THE PROPERTIES OF POST-STARBURST QUASARS BASED ON OPTICAL SPECTROSCOPY

Sabrina L. Cales\textsuperscript{1,2}, Michael S. Brotherton\textsuperscript{2}, Zhaohui Shang\textsuperscript{2,3}, Jessie C. Runnoe\textsuperscript{2}, Michael A. DiPompeo\textsuperscript{3}, Vardha Nicola Bennert\textsuperscript{4}, Gabriela Canalizo\textsuperscript{5,6}, Kyle D. Hiner\textsuperscript{5}, R. Stoll\textsuperscript{7}, Rajib Ganguly\textsuperscript{8}, and Aleksandar Diamond-Stanic\textsuperscript{9,10}

\textsuperscript{1} Departamento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Chile; scales@astro-udec.cl
\textsuperscript{2} Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071, USA; scales@uwyo.edu, mbrother@uwyo.edu, shang@uwyo.edu, jrunnoe@uwyo.edu, ndipompeo@uwyo.edu
\textsuperscript{3} Tianjin Normal University, Tianjin 300387, China
\textsuperscript{4} Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA; vbennert@calpoly.edu
\textsuperscript{5} Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA; gabriela.canalizo@ucr.edu, khine001@ucr.edu
\textsuperscript{6} Institute of Geophysics and Planetary Physics, University of California, Riverside, CA 92521, USA
\textsuperscript{7} Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA; stoll@astronomy.ohio-state.edu
\textsuperscript{8} Department of Computer Science, Engineering, \& Physics, University of Michigan-Flint, Flint, MI 48502, USA; ganguly@umflint.edu
\textsuperscript{9} Center for Astrophysics and Space Sciences, University of California, San Diego, La Jolla, CA 92093, USA; aleks@ucsd.edu

Received 2012 August 12; accepted 2012 November 9; published 2012 December 19

ABSTRACT

We present optical spectroscopy of a sample of 38 post-starburst quasars (PSQs) at $z \sim 0.3$, 29 of which have morphological classifications based on \textit{Hubble Space Telescope} imaging. These broad-lined active galactic nuclei (AGNs) possess the spectral signatures of massive intermediate-aged stellar populations, making them potentially useful for studying connections between nuclear activity and host galaxy evolution. We model the spectra in order to determine the ages and masses of the host stellar populations, and the black hole masses and Eddington fractions of the AGNs. Our model components include an instantaneous starburst, a power law, and emission lines. We find that the PSQs have $M_{\text{BH}} \sim 10^8 M_{\odot}$, accreting at a few percent of Eddington luminosity and host $\sim 10^{10.5} M_{\odot}$ stellar populations which are several hundred Myr to a few Gyr old. We investigate relationships among these derived properties, spectral properties, and morphologies. We find that PSQs hosted in spiral galaxies have significantly weaker AGN luminosities, older starburst ages, and narrow emission-line ratios diagnostic of ongoing star formation when compared to their early-type counterparts. We conclude that the early-type PSQs are likely the result of major mergers and were likely luminous infrared galaxies in the past, while spiral PSQs with more complex star formation histories are triggered by less dramatic events (e.g., harassment, bars). We provide diagnostics to distinguish the early-type and spiral hosts when high spatial resolution imaging is not available.

\textit{Key words:} galaxies: active \& galaxies: evolution \& galaxies: interactions \& galaxies: Seyfert \& galaxies: starburst \& quasars: general

\textit{Online-only material:} color figures

1. INTRODUCTION

Galaxies harbor supermassive black holes (BHs) at their centers (e.g., Kormendy \& Richstone 1995), the masses of which correlate with that of the host galaxies' bulge component ($M_{\text{BH}} \sim 0.15\% M_{\text{bulge}}$; Merritt \& Ferrarese 2001; Magorrian et al. 1998; Gebhardt et al. 2000a). An even stronger correlation exists between the BH mass and the bulge stellar velocity dispersion (Gebhardt et al. 2000b; Ferrarese \& Merritt 2000; Tremaine et al. 2002). These correlations suggest that BHs and their host galaxies have common evolutionary histories. The nature of the mechanism which is responsible for the "coevolution" of both BH and bulge or even whether only one mechanism is responsible over cosmic time remains unclear. In order to grow to their observed masses, accreting BHs (i.e., active galactic nuclei, AGNs, and/or quasars) are expected to be a phase in the life of every galaxy (Richstone et al. 1998).

