HOST GALAXIES OF LUMINOUS TYPE 2 QUASARS AT $z \sim 0.5^*$

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ABSTRACT

We present deep Gemini GMOS optical spectroscopy of nine luminous quasars at redshifts $z \sim 0.5$, drawn from the Sloan Digital Sky Survey type 2 quasar sample. Our targets were selected to have high intrinsic luminosities ($M_V < -26$ mag) as indicated by the $\text{[O III]} \lambda 5007$ Å emission-line luminosity ($L_{\text{[O III]}}$). Our sample has a median black hole mass of $\sim 10^{8.8}$ $M_\odot$ inferred assuming the local $M_{\text{BH}}-\sigma$ relation and a median Eddington ratio of $\sim 0.7$, using stellar velocity dispersions $\sigma$ measured from the G band. We estimate the contamination of the stellar continuum from scattered quasar light based on the strength of broad H$\beta$, and provide an empirical calibration of the contamination as a function of $L_{\text{[O III]}}$; the scattered-light fraction is $\sim 30\%$ of $L_{\text{[O III]}}$ for objects with $L_{\text{[O III]}} = 10^{9.5} L_\odot$. Population synthesis indicates that young poststarburst populations ($< 0.1$ Gyr) are prevalent in luminous type 2 quasars, in addition to a relatively old population ($> 1$ Gyr) which dominates the stellar mass. Broad emission complexes around He $\Pi$ $\lambda 4686$ Å with luminosities up to $10^{8.3} L_\odot$ are unambiguously detected in three of the nine targets, indicative of Wolf–Rayet (WR) populations. Population synthesis shows that $\sim 5$ Myr poststarburst populations contribute substantially to the luminosities ($> 50\%$ of $L_{\text{[O II]}}$) of all three objects with WR detections. We find two objects with double cores and four with close companions. Our results may suggest that luminous type 2 quasars trace an early stage of galaxy interaction, perhaps responsible for both the quasar and the starburst activity.

Key words: galaxies: active – galaxies: evolution – galaxies: interactions – galaxies: nuclei – galaxies: starburst – galaxies: stellar content – quasars: general

Online-only material: color figures

1. INTRODUCTION

Most, if not all, bulge-dominated galaxies harbor supermassive black holes (SMBH; Kormendy & Richstone 1995; Magorrian et al. 1998). Studying the host galaxies of the most luminous quasars is essential for understanding the coupled evolution of SMBHs and galaxies. The linked growth has been strongly informed by the similar redshift evolution of the space density of quasars (e.g., Boyle & Terlevich 1998; Hasinger et al. 2005; Richards et al. 2006) and that of the star formation rate (SFR; e.g., Connolly et al. 1997; Chapman et al. 2005), and the correlation between black hole mass and bulge stellar velocity dispersion (the $M_{\text{BH}}-\sigma$ relation) found in local inactive galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000).

Simulations of gas-rich mergers (e.g., Di Matteo et al. 2005) ascribe SMBH–galaxy co-evolution to merge-induced starburst and quasar activity that in turn outputs energy (“feedback”) regulating further growth (Silk & Rees 1998; Fabian 1999). While these models claim to be successful in interpreting multiple observations (such as the quasar luminosity function and the distribution of Eddington ratios; e.g., Hopkins et al. 2006; Shem 2009), the predicted brief phases of concurrent starburst and quasar activity, in spite of being crucial for the growth of stellar populations and SMBHs, are rarely observed.

There is growing evidence that low-luminosity active galactic nuclei (AGN) are not mainly induced by major mergers (e.g., based on close neighbor or galaxy lopsidedness studies; Fuentes-Williams & Stocke 1988; De Robertis et al. 1998; Pierce et al. 2007; Ellis et al. 2008; Li et al. 2008; Reichard et al. 2009). For the most luminous quasars ($L_\odot > 10^{46}$ erg s$^{-1}$), on the other hand, gas-rich mergers have long been implicated, as supported by the close companions and tidal tails seen in early Hubble Space Telescope (HST) studies of quasar host galaxies (e.g., Bahecall et al. 1997; Kührakos et al. 1999), but the merger scenario remains controversial (e.g., Floyd et al. 2004; Bennert et al. 2008; Urrutia et al. 2008).

In a study of $\geq 20,000$ type 2 AGN with $L_{\text{[O III]}} / L_\odot \sim 10^{5.0} - 10^{8.5}$ (extinction corrected) at $z < 0.3$ selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000), Kauffmann et al. (2003) found that the host galaxies of AGN with higher luminosities have younger mean stellar ages than a control sample of inactive galaxies, while those of AGN with lower luminosities have stellar ages similar to those of normal early-type galaxies. At higher luminosities ($L_{\text{[O III]}} > 10^{8.5} L_\odot$), it is unclear whether luminous quasars preferentially reside in massive elliptical galaxies with little recent star formation activity (e.g., McLure et al. 1999; Nolan et al. 2001; Dunlop et al. 2003), or if there is considerable recent or ongoing forming activity (e.g., Boroson & Oke 1982; Heckman et al. 1997; Canalizo & Stockton 2000; Jahnke et al. 2004; Letawe et al. 2007).

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Studies of the stellar populations and interaction rates in the most luminous quasars are significantly hampered by the high contrast between nuclear and stellar light. Techniques to circumvent this problem include taking off-nucleus spectra (e.g., Hutchings & Crampton 1990; Nolan et al. 2001; Watson et al. 2008; Wolf & Sheinis 2008) and modeling and subtracting nuclear light in observed on-nucleus spectra (e.g., Magain et al. 2005; Letawe et al. 2007; Jahne et al. 2007). Here, we focus on luminous obscured quasars, for which the obscuring material acts as a natural coronagraph, allowing detailed study of the host-galaxy morphology and stellar populations.

Due to the redshift evolution and the shape of the quasar luminosity function (e.g., Boyle et al. 2000; Richards et al. 2006), low-redshift quasars comparable to luminous high-redshift quasars are quite rare, and in addition the obscured ones are hard to find. Reyes et al. (2008) have recently published a sample of ∼100 type 2 quasars with $L_{\text{[O III]}} > 10^{43} \text{L}_\odot$ (among a total of ∼900 type 2 quasars with $L_{\text{[O III]}} > 10^{43} \text{L}_\odot$). This paper presents deep Gemini optical spectroscopy of a pilot sample of nine luminous type 2 quasars with $L_{\text{[O III]}} > 10^{43} \text{L}_\odot$ at redshift $z \sim 0.5$. We determine the relative contribution of old and young stellar populations to probe the starburst–quasar link. We measure stellar velocity dispersions, allowing us to determine black hole masses assuming the $M_\bullet-\sigma$ relation (Tremaine et al. 2002). We combine these measurements with estimates of quasar intrinsic luminosities to obtain accretion rates.

The strict interpretation of AGN unification models (e.g., Antonucci 1993) states that type 1 and type 2 quasars are identical aside from our viewing angle. Here, we test a prediction of unification by quantifying the level of scattered light from the accretion disk present in type 2 quasars, as seen so dramatically in the polarization measurement of Zakamska et al. (2005) and the pilot imaging survey of Zakamska et al. (2006, see also Cid Fernandes et al. 2004). Of course, this scattered-light component is a substantial contaminant to our estimates of ongoing star formation, and it is thus critical to quantify. We also address the more fundamental issue of whether or not strict unification holds; a substantial fraction of type 2 quasars may well suffer from galaxy-scale obscuration associated with vigorous star formation, making the type 2 population as a whole more biased toward star-bursting populations (e.g., Martínez-Sansigre et al. 2006; Rigby et al. 2006; Lacy et al. 2007).

The paper is structured as follows. We discuss sample selection in Section 2, and describe our Gemini observations and data reduction in Section 3. Our data analysis method and results are provided in Section 4. We present implications and discussion in Section 5, and summarize our main conclusions in Section 6. Throughout we use AB magnitudes and assume a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $h = 0.7$.

### 2. SAMPLE SELECTION: THE MOST LUMINOUS SUBGROUP OF SDSS TYPE 2 QUASARS

Our targets were drawn at the high-luminosity end of a parent sample of ∼900 optically selected type 2 quasars in the SDSS (Zakamska et al. 2003; Reyes et al. 2008). The luminosity of the $\text{[O III] } \lambda 5007$ emission line, $L_{\text{[O III]}}$, is adopted as a proxy for the intrinsic quasar luminosity. Arising from the narrow-line region, the forbidden line $\text{[O III] } \lambda 5007$ should be much less affected by circumnuclear obscuration; its luminosity is observed to be correlated with the broadband continuum luminosity in unobscured quasars (e.g., Reyes et al. 2008).

We need sufficient spectral resolution and high enough signal-to-noise ratio (S/N) in the continuum to obtain robust measurements of stellar velocity dispersions. The SDSS spectra have adequate spectral resolution ($R \sim 2000$), but the continuum S/N for most objects at the high-luminosity end is inadequate, typically $<3$ pixel$^{-1}$. Based on $L_{\text{[O III]}}$ measured from the SDSS spectra, we selected a pilot sample of nine objects with $L_{\text{[O III]}} > 10^{43} \text{L}_\odot$ (corresponding to intrinsic luminosities $M_V < -26$ mag; see below) for deep follow-up optical spectroscopy. In addition, all of our targets were selected to be radio-quiet to avoid complications from radio jets in interpreting the results, and to be at redshifts $z \sim 0.5$ for proper wavelength coverage. There is no additional selection criterion other than the visibility of the target at the observing time. In particular, we did not select on continuum flux, so these objects are representative of the parent sample at any fixed $L_{\text{[O III]}}$. The targets are listed in Table 1 in increasing R.A. order.

### 3. OBSERVATION AND DATA REDUCTION

#### 3.1. Follow-up Observation with Gemini GMOS

Optical long-slit spectra were obtained for the nine targets using the Gemini Multi-Object Spectrograph (GMOS) on...
Gemini-North on 12 nights between 2006 August and 2007 January (program ID: GN-2006B-0493). The seeing was variable, ranging from 0.4 to 1.1 arcsec. The slit width used was 0.5 arcsec, corresponding to ~ 3 kpc (physical) at redshifts $z \sim 0.5$ in the assumed cosmology. The spatial sampling of the detector was 0.29 arcsec pixel$^{-1}$. The total exposure time for each target ranged from 1 to 4 hr (with 30 minutes per exposure) depending on weather conditions, and is listed in Table 1. The median S/N per rest-frame 1.0 Å was 22, 32, and 43 over the spectral ranges 3900–3960, 4250–4320, and 5150–5350 Å. These S/N Å$^{-1}$ achieved in GMOS spectra of our targets are at least 10 times larger than those of their SDSS spectra. The slit was centered on the quasar itself and oriented to cover as many objects in the field as possible to observe potential companions and/or extended-emission-line regions.

