internal extinction curve that we adopt for those intermediate-type AGNs. For example, if the intrinsic Hα/Hβ ratio is set to 4.0, there are 13 intermediate-type QSOs remaining and the bias-corrected ratio of type 1 QSOs to intermediate-type QSOs changes to $44:30.8 \approx 1.4$.

This large fraction of obscured quasars has also been reported in many other studies. Through studying the red quasars in the Parkes Half-Jansky Flat-Spectrum Sample, Webster et al. (1995) proposed that 80% of the quasar population is dust-obscured and has been missed by optical surveys, if the dust content around radio-quiet quasars is as extensive as that around the radio-loud ones. Lacy et al. (2002) also suggested that the red quasar population could be very large through modeling the selection effects, which turn out to be effective at removing dust-reddened quasars from magnitude-limited samples. Whiting et al. (2001), however, found that $\approx 40\%$ of the Parkes sources show evidence for optical synchrotron emission, which is responsible for the red color of red radio-loud quasars in Webster et al.’s sample, as Serjeant & Rawlings (1996) argued. In that case, any missing population of quasars would be much smaller. But a recent study by White et al. (2003), based on a sample constructed by comparing the FIRST survey with an $I$-band survey, strongly supports the hypothesis that radio-loud and radio-intermediate quasars are dominated by a previously undetected population of red, heavily dust-obscured objects, although they do not know whether these kinds of quasars are common in the radio-quiet population. Our sample is almost purely optically selected, with only one radio-loud object (see §3.2); therefore we can safely conclude that dust-obscured quasars are also common in the radio-quiet population. As stated in §3.1, the obscuring material should be on small scales in the nucleus of the quasars.

Using the SDSS quasar catalog, Richards et al. (2003) found that the redness of quasars whose colors cannot be fitted with a single power-law continuum is caused by dust extinction instead of synchrotron emission and that moderately dust-obscured $[E(B-V) \leq 0.5]$ quasars account for 15% of broad-line quasars. As mentioned earlier, our sample is focused on heavily obscured quasars $[E(B-V) \gtrsim 0.75]$, with over half of its members from the SDSS galaxy catalog. Considering that Richards et al.’s sample is restricted to the SDSS quasar catalog, our result is marginally consistent with theirs.

3.4. Properties of the Host Galaxies

The host galaxy properties of quasars are generally difficult to determine since the stellar component is usually overwhelmed by the luminous quasars. High-resolution ground and space observations are usually the only way to detect the existence of the host galaxy. Our sample of intermediate-type quasars provides us with an excellent opportunity to study their host galaxies, since their nuclear emission is strongly attenuated by the obscuration. In this subsection, we try to draw some straightforward conclusions about the morphologies of the host galaxies. The study of the star-forming history in the host galaxies of these objects is deferred to another paper.

In Figure 10 we present the SDSS images. For five bright objects with $r' < 17$ mag, we classify the type of host galaxy visually. For the remainder, the criteria for ellipticals are

1. Concentration index $r_{90}/r_{50} \geq 2.5$ in $r^*$ (see Bernardi et al. 2003).
Fig. 10.—Composite SDSS images (from u, g, r, i, and z bands) of the 21 partially obscured QSO candidates. The size of each image is $21'' \times 21''$. 
2. The likelihood of the de Vaucouleurs profile fit is greater than 0.5 and greater than the likelihood of the exponential model by at least 0.1.

The criteria for spirals are

1. Concentration index $r_{90}/r_{50} < 2.5$ in $r^*$. 
2. The likelihood of the exponential model fit is greater than 0.5 and greater than the likelihood of the de Vaucouleurs profile fit by at least 0.1.

Following the above procedure, we classify 13 objects in total: one resides in a spiral and 12 reside in ellipticals (listed in Table 1). The other eight objects are left unclassified. This is consistent with the result from HST observations that the host galaxies of about two-thirds of QSOs are ellipticals (Hamilton et al. 2002).

Some objects show possible evidence of either interacting or peculiar morphology. SDSS J170211.15+065848.1 has two companions, with one at a very close projected distance ($\sim 2.5''$, or less than 10 kpc physical distance). SDSS J170601.87+601732.4 may have companion galaxies also. SDSS J103352.59+004403.4 has a compact core and a very extended (50 kpc in diameter) low surface brightness disk viewed nearly edge-on. SDSS J171832.86+531304.7 has a faint spiral structure and could be a spiral galaxy.

3.5. Notes on Individual Objects

SDSS J101405.89+000620.3.—The broad H$\alpha$ FWHM of this object is extremely large (20.078 ± 419.8 km s$^{-1}$). Its broad H$\alpha$ profile has a flat top, similar to the double-peaked line profile seen in some radio galaxies (e.g., Osterbrock et al. 1976; Halpern & Filippenko 1988; Halpern et al. 1996). It is a 2MASS red AGN (Cutri et al. 2001) with a red near-infrared color of $J-K_s = 2.012 \pm 0.106$ mag and is bright in the near-infrared ($J = 15.240 \pm 0.061$, $H = 14.311 \pm 0.057$, and $K_s = 13.228 \pm 0.045$).

Note that 19 out of the 21 intermediate-type quasars are in the 2MASS PSC; among these only two have $J - K_s > 2$, 16 objects have $1.2 < J - K_s < 2$, and one (SDSS J170601.87+601732.4) has $J - K_s = 1.041 \pm 0.133$. Besides SDSS J101405.89+000620.3, the other red object is SDSS J103352.59+004403.4, with $J - K_s = 2.073 \pm 0.130$. This means that most of the partially obscured quasars would be omitted by the 2MASS red AGN survey ($J - K_s > 2$). The relatively bluer $J - K_s$ colors may be caused by the starlight from their host galaxies.