A new paradigm involving two mechanisms responsible for mutual BH–bulge growth has been suggested (e.g., Hasinger 2008; Hopkins \& Hernquist 2009; Schawinski et al. 2010b; Bennert et al. 2011). In the early universe, major-merger driven evolution dominates and is responsible for producing the bulk of the brightest quasars at $z = 2–3$. Below $z \sim 1$, secular evolution and minor interactions become the main fueling mechanisms. Thus, at lower redshifts, less massive systems preferentially show activity (i.e., AGN cosmic downsizing; e.g., Heckman et al. 2004). Furthermore, transitioning from quasar to Seyfert luminosities, fueling rates, and triggering mechanisms may also change (Hopkins \& Hernquist 2009), such that bars in spiral hosts may be sufficient to fuel the nuclear activity of Seyfert galaxies.

In merger-driven evolutionary scenarios, mergers trigger starbursts and the ignition of AGN activity that can in turn inhibit both star formation and its own fueling through feedback (Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2006). A natural consequence of such models is the existence of objects that have luminous quasar activity, starburst, or post-starburst signatures, along with indications of a recent merger, such as tidal debris. Indeed, objects like this do exist, such as UN J1025−0040 which also been called a post-starburst quasar (PSQ; Brotherton et al. 1999; Canalizo et al. 2000; Brotherton et al. 2002).

The post-starburst classification is given for galaxies exhibiting strong Balmer absorption lines, indicating intense star formation in the past $\sim 1$ Gyr, and a lack of ongoing star formation, as indicated by having little or no nebular emission lines.
(Dressler & Gunn 1983). Recently, the traditional definition for post-starburst galaxies has been found to be too narrow to encompass the full range in post-starburst populations (Falkenberg et al. 2009). In particular, placing a limit on nebular emission lines (i.e., [O II] λ3727) introduces a bias against AGNs (Yan et al. 2006; Wild et al. 2009; Kocevski et al. 2011) and can cause gross underestimation of post-starburst galaxies hosting AGNs since AGNs can power significant emission from [O II].

Several studies of AGN host galaxies in the Sloan Digital Sky Survey (SDSS) have shown that the most luminous AGNs have had a burst of star formation in the past ∼ 1 Gyr (Vanden Berk et al. 2001; Kauffmann et al. 2003). Additionally, there exists mounting evidence that post-starburst signatures are enhanced in AGNs compared to galaxies which do not exhibit AGN activity (Kocevski et al. 2009; Goto 2006; Georgakakis et al. 2008). In particular, Goto (2006) determines that the fraction of AGNs showing post-starburst features is at least 4.2%, while the fraction of normal galaxies exhibiting these features is 0.2%.

Low-redshift objects hosting the most massive starburst populations and most luminous AGNs may be our best chance at finding the analogs of merger-induced systems at the quasar epoch. Cales et al. (2011), hereafter C11, studied the morphology and disturbance fraction of PSQs via HST/ACS F606W imaging of the most luminous PSQ examples at z ∼ 0.3 from a spectroscopically selected catalog (Brotherton et al. 2007). C11 find that PSQs are a heterogeneous population of early-type and spiral hosts, with disturbances being equally distributed among the morphologies. The presence of early-type hosts which appear to be major-merger remnants, along with spiral hosts, both isolated and with companions, is suggestive of a more complicated picture than can be explained by galaxy mergers alone. It has become evident that at least two mechanisms are responsible for triggering PSQs, consistent with studies involving mutual BH–bulge growth.