The R400-G5305 grating was adopted with a dispersion of ~ 0.45 Å pixel$^{-1}$ and a spectral resolution of $R \sim 1900$, spanning an observed wavelength range of 5000–8000 Å. At the redshifts of our targets, this corresponds to rest-frame 3300–5300 Å, a range covering the prominent signatures of both old and young stellar populations (see Section 4.3). An A0 white dwarf (G191B2B) was observed as a flux standard. We also observed a spectroscopic standard star (a K-giant) to calibrate the instrumental resolution (see Section 4.1 for our calibration approach).

### 3.2. Data Reduction

The reduction of the two-dimensional spectra was performed in IRAF using the Gemini GMOS package. The main steps to reduce each science exposure before flux calibration include bias subtraction, flat fielding, interpolation across the chip gaps, cleaning for cosmic rays and bad pixels, wavelength calibration using arc exposures taken right before and after observing each target, sky subtraction, and extraction of the one-dimensional spectrum. The spectra were extracted using a 5 arcsec aperture, which was determined from the extension of the point-spread function (PSF).

The science spectra were then flux calibrated using the photometric standard star and corrected for atmospheric extinction using the curve appropriate for the Gemini observatory with IDL routines as described in Matheson et al. (2008). The spectra were shifted to the heliocentric frame. Different exposures of the same target were calibrated separately before being co-added since they had different air masses and observing epochs. The resulting one-dimensional spectra of the nine targets are displayed in Figure 1.

We check the spectrophotometry of our targets against their SDSS spectra, of which the spectrophotometry for point sources is better than 5% (Adelman-McCarthy et al. 2008). The general agreement between the two observations in both continuum and emission-line luminosities is illustrated in Figure 2. While on average the two measurements agree, for several objects they differ from each other by more than 5%. We have checked that the continua of the GMOS and SDSS spectra of each of our targets are in reasonable agreement, whereas the strongest emission lines [O iii] $\lambda\lambda4959,5007$ Å differ both in shape and in amplitude for several objects. Since we know the [O iii] is spatially more extended, the line-shape differences presumably reflect the different spatial coverage of the SDSS fiber (3” diameter) and the Gemini long slit. Indeed, two-dimensional spectra show that the spatial extent of the strong emission lines is usually larger than that of the continuum. We conclude that the differences between the GMOS and SDSS measurements, if any, are most likely due to the difference in the long-slit and fiber coverage and slit losses due to seeing variations. We take these differences as the estimate of systematic uncertainties. The systematic error added in quadrature to the measurement error is taken as the total uncertainty for the luminosity measurement.

### 4. DATA ANALYSIS AND RESULTS

In this section, we present our data analysis methods and results. We measure stellar velocity dispersions in Section 4.1, estimate scattered light from the strength of broad Hβ in Section 4.2, analyze stellar populations in Section 4.3, and present double cores, companions, and/or extended-emission-line regions covered by our long-slit observations in Section 4.4.

#### 4.1. Stellar Velocity Dispersion

Several stellar absorption features of representative old populations are discernable in Figure 1. These include Ca K $\lambda3934$ Å and the G band $\lambda4304$ Å seen in most of our targets, and Mg I b $\lambda5175$ Å and Fe $\lambda5270$ Å apparent at least in SDSSJ0157−0053. Ca H $\lambda3968$ Å is unusable for all objects in our luminous-quasar sample due to the overlapping strong emission lines of [Ne ii] $\lambda3968$ Å and He λ.

We fit the data with broadened model spectra in pixel space to include a power-law component to account for possible scattered quasar light (Section 4.2), and mask spectral regions containing emission lines, detector gaps, and bad pixels. We use the direct-fitting algorithm of Greene & Ho (2006a) and Ho et al. (2009), with a model spectrum constructed by a stellar template convolved with a Gaussian as an approximation of the line-of-sight (LOS) velocity broadening function, plus a power-law component. We include a power-law component here only to measure stellar velocity dispersions; the quantification of the non-stellar continuum is discussed later in Section 4.2. In addition, the summed components are multiplied by a third-order polynomial in order to model the difference in continuum shape between data and templates, which could result from reddening, template mismatch, and/or calibration uncertainties (Greene & Ho 2006a).Template stars were drawn from the stellar library of Valdes et al. (2004), which have a spectral coverage of 3460–9464 Å with a resolution of ~1 Å full width at half-maximum (FWHM). This resolution corresponds to $\sigma \sim 15$ km s$^{-1}$, much smaller than the ~65 km s$^{-1}$ instrumental resolution of GMOS and SDSS. The difference between the resolution of the stellar templates and the instrumental resolution of GMOS has been subtracted in quadrature from the $\sigma$ measurement. We include several K stars with different subclasses to account for the primary contribution from old populations, plus an F2 star and a G5 star to model potential young stars.

Since the targets are at $z \sim 0.5$, it was impossible to observe a velocity template star with the identical setup as the science targets. We thus adopt the following two-step procedure to calibrate the instrumental resolution. We first obtained arc-lamp exposures before and after observing each science target, from which we measure the instrumental resolution. We then use the spectroscopic standard star spectrum, taken with Gemini, as a sanity check by measuring the instrumental resolution both using our arc-lamp procedure and also from our velocity
Figure 1. Flux-calibrated Gemini GMOS spectra (smoothed by a 6-pixel boxcar for display purpose) of the nine targets in this study. Downward arrows indicate the expected positions of stellar absorption features Ca K $\lambda 3934$ Å, G band $\lambda 4304$ Å, Mg I b triplet $\lambda 5175$ Å, and Fe $\lambda 5270$ Å. Ca K and the G band are discernable in most cases. The Mg I b triplet and Fe, on the other hand, show no clear detections except in SDSSJ0157$-$0053, most likely due to the contamination by adjacent emission lines from Fe and N ions and their intrinsically smaller equivalent widths. In almost all targets, [O III] $\lambda\lambda 4959,5007$ Å lines show significant asymmetry and deviation from Gaussian.

Figure 2. Continuum and emission-line luminosities measured from GMOS and SDSS spectroscopic observations. The SDSS observations are made from 3 arcsec diameter fibers, whereas the GMOS long-slit spectra were extracted using a 5 arcsec aperture with a slit width of 0.5 arcsec. The $B$-band luminosity $L_B$ is calculated as that emitted between rest-frame 3980–4920 Å (Zakamska et al. 2003). The emission-line [O III] $\lambda 5007$ luminosity $L_{[\text{O III}]}$ is obtained from non-parametric fits using the model profile of [O III] lines (Reyes et al. 2008). The symbol size corresponds to ±5% calibration errors. The continuum and emission-line measurements from the two observations agree, given the systematics due to the difference between long-slit and fiber coverage and seeing slit losses.
templates at much higher resolution. The two measurements for the spectroscopic standard star agree, lending support to our overall approach of using arc exposures to calibrate the instrumental resolution.

Spectral fitting was performed using each single star as the template at first and then with a linear combination of different types of stars to yield best-fit parameters. There are seven free parameters in a fit with a single-star template (the center and width for the Gaussian, the amplitude for the power law, and four coefficients for the third-order polynomial). The power-law index is fixed at $\alpha = -1.5$; we found that the dispersion measurements are insensitive to the assumed values of $\alpha$ in the range from $-1.5$ to $-1.0$. The minimization of $\chi^2$ is performed using the nonlinear Levenberg–Marquardt algorithm implemented by the IDL package “mpfit.” The uncertainties are dominated by systematics, which include template mismatch, particularly due to non-solar abundances in the program galaxies and differing intrinsic widths for different spectral types (e.g., Ho et al. 2009). For active galaxies, the situation is further complicated by emission-line contamination (specifically from Fe and N ions in the Mg I b triplet and Fe regions; e.g., Greene & Ho 2006a). In order to mitigate these effects, we first measure the local velocity dispersions over three spectral regions 3700–4020 (Ca K), 4130–4600 (G band), and 5080–5450 (Mg–Fe) Å for every case in which a reasonable fit can be obtained. We define a fit as “acceptable” if the reduced $\chi^2 < 8$ and the model traces stellar absorption features reasonably well as seen by eye. We found acceptable fits to the G band in all cases, whereas we found trustworthy fits for six of the nine objects around Ca K and for only one object over the Mg–Fe region. The Ca K and Mg–Fe regions suffer more severely from surrounding emission lines than the G band. Fitting over these two regions is more difficult also due to the intrinsically smaller equivalent widths (EWs) of Mg I b and Fe, and the narrow cores of Ca K resulting from host-galaxy interstellar absorption. Despite these difficulties, the velocity dispersions from the Ca K and Mg–Fe regions agree with the G band results within 1σ uncertainties in all cases. We take the G band results as fiducial values in the following analysis.

Spectral fittings for the G band over the spectral range 4130–4600 Å are displayed in Figure 3 for all nine targets, and results from the fits are given in Table 2. The velocity dispersions $\sigma_*$ listed have been corrected for instrumental resolution (Section 3.1). The listed total uncertainty of $\sigma_*$ contains the measurement error and the estimated systematic effects, which are mostly dominated by template mismatch. The measured stellar velocity dispersions range from $\sim 120$ to 400 km s$^{-1}$, with a median value of $\sim 290$ km s$^{-1}$. The inferred black hole masses and Eddington ratios are discussed in Section 5.1.

The stellar and gas velocity dispersions (estimated as FWHM/2.35 of [O III]) are compared in Figure 4. In our sample, there is no correlation between them; the Spearman correlation coefficient is $\rho = -0.5$ with $P_{null} = 0.2$ for the whole sample.
objects in our sample (Figure 1). The uncertainty of FWHM [O III] is estimated by template mismatch. The gas velocity dispersion is determined as FWHM / 2.35 of [O III].