SDSS J133021.41+005823.0.—This object may be classified as an FR II radio galaxy according to the usual classification criteria. Like SDSS J101405.89+000620.3, its broad H$\alpha$ profile also has a flat top. One interesting feature of this object is that it shows rare $X$-shaped radio morphology with possible flows from the central radio component to the wings. A detailed discussion of this source was presented in Wang et al. (2003).

SDSS J135717.59+002013.0.—This object may be taken as a heavily reddened cousin of the famous “poststarburst quasar” UN J1025−0040 ($z = 0.634$; Brotherton et al. 1999) located at a lower redshift ($z = 0.283$): its spectrum displays prominent Balmer jump and high-order Balmer absorption lines, indicating a substantial, young stellar population. It is a ROSAT X-ray source, with a fairly high luminosity in the soft X-ray band ($L_X = 7.21 \times 10^{44}$ ergs s$^{-1}$, uncorrected for internal extinction). It has a rather flat ROSAT X-ray spectrum with photon index $\Gamma = 1.1^{+0.51}_{-0.89}$, indicating a heavy internal absorption. It is also fairly luminous in the near-infrared, with $M_g = −25.9$ before internal extinction correction.

SDSS J170601.87+601732.4.—As mentioned in § 3.2, its spectrum is the only one in the parent sample that cannot be well fitted even using 24 eigenspectra derived from the STELIB library. Its unusual spectrum is probably not due to contamination by a foreground star, since the nearest star is 10$''$ away. However, the possibility of a foreground star sitting right on the galaxy cannot be completely ruled out. The poor spectral fit should not be due to improper flux calibration or sky subtraction either, for other spectra in the same plate look well-calibrated.

In light of prominent absorption lines and absorption bands presented in the spectrum, we propose that this spectrum is dominated by a very old and high-metallicity stellar population, which is beyond the coverage of the STELIB library and thus cannot be modeled by our galaxy templates, which are based on the library. As noted in § 3.2, this object is LINER-like. Most LINERs are found to have predominantly old stellar populations (Cid Fernandes et al. 2004; González Delgado et al. 2004), which reinforces our proposal. We tend to believe that the broad H$\alpha$ component in this object is real, but not formed by nearby absorption of neutral metals and molecules in an old stellar population, because (1) its conspicuous and smooth line profile is different from that of the other smaller bumps blueward of it, which are likely due to nearby absorption, and (2) there is no strong absorption redward of the H$\alpha$ emission line. Thus, SDSS J170601.87+601732.4 may be a heavily reddened, luminous version of “LINER 1s” (Ho et al. 1997b).

4. SUMMARY AND FUTURE PROSPECTS

We have compiled a sample of 21 objects with relatively strong broad H$\alpha$ but very weak broad H$\beta$ emission. Assuming that the broad line is produced by photoionization process and that the large Balmer decrement is due to internal reddening, the intrinsic optical continuum luminosity of the nuclei, or the lower limit on it, is estimated to have absolute magnitude $M_\beta \leq −22.5$ mag, implying that these are intermediate-type quasars. The ratio of these intermediate-type quasars to type 1 quasars is similar to that of intermediate-type Seyfert galaxies to type 1 Seyfert galaxies, indicating that quasars may be somewhat similar to Seyfert galaxies in structure. The narrow lines of these intermediate-type quasars are found to be similar to those of Seyfert galaxies in line ratios, but more luminous. Our study has revealed that these partially obscured quasars tend to be hosted in early-type galaxies more frequently than in late-type galaxies. Thus, these partially obscured quasars are important for the studies of the host galaxies related to morphology, stellar velocity dispersion, and stellar population, and also for studies of the relation between the QSO phenomenon and galactic evolution. A larger sample with a higher S/N is being based on the observations in the SDSS Data Release 2.

Further multiband observations are essential to reveal the nature of these intermediate-type quasars. Some individual objects in the sample are also very interesting and deserve further research. Hard X-ray observations, which could be done by XMM-Newton and/or Chandra (Wilkes et al. 2002), would enable us to study the strong obscuration and to derive the intrinsic luminosity using an independent approach. Optical polarization spectroscopy would also help determine the geometry of scattering/obscuring matter inside these objects, using an approach similar to that carried out for infrared-selected quasars (Smith et al. 2002).
PARTIALLY OBSCURED QSOs

This work is supported by Chinese NSF grants NSFC-19925313 and NSFC-10233030 and a key program of the Chinese Science and Technology Ministry. This work has made use of the data products of the SDSS.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, the Johns Hopkins University, Los Alamos National Laboratory, 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. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

We wish to thank an anonymous referee for several very careful and thorough reviews and valuable suggestions, and the editor who spent plenty of time correcting the numerous English errors in our paper before it could be accepted for publication.

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ERRATUM: “PARTIALLY OBSCURED QUASARS IN THE SLOAN DIGITAL SKY SURVEY EARLY DATA RELEASE” (2005, ApJ, 620, 629)

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Several numbers in the article were incorrect as a result of typographical errors. In Section 2.1, the definition of the 4000 Å break index $D_{4000}$ uses bands 3850–3950 Å and 4000–4100 Å. The number “3950” was mistyped as “3890.” In Table 1 (Column 7, $M^\text{Est}$), three numbers, “$-21.5$”, “$-21.0$”, and “$-21.2$”, should be “$-24.5$”, “$-24.0$”, and “$-24.2$”, respectively. These correct values have been plotted in Figure 4 (y-axis) and discussed in Section 2.4. A tick label of the x-axis of Figure 4, “30”, was mistyped as “32”. None of these changes affect the results of the paper.