Our follow-up project uses Keck and KPNO 4 m optical spectroscopy of a sample of 38 PSQs at z ∼ 0.3. We aim to characterize the BH masses, Eddington fractions, starburst masses, and starburst ages of PSQs via spectral modeling. Furthermore, 29 of these objects have morphological data from C11. We continue to characterize the fundamental properties of the AGN and starburst in PSQs and extend the study by investigating the interplay between the properties of PSQs and their morphological subpopulations.

We describe our sample, selection, and data reductions in Section 2. The methodology for decomposing AGNs and starburst stellar populations along with the outputted results and derived fundamental AGNs and post-starburst properties are given in Section 3. We present correlations between fitted and derived properties of the AGN and starburst features in addition to describing how the early-type and spiral host populations differ in Section 4. A summary of our results is given in Section 5. We adopt the cosmology $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and a flat universe where $\Omega_M = 0.3$ and $\Omega_L = 0.7$.

2. DATA

2.1. Sample

We investigate a sample of 38 objects spectroscopically selected from the Sloan Digital Sky Survey data release 3 (SDSS DR3; Abazajian et al. 2005) that meet the following criteria.

1. Broad emission lines as defined by the SDSS DR3 online database (FWHM > 1000 km s$^{-1}$).
2. $r$ model magnitudes $\lesssim 19$.
3. $0.25 < z < 0.45$.
4. S/N > 8 between rest wavelengths of 4150 and 4250 Å in the SDSS spectra.
5. Summation of the Balmer absorption lines Hδ, Hβ, and Hγ > 2 Å rest-frame equivalent width at a significance greater than 6σ.
6. Hβ > 1 Å rest-frame equivalent width.
7. Balmer break > 0.9; based on the ratio of the fluxes at two 100 Å wide regions centered at rest wavelengths 4035 and 3790 Å.

The above criteria ensure that all objects in the sample are luminous AGNs with clear post-starburst stellar populations. We call these objects PSQs regardless of whether their AGN component alone exceeds a formal luminosity separating quasar from Seyfert galaxy. Table 1 characterizes some observational properties of the sample. C11 classified morphologies and measured quasar-to-host light contributions based on HST/ACS imaging of a subsample of 29 of these objects. The following sections provide details of our additional ground-based spectroscopy which we obtained in order to improve signal-to-noise ratio (S/N) and wavelength coverage compared to the SDSS spectra.

2.2. KPNO Observations

We obtained long-slit spectra of 12 PSQs and their companions using the Kitt Peak National Observatory (KPNO) 4 m Mayall telescope on the nights of 2006 May 20–21. We used the R-C spectrograph along with the 312 groove mm$^{-1}$ KPC-10A grating, in first order, producing a dispersion of 2.75 Å pixel$^{-1}$ and a resolution of 6.9 Å FWHM on the TK2B 2048 × 2048 CCD detector. The wavelength range covered is 3200 to 7200 Å. The detector read noise and gain are 4 e$^-$ and 1.9 e$^-$ ADU$^{-1}$, respectively. The long slit is covered at a scale of 0.69 pixel$^{-1}$; the slit width was 300 μm or 2″.

We applied a standard observation strategy with the exception of rotating the slit in order to observe the primary PSQ and its nearest bright companion within 20″ (to be presented in a future publication). We obtained three 1200 s exposures for each target PSQ. There were three instances where we observed the same target twice, changing the slit angle in order to observe a different companion (i.e., SDSS J111515.59+673604.8, SDSS J123043.41+614821.8, and SDSS J164444.92+433204.5). In these cases, we obtained six 1200 s exposures of the primary PSQ. For one source (SDSS J170819.80+603759.4), two of the three 1200 s exposures had low S/N due to poor conditions, and we use the data from a single exposure in our analysis.