Figure 2. The two objects marked with open circles have resolved double core objects (Bernardi et al. 2006). Similarly, our measurements may be biased by additional stellar components covered by the slit. Indeed, as discussed in Section 4.4, SDSSJ0950+0511 and SDSSJ0823+3231 are both such double-core systems marginally resolved in our longslit observations. As discussed in Section 5.1, their black hole masses (Eddington ratios) listed in Table 2 are therefore likely to be overestimated (underestimated). Second, our results have not been corrected for aperture effects. At redshifts of 0.5, the size of our aperture (corresponding to ~ 30 kpc) is large enough that the old stellar populations from which we measure σ, and also contain those in the disk component, if any, so that the σ, (and extension black hole masses) are likely to be overestimated. However, we estimate that this contamination should be small, considering that most of the host galaxies of luminous type 2 quasars in our parent sample are likely to be dominated by ellipticals with de Vaucouleurs light profiles as seen in the imaging study of a pilot sample (Zakamska et al. 2006).

Figure 4. Comparison of stellar and gas velocity dispersions. The stellar velocity dispersion σ∗ is from the G band (Figure 3), the error of which is dominated by template mismatch. The gas velocity dispersion is determined as FWHM/2.35 of [O III]5007, which exhibits asymmetry and narrow lines seem to have several components at different velocities (Figure 1). This might be further evidence for interaction in addition to its close companion (see Section 4.4).

Table 2
Stellar Velocity Dispersions, Black Hole Masses, and Eddington Ratios

| Target Name           | σ○ (2) | σCa (3) | σMg (4) | M BH (5) | Mbh(M⊙) (6) | L Bol (7) | L Bol/L Edd (8) |
|-----------------------|--------|---------|---------|----------|-------------|-----------|----------------|
| SDSSJ0056+0032        | 119 ± 16 | 104 ± 13 | ···      | 7.2 ± 0.2 | ···         | 12.8 ± 0.5 | 12.9 ± 0.9     |
| SDSSJ0134+0014        | 180 ± 21 | 157 ± 33 | ···      | 7.9 ± 0.2 | ···         | 13.1 ± 0.5 | 4.8 ± 1.4      |
| SDSSJ0157−0053        | 212 ± 15 | 229 ± 27 | 182 ± 9 | 8.2 ± 0.1 | 9.2 ± 0.4   | 13.3 ± 0.5 | 5.0 ± 1.1      |
| SDSSJ0210−1001        | 346 ± 43 | ···      | ···      | 9.1 ± 0.2 | 9.2 ± 0.4   | 13.3 ± 0.5 | 5.0 ± 1.1      |
| SDSSJ0319−0058        | 286 ± 15 | 299 ± 35 | ···      | 8.8 ± 0.1 | ···         | 13.2 ± 0.6 | 5.7 ± 0.6      |
| SDSSJ0801+4412        | 250 ± 43 | ···      | ···      | 8.5 ± 0.3 | 9.1 ± 0.4   | 12.9 ± 0.6 | 7.2 ± 0.4      |
| SDSSJ0823+3231        | 348 ± 56 | 338 ± 336 | ···    | 9.1 ± 0.3 | 9.2 ± 0.3   | 13.2 ± 0.5 | 5.9 ± 0.1      |
| SDSSJ0943+3456        | 358 ± 50 | ···      | ···      | 9.1 ± 0.2 | 9.6 ± 0.3   | 13.3 ± 0.5 | 4.3 ± 0.3      |
| SDSSJ0950+0511        | 423 ± 61 | 363 ± 75 | ···      | 9.4 ± 0.3 | ···         | 12.9 ± 0.6 | 4.0 ± 0.6      |

Notes. Columns 2–4: stellar velocity dispersion in units of km s⁻¹ (corrected for instrumental resolution; Section 4.1). The total uncertainty consists of the measurement error and the systematics dominated by template mismatch estimated using template stars with different types; Column 5: black hole mass in the form of log(MBH/M⊙) inferred from σ, assuming the MBH–σ relation of Tremaine et al. (2002). The uncertainty on MBH listed here is propagated from that of σ, which does not include the intrinsic scatter in the MBH–σ relation (smaller than 0.25–0.3 dex on MBH; Tremaine et al. 2002); Column 6: virial black hole mass in the form of log(M/M⊙), which is derived based on the width of the broad-Hβ line and the intrinsic quasar continuum luminosity inferred from L[O III] (see Table 3) using the formula of Greene & Ho (2005). The uncertainty is dominated by the error of the quasar intrinsic luminosity; Column 7: quasar bolometric luminosity in the form of log(L/L⊙) inferred from L[O III]; See Section 5.1 for details; Column 8: Eddington ratio. The uncertainty is estimated with error propagation from the uncertainties of MBH and L Bol, where L Edd = c²GMBH/σ∗. Two caveats must be mentioned here.

and ρ = −0.2 with P null = 0.7 when excluding the two double-core objects (see below). Other than the two double-core objects, five out of seven objects have σ > FWHM[O III]/2.35. Greene et al. (2009) also find no correlation in a sample of > 100 SDSS type 2 quasars with L[O III] / L⊙ ~ 10⁵−⁷. SDSSJ0943+3456 (the object at the upper right corner in Figure 4) has the largest gas velocity dispersion in our sample (FWHM/2.35 of [O III] ~ 300 km s⁻¹). While its two-dimensional spectrum shows no strong evidence for extended gas, it is conceivable that the gas is highly disturbed since the narrow lines seem to have several components at different velocities (Figure 1). This might be further evidence for interaction in addition to its close companion (see Section 4.4).
starlight from young stellar populations and scattered quasar light in the continuum, we need to determine and remove the contamination from scattered light before performing stellar population modeling to the continuum.

To quantify the level of scattered quasar light, we model the Hβ line as the sum of a narrow and an underlying broad component from scattered light. Then, we make use of the tight correlation between the Hβ and the continuum luminosities observed in unobscured AGN (e.g., Greene & Ho 2005) to infer the corresponding non-stellar continuum. The rms scatter of this correlation is $\sim 0.2$ dex (Greene & Ho 2005) and is added in quadrature with the measurement error into the uncertainty of our estimate of the scattered light. The assumption of our approach is that if broad lines are present with a certain flux, the quasar continuum should also be present at a level proportional to the broad emission-line flux. Hβ is adopted because it is the strongest permitted line in the wavelength range covered by the GMOS spectra.

The procedure to quantify the broad-Hβ component is the following. First, a continuum model is constructed by performing a $\chi^2$ fit to the emission-line-masked spectrum over the range of 3600–5600 Å using multiple instantaneous starburst templates of Bruzual & Charlot (2003) broadened with the measured stellar velocity dispersion and a power-law component assuming $\alpha_\lambda = −1.5$. Next, we make a four-component fit (broad Hβ, narrow Hβ, [O iii] $\lambda$4959, and [O iii] $\lambda$5007) to the continuum-subtracted GMOS spectrum over the range of 4780–5100 Å. We fit each of the three narrow emission lines non-parametrically with an [O iii]-profile model constructed using the blue wing of [O iii] 4959 and the red wing of [O iii] 5007 (Reyes et al. 2008). For objects like SDSSJ0943+3456, which appears to have several components with different velocities in its narrow lines, we do not need to use multiple components to fit the narrow-line profile, since they are accounted for at all once using the model constructed from the [O iii] lines. Unlike parametric multi-component fits, this non-parametric approach is free from degeneracies between multiple narrow and broad components, introducing no additional uncertainty to the measurement of broad Hβ. The assumption here is that the narrow Hβ component has the same profile as that of [O iii]. Their redshifts are constrained to be the same as they all originate from the narrow-line region. The broad Hβ is fitted as a single Gaussian. There are seven free parameters in one fitting (a redshift for the three narrow lines, an amplitude for each narrow line, and three parameters for the Gaussian). Although, in principle, one should iterate the continuum and emission-line fits, in practice we have found the broad-Hβ component to be insensitive to the details of the continuum fit so that one iteration is enough.

As pointed out by Reyes et al. (2008), it is important to use the [O iii] line profiles instead of Gaussians or Lorentzians to fit the strong narrow emission lines. Almost all the objects in our luminous-quasar sample have narrow-line profiles which deviate significantly from Gaussian and Lorentzian profiles, often with strong asymmetries and sometimes double peaks. The specific profiles of the strong narrow emission lines, if not properly accounted for, can cause false broad-Hβ detections.

The broad-Hβ measurements are summarized in Table 3. We unambiguously detect broad-Hβ components in four objects; we list 1σ upper limits on broad Hβ for the other five objects. The uncertainty on the broad-Hβ luminosity is estimated using the 1σ flux-density error spectrum integrated over 4794–4932 Å, which is equivalent to assuming a Gaussian with a FWHM of 8000 km s$^{-1}$ centered at 4863 Å. This is a rather conservative estimate, considering that the broad-Hβ components detected in our sample all have FWHM $\gtrsim 4000$ km s$^{-1}$.

Figure 5 presents examples of significant and null broad-Hβ detections, respectively. The unambiguous broad-Hβ detections or robust upper limits rely on the high S/N achieved by our GMOS observations (a median S/N of 56 per rest-frame 1.0 Å over the spectral range of 4841–4881 Å).

Using the correlation between Hβ luminosity and monochromatic continuum luminosity $L_{5100}$ determined from unobscured AGN by Greene & Ho (2005), we quantify the amplitude of the scattered-light component $L_{5100}^{\text{scattered}}$ (or its upper limit when undetected) as listed in Table 3. We adopt a scattered-light spectrum with a spectral index of $\alpha_\lambda = −0.44$ (Vanden Berk et al. 2001).

One caveat that must be mentioned here is that we are measuring the scattered light inside our slit, the contribution of which could vary with slit position because the scattering can be very asymmetric (e.g., Zakamska et al. 2006). In particular, if the slit is oriented perpendicular to the axis of the scattering cone, the scattered light covered by long-slit spectroscopy could be much smaller than that detected by broadband polarimetry. In our sample, only SDSSJ0056+0032 has broadband (observed 480–600 nm) polarization measurement (P. Smith 2009, private communication; Zakamska et al. 2006), which indicates a high level of polarization (10.2% ± 1.6%) suggesting a significant scattered-light contribution (> 10%) around rest-frame ~ 3600 Å. A scattered-light fraction of 10% at ~ 3600 Å will translate into 5% at 5100 Å (both in rest frame) given the spectrum of SDSSJ0056+0032, assuming $\alpha_\lambda = −0.44$, which is not in conflict with our 1σ upper limit ($L_{5100}^{\text{scattered}}/L_{5100}^{\text{obs}} < 9\%$).

However, the estimate of scattered-light fraction at 5100 Å based on polarization measurement can be larger than 5% assuming a more typical intrinsic continuum polarization (e.g., 20%), and thereby differ from our estimate based on the strength of broad Hβ. This possible discrepancy may be due to the difference in coverage of the long-slit and broadband observations. Indeed, the GMOS slit was oriented within 15% of the polarization position angle and was therefore almost perpendicular to the scattering direction.

4.3. Stellar Populations

Our Gemini spectra cover a spectral range containing various signposts for both young and old populations. These include: (1) the 4000 Å break and stellar absorption lines (such as Ca ii K&H at 3934, 3968 Å, the G band at 4304 Å, the Mg b triplet at 5175 Å, and Fe 5270 Å) indicative of relatively old populations (i.e., with ages > a few Gyr); (2) the Balmer continuum limit at 3646 Å and the Balmer absorption-line series representing poststarburst populations (with ages < 1 Gyr); and (3) the broad Wolf–Rayet (WR) emission complexes around ~ 4660 Å which trace very recent starburst activity in the last 5 Myr.

As foreshadowed by Heckman et al. (1997) in their study of Mrk 477, one of the most luminous local type 2 quasars, detecting poststarburst signatures through Balmer absorption becomes more difficult at high luminosity, because of the strong Balmer emission lines excited by the AGN. Indeed as seen in Figure 1, the Balmer absorption series is barely discernable for most of the nine luminous quasars. The only exception is SDSSJ0056+0032 (which lies at the low-luminosity end of our sample, and has prominent very young stellar populations, see below), for which the high-order Balmer absorption lines (H8, H9, and H10) are visible.
Figure 5. Quantifying the broad-Hβ component to constrain scattered-light contamination of the stellar continuum. The two examples represent null (SDSSJ0056+0032) and significant (SDSSJ0823+3231) detections, respectively. Each of the narrow emission lines, Hβ and [O iii] λλ 4959, 5007, is modeled using a template combining the blue wing of [O iii] λ 4959 and the red wing of [O iii] λ 5007 (Reyes et al. 2008). The broad-Hβ component is modeled as a Gaussian. Top row: spectra are presented over the fitting range 4780–5100 Å. Data are plotted in black and best-fit models are in green. Gray curves show the continuum model which has been subtracted before line fitting. Middle row: continuum-subtracted spectra zoomed in at the base. The model for the broad/narrow Hβ is shown in red/blue. Bottom row: residuals from the fittings (smoothed with 6-pixel boxcar) are shown (solid), along with 1σ error spectra (dotted) and null residuals (dashed). (A color version of this figure is available in the online journal.)

Table 3
Scattered-Light Quantification and Continuum Decomposition Based on Broad-Hβ Measurement

| Target Name               | L_{broad}^{Hβ} (10^43 erg s^{-1}) | L_{scattered}^{5100} (10^43 erg s^{-1}) | I_{scattered}/I_{QSO}^{5100} (%) | I_{scattered}/I_{obs}^{5100} (%) |
|---------------------------|------------------------------------|----------------------------------------|---------------------------------|---------------------------------|
| Obj. w/o detected broad Hβ |                                    |                                        |                                 |                                 |
| SDSSJ0056+0032            | <7.29                              | <0.74                                  | <9                              | <0.2                            |
| SDSSJ0134+0014            | <7.66                              | <1.6                                   | <17                             | <0.2                            |
| SDSSJ0157−0053            | <7.04                              | <0.45                                  | <8                              | <0.2                            |
| SDSSJ0319−0058            | <7.66                              | <1.6                                   | <17                             | <0.2                            |
| SDSSJ0950+0511            | <7.69                              | <1.7                                   | <5                              | <0.4                            |
| Obj. with detected broad Hβ |                                    |                                        |                                 |                                 |
| SDSSJ0210−1001            | 7.84^{+0.31}_{-0.21}               | 2.3^{+0.2}_{-0.1}                      | 37 ± 22                         | 0.5^{+0.4}_{-0.3}               |
| SDSSJ0801+4412            | 7.70^{+0.26}_{-0.20}               | 1.7^{+0.3}_{-0.2}                      | 45 ± 36                         | 0.2^{+0.1}_{-0.1}               |
| SDSSJ0823+3231            | 8.16^{+0.08}_{-0.07}               | 4.3^{+0.3}_{-0.2}                      | 55 ± 12                         | 0.4^{+0.3}_{-0.2}               |
| SDSSJ0943+3456            | 8.09^{+0.15}_{-0.11}               | 3.7^{+0.9}_{-0.7}                      | 26±8                           | 0.3^{+0.2}_{-0.2}               |

Notes. Column 2: luminosity of the broad-Hβ component in the form of log(L/L_⊙) determined from emission-line fits over the continuum-subtracted GMOS spectra. For objects with null broad-Hβ detection, 1σ upper limits are given. The fitting method and error estimation are described in Section 4.2; Column 3: quasar (scattered light) monochromatic luminosity L_{5100} = λL_5100 at rest-frame λ = 5100 Å, determined from the broad-Hβ luminosity, using the L_{5100}−L_{Hβ} calibration of Greene & Ho (2005). The uncertainty contains both that propagated from the broad-Hβ luminosity and the scatter in the observed L_{5100}−L_{Hβ} correlation; Column 4: percentage of scattered quasar light relative to the total observed luminosity at rest-frame λ = 5100 Å. The uncertainty is propagated from the errors of L_{scattered}^{5100} and L_{obs}^{5100}. Since this ratio is a relative quantity, it is independent of the calibration uncertainty of the GMOS spectra; Column 5: percentage of the nuclear quasar light scattered into our line of sight. The intrinsic L_{QSO}^{5100} (unobscured) is inferred from L_{[O iii]} using the L_{[O iii]}−M_{2500} calibration (Reyes et al. 2008) and assuming a spectral index of α_v = −0.44 (Vanden Berk et al. 2001). The uncertainty contains both that propagated from L_{scattered}^{5100} and the scatter in the L_{[O iii]}−M_{2500} relation (Reyes et al. 2008).
The broad emission complex around He II λ 4686 Å due to WR stars, on the other hand, is more prominent in luminous type 2 quasars. WR stars are very massive evolved stars that appear only ∼2–5 Myr after a burst of star formation (e.g., Vacca & Conti 1992; Schaerer & Vacca 1998), whose several km s⁻¹ winds produce the broad emission features. Because of their short duration, WR stars are an excellent clock for very recent starburst activity. In addition, the subtypes of WR stars (e.g., WN or WC) can be inferred from the relative strengths of different WR features, and the WR luminosity can then be further translated into the number of WR stars present (e.g., Smith 1991; Schaerer & Vacca 1998).

### 4.3.1. Wolf–Rayet Populations

In this section, we address the frequency of WR populations in luminous type 2 quasars. Conspicuous WR signatures in the optical are less affected by dust obscuration than are UV tracers in characterizing starburst activity (e.g., Kunth & Contini 1999). WR populations have been observed in a number of quasar hosts in the nearby universe, including the famous infrared-luminous galaxy IRAS 09104+4109 (Kleinmann et al. 1988; Trane et al. 2000), and three luminous type 2 Seyfert nuclei studied by González Delgado et al. (2001) including Mrk 477 (Heckman et al. 1997). However, the frequency of their occurrence and their relation to the nuclear activity in luminous quasars remain important open issues.

In order to quantify WR populations, we fit the broad WR emission features and the surrounding nebular emission lines simultaneously to the continuum-subtracted GMOS spectra over 4550–4800 Å. Here, we use “nebular” to denote the emission lines that do not arise from WR stellar outflows (which are narrow for the forbidden lines and could have broad bases due to scattered light for the permitted lines). Fitting both simultaneously is required to isolate the WR features (Brinchmann et al. 2008), but is only possible with high S/N spectra. The continuum model is constructed in an identical way as that in the broad-Hβ fits (Section 4.2).

The WR features to be detected include: N v λ 4610, N iii λ 4640, C iii/iv λ 4650, and He ii λ 4686 Å. They are fitted with four Gaussians. While there are no constraints applied on the widths of these four WR features, only those broader than the narrow emission lines are considered as detections. The WR features are broadened as they arise from stellar outflows and the widths can vary significantly among individual WR stars.

The surrounding nebular emission lines include [Fe iii] λ 4658, [Fe ii] λ 4669, He ii λ 4686, [Fe iii] λ 4701, [Ar iv] λ 4711, He i λ 4713, [Ne iv] λ 4714, [Ne iv] λ 4725, [Ar iv] λ 4740, and [Fe iii] λ 4755 (for the line list, see, e.g., Heckman et al. 1997; Brinchmann et al. 2008). The nebular He ii λ 4686 Å is modeled with the profile of Hβ, which conveniently accounts for the scattered light, if any, to avoid false WR detection of He ii; each of the other nebular emission lines is fitted with a single Gaussian, the width of which is fixed to be that from a combined fit of the strong narrow lines (narrow Hβ and [O iii] λ 4959,5007). Gaussian profiles are adequate for these relatively weak forbidden lines (from ions of Fe, Ar, and Ne, with Ar lines being the strongest among them), as we find that given the S/N of our spectra, the asymmetries in these lines are insignificant. The redshifts of all the features are fixed to be the same as that of the strong [O iii] lines.

WR features have been unambiguously detected in three out of the nine targets, as shown in Figure 6. Also displayed in comparison are two objects with null detections and one object with only suggestive WR features, which we do not count as a detection (see figure caption for details). We list results for the three targets with definitive WR detections in Table 4. Luminosities emitted in each of the WR features and the total WR luminosity are presented with measurement uncertainties. The WR luminosities are comparable to or higher than the most luminous WR galaxies known (e.g., Osterbrock & Cohen 1982; Armus et al. 1988). The inferred subtypes and the numbers of WR stars are also listed, along with the ratio between WR and Hβ (narrow) luminosities which can be viewed to first-order approximation as the ratio between WR and O stars (e.g., Smith 1991). The three targets with unambiguous WR populations all have WN subtypes (Smith et al. 1996), similar to Mrk 477 (Heckman et al. 1997). The C iii/iv bump at 4650 Å indicative of WC subtypes is not detected in any of the nine objects. We list the estimates of WN subtypes from the intensity ratio between different WR features according to Smith et al. (1996). The line widths are consistent with those expected from the corresponding WN subtypes (Smith et al. 1996).

### 4.3.2. Population Modeling of the Stellar Continuum

We now fit stellar population models to the stellar continuum to get a more complete view of the mix of ages in the host galaxies. First, we fit the stellar continuum using a linear combination of nine instantaneous starburst models with ages of 0.005, 0.025, 0.10, 0.29, 0.64, 0.90, 1.4, 2.5, and 5.0 Gyr from Bruzual & Charlot (2003), after masking emission lines and detector chip gaps. We use those nine age grids to sample the whole history of a z ∼ 0.5 galaxy, having in mind a model in which the bulk stellar population in a galaxy was built up in multiple starburst events at different epochs. For objects that have broad-Hβ detections (Section 4.2), a model of scattered quasar light is subtracted assuming α = -0.44 (Vanden Berk et al. 2001). In producing the instantaneous starburst model, we assume “Padova1994” stellar evolutionary tracks (Bruzual & Charlot 2003) and a Chabrier initial mass function (IMF; Chabrier 2003) with a low- and high-mass cutoff of 0.1 and 100 M☉, respectively. We adopt solar metallicity in the baseline models; assuming super-solar metallicity would result in smaller age estimates whereas assuming subsolar metallicity would result in larger ages. Template spectra are broadened by the measured stellar velocity dispersions (Section 4.1).

Fitting was performed over the rest-frame spectral range of 3650–5600 Å. Fitting instead over the range 3600–5600 Å results in a slightly higher contribution from young stellar populations for the objects with the largest L[O iii] in our sample. This is most likely due to the Balmer continuum emission blueward of 3646 Å from the quasar which could bias stellar ages toward younger values.

We have also tested fitting the stellar continuum using only one instantaneous starburst template to the scattered-light-subtracted spectra (using scattered-light models constructed with either detected broad-Hβ components or upper limits). The reduced χ² as a function of age is shown in Figure 7. For each object, there are two ages at which the reduced χ² reaches a local minimum. In almost all cases, they represent two populations, one relatively young (<0.1 Gyr) and one relatively old (>1 Gyr), which dominate the starlight. Fitting a single-age model prefers a young population (<0.1 Gyr) over an older (>1 Gyr) one in most cases. Thus, the data cannot be explained by pure old populations plus scattered light; there is a substantial contribution from young populations. The ages of the young populations that we find are significantly smaller...
Figure 6. Broad Wolf–Rayet (WR) emission complexes around He\ ii\ \(\lambda\) 4686 Å. They include: N\ v\ doublet\ \(\lambda\) 4610 Å, N\ iii\ \(\lambda\) 4640 Å, C\ iii/iv\ \(\lambda\) 4650 Å, and He\ ii\ \(\lambda\) 4686 Å. In each example shown, data (black) and best-fit model (dark gray) are displayed on the top and residuals from the fits (smoothed by a 6-pixel boxcar) are shown on the bottom along with 1\σ error spectra (dotted) and null residual (dashed). Models for WR features are shown in red. Plotted in blue is the model for He\ ii\ \(\lambda\) 4686, the strongest nebular line in this range, which is fit non-parametrically with the observed H\ β-line profile. Details of our fitting method are presented in Section 4.3.1. Two examples of null WR detection are presented in the top row: SDSSJ0157−0053 has no detectable scattered light, while SDSSJ0823+3231 has scattered light detected in a broad component to H\ β\ (Figure 5). WR features are detected unambiguously in three targets (SDSSJ0056+0032, SDSSJ0134+0014, and SDSSJ0950+0511). The suggestive WR feature is less convincing in SDSSJ0801+4412: the apparent WR component of He\ ii\ \(\lambda\) 4686 could in fact be due to the degeneracy with the nebular component, and the detections of the other three WR features are marginal. Results from the three clear detections are summarized in Table 4.

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

than the typical poststarburst ages (\(\gtrsim\) 1–2 Gyr) estimated in host galaxies of quasars with lower luminosities (Kauffmann et al. 2003; Canalizo et al. 2007; Bennert et al. 2008, see Section 5.4).

Similarly, in the nine-component fittings, we find that two components dominate the fits in almost every case, one relatively old (\(\gtrsim\) 1 Gyr) and one relatively young (\(<\) 0.1 Gyr), so that we redo the fits with just these two. The two components with the highest weights in a nine-component fit also produce the best fit when we allow the ages to vary (among the adopted nine age grids) in a two-component fit, which justifies our choice. Two-population fitting produces a reduced \(\chi^2\) at least 10% smaller than that when we fit the data with a single population, while adding a third population does not significantly improve the fits.

Figure 8 displays two examples of population synthesis results for objects without detectable scattered quasar light, and the fit for the object with the highest scattered-light fraction is illustrated in Figure 9. In Table 5, we list the estimated total stellar masses, ages, and fractional contributions to stellar luminosity and mass of the two populations. The uncertainty of the age estimates can be inferred from the population model grids we use. For example, if the listed best-fit age is 0.005 Gyr, the next model examined was 0.025 Gyr, so its uncertainty can be estimated as \(<\) 0.025 Gyr. We find that eight of our nine targets contain a very young (\(<\) 0.1 Gyr) and an old (\(\gtrsim\) 1 Gyr) population; in half of these, the age estimates for the young components are \(<\) 25 Myr. The one object which does not have a considerable contribution from a \(<\) 0.1 Gyr population (SDSSJ0157−0053) has an age estimate for its younger population of 1.4 Gyr. The young stellar populations in the three objects with WR populations (Section 4.3.1) all have best-fit ages of 5 Myr for the young population, and this population contributes \(>\) 50% of \(L_{5100}\) in all three cases. This age estimate from population modeling of the stellar continuum...
Table 4
Measurements of Wolf–Rayet Features Around He ii 4686

| Target Name (1) | \(L_{\text{NV}}\) (2) | \(E_{\text{NV}}\) (3) | \(\text{FWHM}_{\text{NV}}\) (4) | \(L_{\text{OIII}}\) (5) | \(E_{\text{OIII}}\) (6) | \(\text{FWHM}_{\text{OIII}}\) (7) | \(L_{\text{HeII}}\) (8) | \(E_{\text{HeII}}\) (9) | \(\text{FWHM}_{\text{HeII}}\) (10) | \(L_{\text{WR}}\) (11) | Type (12) | \(N_{\text{WR}}\) (13) | \(L_{\text{WR}}/N_{\text{WR}}\) (14) |
|----------------|---------------------|--------------------|---------------------|-------------------|--------------------|---------------------|-------------------|--------------------|---------------------|------------------|--------------|--------------|------------------|
| SDSSJ0056+0032 | 7.04^{+0.04}_{-0.05} | 2.4 ± 0.2 | 1920 ± 200 | 7.18^{+0.05}_{-0.06} | 3.3 ± 0.4 | 1830 ± 250 | 7.42 ± 0.05 | 4.5 ± 0.5 | 1830 ± 250 | 7.67 ± 0.06 | WN6–8 | 10^5 | 0.10 ± 0.01 |
| SDSSJ0134+0014 | 7.33^{+0.07}_{-0.08} | 3.9 ± 0.7 | 2680 ± 540 | 7.40^{+0.04}_{-0.05} | 4.5 ± 0.5 | 1600 ± 230 | 7.67 ± 0.06 | 11.9 ± 0.3 | 6410 ± 250 | 8.28^{+0.01}_{-0.04} | WN8 | 10^5 | 0.14 ± 0.02 |
| SDSSJ0950+0511 | 7.06^{+0.03}_{-0.08} | 3.9 ± 0.7 | 1520 ± 280 | 8.28^{+0.01}_{-0.04} | 11.9 ± 0.3 | 8.31 ± 0.01 | 8.28^{+0.01}_{-0.04} | 11.9 ± 0.3 | 8.31 ± 0.01 | 8.28^{+0.01}_{-0.04} | WN3–4 | 10^6 | 0.80 ± 0.03 |

Notes. Rows 2, 5, and 8: luminosity of the WR feature in the form of \(\log(L/L_\odot)\); Rows 3, 6, and 9: equivalent width of the WR feature; Rows 4, 7, and 10: full width at half-maximum of the WR feature; Row 11: total luminosity combining all the WR features detected around He ii 4686 in the form of \(\log(L/L_\odot)\); Row 12: subclass of WR stars estimated based on the intensity ratio between different WR features according to the classification of Smith et al. (1996); Row 13: number of WR stars present estimated from the luminosity and the subclass; Row 14: ratio of the WR and H\beta luminosities. This can be estimated as the lower limit to \(N_{\text{WR}}/N_{\text{HeII}}\) first-order approximation (e.g., Smith 1991).

Figure 7. Reduced \(\chi^2\) from stellar population fitting using a single-age instantaneous starburst model. Contamination from scattered quasar light has been excluded before the fitting. Results for different targets are color coded as labeled on the plot. See Section 4.3.2 for more discussion.

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

...is in good agreement with the detection of WR populations, even though they were constrained independently.

In Table 5, we also list the average SFRs in the past \(< 0.1\) Gyr estimated from the stellar masses contained in the young stellar population divided by its estimated age. The inferred median SFR in our sample is ~ \(44\, M_\odot\, \text{yr}^{-1}\) (uncorrected for extinction). This is smaller than the median SFR (~ \(87\, M_\odot\, \text{yr}^{-1}\)) inferred from the IR luminosities of the Zakamska et al. (2008) sample of 12 SDSS type 2 quasars (with a median \(L_{[\text{OIII}]}\) of \(10^{44}\, L_\odot\), comparable to that of our sample) assuming the calibration of SFR–\(L_{[\text{OIII}]i}\) for starbursts from Kennicutt (1998). In particular, SDSSJ0056+0032 is also in the Zakamska et al. (2008) sample and our estimate of its SFR from population synthesis (~ \(36\, M_\odot\, \text{yr}^{-1}\)) is smaller than that inferred from its IR luminosity (~ \(137\, M_\odot\, \text{yr}^{-1}\)). The discrepancy in its two SFR estimates suggests an extinction level of ~ 1.5 mag.

Several caveats must be considered here. First, the results are all based on spectra uncorrected for internal reddening or extinction so that the inferred contribution from young stellar populations and the stellar luminosity and mass estimates could be underestimated. If scattering is by dust, then the spectral energy distribution (SED) of the scattered light may be bluer (or redder) than the intrinsic \(\alpha_v = -0.44\), leading to an overestimate (or underestimate) of the young population contribution. The effects of dust in the narrow-line region are discussed in Section 5.3. Third, while we have subtracted scattered quasar light based on the detection of broad H\beta (Section 4.2), there still might be some underestimated scattered light which could contaminate the stellar continuum if the broad component had width \(> 8000\) km s\(^{-1}\). Nevertheless, the effect of this possibility on our results is likely to be small, considering broad-line quasars with such extreme line widths are quite rare. Finally, since our targets were selected from luminous type 2 quasars, the results on host galaxies may not necessarily apply to unreddened luminous type 1 quasars, since they may trace different evolutionary phases (discussed below).

4.4. Double Cores, Companions, and Extended-emission-line Regions

In Figure 10, we show spatial profiles of the nine targets constructed by collapsing the spectra over the whole observed wavelength range, centered on the most luminous peak along the spatial direction. The spatial profile of the photometric standard star is also shown for comparison. While in many objects the central spatial profiles are consistent with a single PSF, those of at least two objects (SDSSJ0823+3231 and SDSSJ0950+0511) deviate significantly from a single PSF and exhibit evidence for two components within the central 5 arcsec (what we call “double cores”). Arrows mark all the cases of double cores, companions, and extended-emission-line regions (we refer to the latter two cases as “companions” in general) that are physically associated with the central components. The physical association is verified by determining the redshifts of companions using either emission or absorption lines. The
two-dimensional spectra of the two objects with double cores centered on Hβ and [O iii] along the wavelength direction are shown in Figure 11.

There are several possibilities concerning the nature of the companions, which include: (1) a cloud of gas which either is photoionized by the central nucleus and/or heated by shocks, or whose dust is reflecting nuclear light, (2) a region of active star formation, and (3) a companion galaxy which either is merging with the central nucleus or is a leftover from a past interaction event, or a small satellite which is not interacting with the nucleus at all (at the time of observations). Discriminating among these possibilities is useful to assess the significance of galaxy interactions in triggering luminous-quasar activity. We list the projected spatial offsets, LOS velocity offsets, SDSS magnitudes, and several diagnostic emission-line measurements of the companions and double cores in Table 6. A companion to SDSSJ0056+0032 and a companion to SDSSJ0319−0058 with relative radial velocities > 1000 km s$^{-1}$ are not listed.

The companions in SDSSJ0319−0058 and in SDSSJ0950+0511 are likely to be regions of active star formation, given their diagnostic emission-line ratios [O ii]/[O iii] and/or Hβ/[O iii] (e.g., Osterbrock 1989). For the companion in SDSSJ0319−0058, there is no evidence for disturbance or interaction with the central nucleus in its two-dimensional spectrum (e.g., multiple components at different velocities or tidal tails). In the double-core system SDSSJ0950+0511, it is likely (see below) that galaxy interaction is responsible for both the quasar and the young starburst activity, and that the luminous type 2 quasar is at an early stage of interaction. The companion at ∼−32 kpc has an LOS velocity offset (relative to the more luminous core) similar to that of the less luminous core (Figure 11, right panel). This suggests that the companion is physically associated with the less luminous core and might have been stripped off as a result of the merger in the nucleus (which is marginally resolved in this case).

The companion in SDSSJ0943+3456 is an absorption-line galaxy. It is likely to be a relic core from a past interaction event with the central galaxy, because it has a best-fit stellar age of 5 Gyr from stellar population synthesis, which is the same as the older population in the circumnucleus stellar component.
We have detected several stellar absorption features (including Ca K&H, the G band, Mg I b, and Fe 5270) in its spectrum and measured its resulting from the ongoing merger. Since SDSSJ0823+3231 is scattered light from gas clouds outside the ionizing cones are unlikely to be galaxies, as there are no stellar features detected in the continua. The non-stellar continua are most likely scattered quasar light. The emission lines seem to be from gas photoionized by the central nucleus. The absence of broad lines, and the large EWs than regions of active star formation. They are unlikely to be gas clouds either photoionized by the central nucleus and/or heated by shocks, or their dust is reflecting quasar light, or various origins, including a leftover galaxy core dominated by old stellar populations, merging galaxies with active star formation, and perhaps gas clouds shredded by the merger.

In summary, our long-slit spectroscopy reveals that at least four of our nine targets contain double cores and/or physically associated companions. Three of the four objects show evidence for galaxy interactions which may be responsible for the quasar and starburst activity. The companions in these systems have various origins, including a leftover galaxy core dominated by old stellar populations, merging galaxies with active star formation, and perhaps gas clouds shredded by the merger. We oriented the slit to cover potential companions seen in the imaging data, our spectra do not resolve scales < 1 arcsec so that the interaction fraction we find is a lower limit to the true value.

5. IMPLICATIONS AND DISCUSSION

In this section, we present implications and discussion on our results. We infer black hole masses and Eddington ratios in Section 5.1, and discuss the origins of the blue continua in luminous type 2 quasars in Section 5.2, with a prescription for the scattered quasar light in Section 5.2.1 and the starburst–quasar link in Section 5.2.2. Extinction and its effects on our results are provided in Section 5.3. In Section 5.4, we compare our results with those from other quasar host-galaxy studies, both obscured (Section 5.4.1) and unobscured (Section 5.4.2).

5.1. Black Hole Mass and Eddington Ratio

We infer black hole masses from the measured stellar velocity dispersions (Section 4.1) based on the correlation between bulge stellar velocity dispersion and dynamical black hole masses observed in local inactive galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000), using the calibration of Tremaine et al. (2002). The calibration for local inactive galaxies does not necessarily directly apply to active galaxies (e.g., Greene & Ho 2006b), considering that black holes in active galaxies are still in growth (e.g., Ho et al. 2008). Furthermore, while our targets only have moderate redshifts $z \sim 0.5$, there could be non-negligible redshift evolution in the $M_{\text{BH}}-\sigma_*$ relation (e.g., Woo et al. 2008; Canalizo et al. 2008). For objects with detected broad Hβ, we examine this redshift evolution in Section 5.1.2. We estimate accretion rates bearing in mind these uncertainties. Adopting $L_{\text{OIII}}$ as a proxy for quasar intrinsic power (see Section 5.1.1), we obtain quasar bolometric luminosities and Eddington ratios.

Black hole masses, quasar bolometric luminosities, and the inferred Eddington ratios are listed in Table 2 and displayed in Figure 12. Our sample has a median black hole mass of $10^{8.8} M_\odot$ and a median Eddington ratio of $\sim 0.7$. As cautioned in Section 4.1, SDSSJ0823+3231 and SDSSJ0950+0511 have resolved double cores in their central 5 arcsec which could bias $\sigma_*$ toward larger values, resulting in overestimated black hole masses and underestimated Eddington ratios for the central nuclei. Taking into account all the associated uncertainties, almost all of our targets are accreting at higher than 10% of the Eddington rates. The two targets estimated to have super-Eddington ratios both have WR detections. The Eddington ratios we find overlap with those of SDSS type 1 quasars studied by Shen et al. (2008) with comparable bolometric luminosities at similar redshifts (also see Greene et al. 2009).

The contamination on $L_{\text{OIII}}$ from star formation in our targets seems negligible given their $\text{OII}/\text{OIII}$ emission-line flux ratios listed in Table 7 (e.g., Ferland & Osterbrock 1986; Ho et al. 2008).
5.1.1. Bolometric Correction for Type 2 Quasars

We estimate bolometric luminosities \( L_{\text{Bol}} \) of type 2 quasars based on \( L_{\text{[OIII]}} \). First, we infer the intrinsic \( M_{2500} \) from \( L_{\text{[OIII]}} \) using the calibration by Reyes et al. (2008) of the \( M_{2500} - L_{\text{[OIII]}} \) relation observed in SDSS type 1 quasars. Then, we estimate \( L_{\text{Bol}} \) from \( M_{2500} \) using the bolometric correction for type 1 quasars (Marconi et al. 2004; Richards et al. 2006) and estimate the systematic uncertainty of the bolometric correction (the \( M_{2500} \) to \( L_{\text{Bol}} \) conversion) to be 0.1–0.2 dex in the relevant luminosity range (see below). The final calibration obtained is given by

\[
\log \left( \frac{L_{\text{Bol}}}{L_\odot} \right) = 0.99 \times \log \left( \frac{L_{\text{[OIII]}}}{L_\odot} \right) + 3.5, \tag{1}
\]

with a total 1\( \sigma \) uncertainty of 0.5 dex on \( \log(L_{\text{Bol}}/L_\odot) \) at \( L_{\text{Bol}} \sim 10^{13} L_\odot \). The total uncertainty of \( L_{\text{Bol}} \) convolves the errors propagated from the measurement error of \( L_{\text{[OIII]}} \), the 0.36 dex scatter of the \( M_{2500} - L_{\text{[OIII]}} \) relation (Reyes et al. 2008), the 0.05 dex scatter on \( L_{\text{B}}/L_{\text{Bol}} \) (Marconi et al. 2004), and the additional 0.1–0.2 dex systematic uncertainty (depending on \( L_{\text{[OIII]}} \)) from bolometric corrections using different estimates. The total uncertainty is dominated by the intrinsic scatter of the \( M_{2500} - L_{\text{[OIII]}} \) relation.

The systematic uncertainty of the bolometric correction for type 1 quasars is estimated by comparing three correction approaches: (1) converting from \( M_{2500} \) to \( L_{\text{B}} \) assuming \( \alpha_{\nu} = -0.44 \) (Vanden Berk et al. 2001) and to \( L_{\text{Bol}} \) with the luminosity-dependent \( B \)-band bolometric correction of Marconi et al. (2004), (2) converting from \( M_{2500} \) to \( L_{\text{Bol}} \) using the luminosity-independent bolometric correction of Richards et al. (2006), and (3) same as (2), but in the calculation of the bolometric correction, we extrapolate the 5000–10000 Å quasar spectrum into the mid-IR to avoid double counting of re-emitted radiation (Marconi et al. 2004; Reyes et al. 2008). At \( L_{\text{[OIII]}} > 10^{40} L_\odot \), method (2) gives results <0.2 dex higher than those of method (1), while method (3) gives results <0.2 dex lower than those of method (1). We take the results from method (1) as our baseline values and the differences among the three as our estimate of the systematic uncertainties.

5.1.2. Comparing Black Hole Mass Estimates Based on \( \alpha_{\nu} \) and Scattered Quasar Light

For the subset of targets which have broad-H\( \beta \) detection (Section 4.2), we could estimate virial black hole masses using the FWHMs from broad-H\( \beta \) measurements and the restored intrinsic quasar continuum luminosity \( L_{\text{QSO}} \) (Table 3) converted from \( L_{\text{[OIII]}} \) using the \( M_{2500} - L_{\text{[OIII]}} \) relation of Reyes et al. (2008) and assuming \( \alpha_{\nu} = -0.44 \) (Vanden Berk et al. 2001). Although it depends on the uncertain H\( \beta \) FWHM mass inferences (e.g., Marconi et al. 2009), and on the bolometric corrections for type 2 quasars, which again have a large systematic uncertainty, the scattered broad-line approach allows us to independently calibrate the estimation of black hole mass from host-galaxy properties (bulge stellar velocity dispersions and luminosities) in type 2 quasars. Results on the black hole mass \( M_{\text{BH}}^{\text{vir}} \) using the virial formula (e.g., Greene & Ho 2005) are listed in Table 2. The uncertainty of \( M_{\text{BH}}^{\text{vir}} \) is dominated by that propagated from the quasar intrinsic power. While the two approaches for estimating black hole mass are based on completely different assumptions and have separate systematic uncertainties, the virial estimates based on scattered quasar light are consistent with \( \alpha_{\nu} \)-based black hole masses within the estimated uncertainties. This

This statement still holds in the two super-Eddington targets.
general agreement lends further support to the robustness of both our scattered-light and \( \sigma_v \) measurements, at least for the small subset of targets having broad-H\( \beta \) detections. Based on our current data, we cannot draw any firm conclusion on redshift evolution considering the large uncertainties and the small sample size. While the associated uncertainties are large in practice, the approach offers the possibility to test the \( M_{BH} - \sigma_v \) relation in a \( \sigma_v \) range where it is not well tested at low redshifts (Lauer et al. 2007).
In this section, we first present the implications of the prevalence of young stellar populations in luminous type 2 quasars. (e.g., SDSSJ0056+0032). In this section, we first present the implications of the prevalence of young stellar populations in luminous type 2 quasars.

5.2.1. A Prescription for Scattered Light

The scattered-light contamination in low-luminosity type 2 AGN rarely exceeds 5% in the rest-frame optical (e.g., Cid Fernandes & Terlevich 1995; Schmitt et al. 1999; Kauffmann et al. 2003). However, we find that it can be significant when \( L_{[\text{O} \text{III}]} \) is large (Section 4.2), confirming the results of Zakamska et al. (2005, 2006) based on spectroscopic and HST imaging that a significant fraction of continuum emission can be due to scattered light in luminous type 2 quasars. The ratios \( L_{\text{scattered}}^{5100} / L_{\text{obs}}^{5100} \) for our nine targets range from < 5% to 55% (Table 3); combined with the estimated quasar intrinsic luminosity from \( L_{[\text{O} \text{III}]} \) (Section 5.1.1), the inferred scattered-light fractions \( L_{\text{scattered}}^{5100} / L_{\text{QSO}}^{5100} \) for our nine targets range from < 2% to 0.4%. In view of the high incidence of scattered light in luminous quasars, its quantification is particularly important for robust determination of stellar populations (Section 4.3).

Figure 13 displays both scattered-light luminosity and its fractional contribution as a function of \( L_{[\text{O} \text{III}]} \). Also shown are measurements compiled from the literature for comparison (see figure caption for details). The best-fit linear models to all the measurements compiled from the literature for comparison (see Section 5.1 for more discussion).

**Table 7**

| Target Name          | \( E_{[\text{B} - \text{V}]} \) | \( E_{[\text{B} - \text{V}]} \) | \( E_{[\text{B} - \text{V}]} \) | \( E_{[\text{B} - \text{V}]} \) |
|----------------------|-----------------|-----------------|-----------------|-----------------|
| SDSSJ0056+0032       | 0.35 ± 0.004    | 0.14 ± 0.003    | 0.54 ± 0.02     | 0.77 ± 0.03     |
| SDSSJ0134+0014       | 0.40 ± 0.005    | 0.20 ± 0.004    | 0.29 ± 0.02     | 0.30 ± 0.03     |
| SDSSJ0157–0053       | 0.45 ± 0.004    | 0.24 ± 0.003    | 0.05 ± 0.02     | 0.06 ± 0.02     |
| SDSSJ0210–1001       | 0.65 ± 0.005    | 0.34 ± 0.003    | −0.67 ± 0.01    | −0.38 ± 0.01    |
| SDSSJ0319–0058       | 0.56 ± 0.006    | 0.27 ± 0.004    | −0.36 ± 0.02    | −0.10 ± 0.02    |
| SDSSJ0801+4412       | 0.46 ± 0.008    | 0.24 ± 0.005    | −0.01 ± 0.03    | 0.07 ± 0.03     |
| SDSSJ0823+3231       | 0.40 ± 0.004    | 0.22 ± 0.003    | 0.29 ± 0.02     | 0.18 ± 0.02     |
| SDSSJ0943+3456       | 0.47 ± 0.005    | 0.19 ± 0.003    | −0.02 ± 0.02    | 0.33 ± 0.02     |
| SDSSJ0950+0511       | 0.38 ± 0.007    | 0.10 ± 0.005    | 0.38 ± 0.04     | 1.18 ± 0.06     |

**Notes.** Columns 2 and 3: emission-line ratios measured over continuum-subtracted GMOS spectra uncorrected for reddening. The quoted uncertainties were derived based on error spectra; Columns 4 and 5: color excess estimated from the intensity ratio \( F_{\lambda}/F_{\text{Bol}} \) (for Column 4) and \( F_{[\text{O} \text{III}]}/F_{[\text{O} \text{II}]} \) (for Column 5), assuming the intrinsic case B values of 0.466 and 0.256, respectively, for \( T = 10^4 \) K (Osterbrock 1989) and the extinction curve of Cardelli et al. (1989) with \( R_V = 3.1 \). For most of our targets (7 out of 9), the two reddening estimates do not agree with each other and some are negative, indicating deviations from standard reddening laws and the assumed foreground dust-screen model; Column 6: emission-line ratio \( F_{[\text{O} \text{III}]}/F_{[\text{O} \text{II}]} \) characterizing the ionization parameter. The \([\text{O} \text{III}],3727\) line of SDSSJ0319–0058 overlaps the GMOS chip gap and its listed value is measured from SDSS spectra.
coverage of the scattering cone by different observations even at a given observation angle, the empirical models are useful for a quick estimate of scattered light given any $L_{\text{OIII}}$. We caution that the scattered-light fraction estimated here (within the slit) is a lower bound to the total scattered-light fraction, since there could be considerable amount of scattered light outside our slit.

5.2.2. Young Starbursts

After the removal of scattered light, there is still considerable blue light in the spectra of our targets even before reddening correction. We found significant contributions ($\gtrsim 50\%$ of scattered-light-subtracted $L_{\text{5100}}$) from very young populations ($\lesssim 25$ Myr) in four out of nine of our objects; eight of our nine targets have $\gtrsim 20\%$ of $L_{\text{5100}}$ contributions from very young stellar populations (Table 5). In six of these objects, very young stars account for $< 5\%$ of the stellar mass.

Considering the short duration of the WR phase (2–5 Myr after a burst of star formation), the fact that $\gtrsim 30\%$ of our objects show WR features suggests that if the starburst and Eddington-rate feeding to the SMBH proceed coevally, the Eddington-rate quasar activity directly associated with the starburst lasts $\lesssim 10$ Myr, assuming type 2s do not evolve into type 1s. While a more careful estimate for the timescale can be obtained by assuming models for the quasar light curve and the evolving circumnuclear obscuration, the crude estimate here is in agreement with that based on black hole demographics (e.g., Yu & Tremaine 2002). Enhancing the statistical significance of our results will require studying a larger sample of Eddington-rate type 2 quasars. The general approach of using WR features as a clock demonstrated with our pilot sample here is another way to observationally estimate the Eddington-rate quasar duty cycle.

Our data do not have the spatial resolution to determine if these starburst events are in the immediate circumnuclear regions or are occurring on much larger galaxy scales. Nevertheless, it appears that galaxy interactions are responsible for or coincident with both the quasar and the starburst activity, at least in the double-core systems (Section 4.4).

5.3. Extinction and Its Effects on Our Results

Most of the results above are based on spectra uncorrected for dust extinction in the galaxies themselves. In Table 7, we list reddening estimates in the narrow-line regions from the intensity ratios $H_\beta/H_\delta$ and $H_\alpha/H_\beta$ using the Balmer decrement method, assuming the intrinsic case B values of 0.466 and 0.256, respectively, for $T = 10^4$ K (Osterbrock 1989), the extinction curve of Cardelli et al. (1989) with $R_V = 3.1$, and a model of a foreground obscuring screen. However, as found by Reyes et al. (2008) in a subset of the parent quasar sample having $L_{\text{OIII}} > 10^{40} L_\odot$, the intensity ratios $H_\alpha/H_\beta$ and $H_\gamma/H_\beta$ do not obey standard reddening laws, nor can they be described by a simple dust screen. We find a similar situation in our sample by comparing the intensity ratios $H_\gamma/H_\beta$ and $H_\delta/H_\beta$, seven out of nine of which have significantly different reddening estimates for the same object (Table 7).

Despite this caveat, the estimated color excesses $E(B-V)$ for our nine targets range from $-0.67 (-0.38)$ to 0.54 (1.18) with a median of 0.05 (0.18) according to $H_\gamma/H_\beta$ ($H_\delta/H_\beta$). The color excess estimated for the ULIRG, IRAS 09410+4109, by Tran et al. (2000) is $E(B-V) = 0.24$, also using the Balmer decrement combining the intensity ratios $H_\gamma/H_\beta$ and $H_\delta/H_\beta$, a value very similar to those found in our sample. However, the small color excesses derived using the Balmer decrement do not necessarily represent the true dust content of these objects; IRAS 09410+4109 is hyper-luminous in the infrared ($L_{\text{IR}} \gtrsim 10^{13} L_\odot$; Kleinmann et al. 1988) yet has a small color excess according to the Balmer decrement. This just suggests that most of the dust is concentrated on scales smaller than the Balmer lines are emitted. High extinction with little reddening could arise in objects with very patchy and optically thick dust clouds.

In view of the uncertainties in extinction geometry (e.g., Section 6.2 of Reyes et al. 2008), we do not apply corrections but rather keep in mind the potential effects on our results. The unaccounted extinction would also bias emission-line luminosity measurements smaller, which means that the quasar luminosities and Eddington ratios (Section 5.1; Figure 12) could be underestimated. The unaccounted reddening would bias the stellar ages higher and the estimates of the contribution from young populations lower (Section 4.3.2).
5.4. Comparison with Other Quasar Host-galaxy Studies

5.4.1. Host-galaxy Studies of Type 2s

We now compare our results with other host-galaxy studies of type 2 AGN. The present work is the first deep optical spectroscopic study of luminous type 2 quasars with $L_{[O\text{III}]} > 10^{9.3} L_\odot$. A number of previous groups have found that the presence of young stellar populations is a general property of type 2 AGN with high [O III] luminosities (e.g., Schmitt et al. 1999; González Delgado et al. 2001; Kauffmann et al. 2003; Cid Fernandes et al. 2004; Wild et al. 2007). However, the typical ages of young stellar populations ($<0.1$ Gyr) we find are much smaller than the poststarburst ages (1–2 Gyr) seen in the Kauffmann et al. (2003) subsample with $L_{[O\text{III}]} / L_\odot \sim 10^{7.9} - 10^{8.5}$ (reddening corrected). This result suggests that the luminosity dependence of host-galaxy stellar age and poststarburst fraction seen at lower luminosities (e.g., Heckman 1980; Ho et al. 2003; Kauffmann et al. 2003) extends to the most luminous quasars. Within our luminous-quasar sample, we do not see a dependence of stellar age on $L_{[O\text{III}]}$, but the scatter of the correlation (if any) should be large, and our sample may simply be too small to see such a correlation. A much larger sample is needed to study the luminosity dependence of host-galaxy properties in luminous type 2 quasars.

Most intriguingly, we detect WR populations in a third of our sample; WR features are much less often seen at lower luminosities (e.g., González Delgado et al. 2001). The fraction should be treated as a lower limit since it does not account for regions so obscured that they do not contribute to the optical emission. If starburst and quasar activity peak coevaly (e.g., Di Matteo et al. 2005), the chance of detecting the WR phase would be much larger in luminous quasars close to the peak activity than in less luminous quasars which are in their later stages of evolution, after WR features fade away and intermediate-age poststarburst signatures take over.

5.4.2. Host-galaxy Studies of Type 1s

We now compare our results with those from host-galaxy studies of type 1 quasars and address the issue of whether type 2s and type 1s follow a temporal sequence (e.g., Sanders et al. 1988; Hopkins et al. 2006). Our type 2 targets have quasar intrinsic luminosities of $M_V < -26$ mag (Section 5.1.1). There is virtually no spectroscopic information on host galaxies of type 1 quasars at this luminosity scale (but see Boroson & Oke 1982, for 3C 48).

Floyd et al. (2004) imaged 17 type 1 quasars with $-28 < M_V < -24$ mag and $z \sim 0.4$, and found them to be massive bulge-dominated galaxies. The Eddington ratios these authors find are comparable to those of our targets, despite the very different systematic uncertainties. Urrutia et al. (2008) studied 13 reddened type 1 quasars with $-26 < M_B < -24$ mag and $z \sim 0.7$, and found that 11 of them show evidence for recent interactions, a much higher fraction than that found by Floyd et al. (2004) and Guyon et al. (2006). While it is possible that deeper high-resolution imaging will reveal weak interaction features (see below), Urrutia et al. (2008) suggest that this inconsistency can be explained in the evolutionary scenario for quasar obscuration proposed by Sanders et al. (1988), in which dust-reddened type 1 quasars trace an earlier evolutionary phase than ordinary type 1 quasars, and thereby are more prone to signs of a merger.

If the evolutionary argument is true, we should also see a high interaction fraction in our obscured quasar sample. Zakamska et al. (2006) found almost half in their obscured quasar sample show signs of mergers or interactions. Only two of our targets show double cores (Section 4.4), but the stellar population results clearly suggest that our targets trace an early stage of galaxy interactions if they are responsible for the young starburst activity.

While the strict AGN unification model states that type 2s are the same as type 1s other than the difference in our viewing angle (e.g., Antonucci 1993), it is likely that orientation and evolutionary effects are both at work, and both need to be considered to interpret the selection of a type 2 quasar sample. If the opening angle increases as an object proceeds from the reddened to the ordinary quasar phase and the ordinary phase does not last much longer than the reddened phase (a statement that needs to be tested), both of which have ~ Eddington accretion rates, then by construction (averaged over both orientation and time), the majority in a sample of luminous type 2 quasars would be the obscured counterpart of reddened luminous type 1 quasars, with only a minority resembling regulars. In at least some type 2 quasars, extinction processes are observed to operate both at small scales due to circumnuclear dusty tori, and at galaxy scales due to star formation (e.g., Martínez-Sansigre et al. 2006; Rigby et al. 2006; Lacy et al. 2007). Using Spitzer spectra, Zakamska et al. (2008) show that SDSS type 2 quasars have the highest SFR among all quasar samples except for other samples of type 2 quasars. Luminous type 2 quasars, the majority of which resemble reddened type 1 quasars, should be sensitive to the early stages of quasar evolution, and hence are ideal for quantifying the role played by galaxy interactions.

Quasars with lower luminosities ($-25.5 < M_V < -23.5$ mag) and with smaller Eddington ratios ($0.01 < L/L_{\text{Edd}} < 0.1$) almost all reside in massive ellipticals with relaxed light profiles (Dunlop et al. 2003). Deeper imaging studies of a few objects in the Dunlop et al. (2003) sample have revealed shells and ripples which are interpreted as merger relics, with ages of several hundred of Myr to 1 Gyr estimated based on merger simulations (Canalizo et al. 2007; Bennert et al. 2008), consistent with spectroscopically determined poststarburst ages (e.g., Canalizo et al. 2007; 1.4 Gyr). While shells and ripples are telltale signatures of galaxy interactions, these systems are observed at a late stage of mergers, similar to the small subset associated with mergers in type 2 AGN (Kauffmann et al. 2003). The typical poststarburst ages of 1–2 Gyr (see also Jahnke et al. 2007; Letawe et al. 2007) are significantly larger than those of our targets ($< 0.1$ Gyr).

In summary, our results combined with those of other quasar host galaxies spanning different ranges of quasar luminosity and Eddington ratio may indicate that host-galaxy stellar population properties depend on both quasar luminosity (or more fundamentally Eddington ratio) and obscuration. This is because the two factors both characterize the phase of quasar evolution and by extension that of stellar evolution if the growth of SMBHs and stellar bulges are coupled. Clearly, more spectroscopic data and images with higher resolution are needed to better understand the host galaxies of both type 1 and type 2 quasars with luminosities comparable to luminous $z > 2$ quasars. It is important to quantify the fraction of objects containing WR populations in luminous type 1 quasars and to compare with our results
for luminous type 2 quasars, although doing so will be quite challenging because of the brightness of the quasar continuum.

6. SUMMARY

We present deep Gemini GMOS optical spectroscopy of nine luminous type 2 quasars at redshifts $z \sim 0.5$, drawn from the SDSS type 2 quasar sample of Zakamska et al. (2003) and Reyes et al. (2008). Our targets were selected to have high intrinsic luminosities ($M_V < -26$; $L_{\text{Bol}} \sim 10^{13} L_\odot$) inferred by the [O\textsc{iii}] luminosity.

Our main findings are as follows.

1. We unambiguously detect WR populations in three of our nine objects. These very young poststarburst populations are independently confirmed by population modeling of the stellar continuum: in all three targets with WR detections, a 5 Myr poststarburst population contributes substantially ($> 50\%$ of $L_{5100}$) to stellar continuum luminosities. In five of the six targets without WR detections, population modeling shows the presence of considerable ($> 20\%$ of $L_{5100}$) young ($< 0.1$ Gyr) poststarburst populations. We estimate a median SFR of our sample of $\sim 44 M_\odot$ yr$^{-1}$ (uncorrected for extinction).

2. We have subtracted continuum scattered light before performing our stellar population synthesis analysis. The scattered light is quantified by measuring a broad-H$\beta$ component underlying the strong narrow H$\beta$ line. The broad-H$\beta$ component is detected in four targets, and the inferred scattered light contaminates 30$\%$–60$\%$ to the total observed continuum at 5100 Å. The scattering fraction (within the slit) is estimated to be $\lesssim 0.4\%$ at 5100 Å in all our objects, while we caution it is a lower bound to the total scattered-light fraction, since there could be considerable amount of scattered light outside our slit. We provide a prescription for scattered light as a function of $L_{[\text{O}\textsc{iii}]}$ (Equation (2)) which can be used to get a quick but rough estimate of the contamination level.

3. We obtain stellar velocity dispersion measurements $\sigma_*$ for the host galaxies from the G band stellar absorption feature, which range from 120 to 420 km s$^{-1}$ in our sample. These correspond to black hole masses of $\sim 10^{7.2} - 10^{9.4} M_\odot$ with a median value of $10^{8.8} M_\odot$, assuming the $M_{\text{BH}} - \sigma$ calibration of Tremaine et al. (2002). Combined with the estimated intrinsic quasar power from $L_{[\text{O}\textsc{iii}]}$ (Equation (1)), the inferred Eddington ratios are $\sim 0.1$–12, with a median of 0.7 and a scatter consistent with measurement uncertainties.

4. Our long-slit spectroscopy shows that four of our nine targets contain double cores and/or physically associated companions. At least in three systems, a galaxy interaction might be responsible for both the quasar and the young starburst activity, and that luminous type 2 quasars with Eddington ratios close to unity perhaps trace an early stage of interaction. Our results combined with those from other quasar host-galaxy studies may suggest that host-galaxy stellar population properties depend on both luminosity and obscuration which characterize the phase of quasar evolution.

By targeting the obscured population, we are able to study stellar populations in quasars that are as luminous as the majority of $z > 2$ quasars. We are directly seeing the youngest stellar populations in quasar hosts, providing strong evidence for a direct link between ongoing starburst and luminous-quasar activity. However, our pilot sample is too small to study the correlations between quasar and host-galaxy properties, to probe the physical links and mutual influence of starburst and luminous-quasar activity. Correlation studies of AGN and their hosts at lower luminosities have yielded extensive physical insight (e.g., Kauffmann et al. 2003; Heckman et al. 2004) but are only enabled with the assembly of statistically large samples. We are going to carry out more observations in the optical to do such correlation studies in luminous type 2 quasars at $z \sim 0.5$. We look forward to the next generation of ground-based near-IR multi-object spectrographs (e.g., Bell et al. 2009) that will provide statistical samples of luminous obscured quasars at high redshifts to better understand the coupled growths of stellar populations and SMBHs in the early universe.

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