Reductions of the spectra were carried out in a standard manner using the IRAF$^\dagger$ software. After initial trimming, bias removal, and flat fielding, we extracted the one-dimensional cleaned spectrum using apall. We found the dispersion solution by identifying the lines of an He–Ne–Ar lamp. The spectra were flux calibrated using observations of several spectrophotometric standard stars (Massey et al. 1988). We median combined the individual spectrum with S/N weights using scombine. The combinations also include the SDSS spectrum in order to increase the S/N and the wavelength coverage of the resulting spectrum. Additional photometric corrections and combinations with other spectra were performed in a similar fashion as the Keck spectra and are described in Section 2.4.

$^\dagger$ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The position angles were selected so as to include nearby companion galaxies. The majority of objects were observed at low airmass to minimize the effects of differential atmospheric refraction. The only object that was not observed near transit was SDSS J040210.90—054630.3, which was observed at an airmass of 1.43.

The spectra were reduced with IRAF, using standard reduction procedures. After subtracting bias, dividing by a normalized halogen lamp flat-field frame and removing sky lines, we rectified the two-dimensional spectra and placed them on a wavelength scale using the least-mean-squares fit of cubic spline segments to identified lines in an Hg–Ne–Cd–Zn lamp. We calibrated the spectra using the spectrophotometric standards from Massey et al. (1988). The distortions in the spatial coordinate were removed with the IRAF apextract routines. For each slit position, we had two or three individual frames; we averaged the spatially corrected spectra using the IRAF task scombine.

2.3. Keck Observations

Spectroscopic observations were carried out on 2005 November 1 and 2 with the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I telescope. For the blue side (LRIS-B), we used the 600 groove mm$^{-1}$ grism blazed at 4000 Å, yielding a dispersion of 0.63 Å pixel$^{-1}$. For the red side (LRIS-R), we used the 400 groove mm$^{-1}$ grating blazed at 8500 Å, yielding a dispersion of 1.86 Å pixel$^{-1}$. The slit was 1′′ wide, projecting to ~7 pixels on the UV and blue-optimized CCD on LRIS-B and ~5 pixels on the Tektronix 2048 × 2048 CCD on LRIS-R.

We obtained between one or two exposures for each object, typically 1200 s each, dithering along the slit between exposures. The typical seeing for all observations was 0.′′1. Two or three spectrophotometric standards from Massey et al. (1988) were observed at parallactic angle each night for flux calibration.

| Object SDSS | $z$ | $r^a$ | $M_r^b$ | Total Int. Time (s) | Spectroscopy | Imaging$^c$ |
|-------------|-----|-------|---------|---------------------|--------------|------------|
| J003043.59—103517.6 | 0.296 | 18.26 | −22.98 | 1200 | Keck | HST |
| J005739.19+010044.9 | 0.253 | 17.61 | −23.23 | 1200 | Keck | HST |
| J015259.46+142738.0 | 0.311 | 18.44 | −22.87 | 1200 | Keck | HST |
| J020258.94—002807.5 | 0.339 | 18.19 | −23.50 | 1200 | Keck | HST |
| J021447.00—003250.6 | 0.349 | 18.54 | −23.09 | 1200 | Keck | HST |
| J022325.42—082832.1 | 0.265 | 17.50 | −23.54 | 1200 | Keck | ... |
| J023700.30—010130.5 | 0.344 | 18.58 | −23.05 | 1200 | Keck | HST |
| J025735.33—001631.3 | 0.362 | 18.67 | −22.95 | 1200 | Keck | ... |
| J032143.15—064517.5 | 0.365 | 19.26 | −22.56 | 2400 | Keck | ... |
| J040210.90—054630.3 | 0.270 | 18.70 | −22.45 | 1600 | Keck | HST |
| J074621.06+335040.7 | 0.284 | 17.97 | −23.12 | 1200 | Keck | HST |
| J075045.00+212546.3 | 0.408 | 18.01 | −24.18 | 1200 | Keck | HST |
| J075521.30+295039.2 | 0.334 | 18.69 | −22.83 | 1200 | Keck | HST |
| J075549.56+321704.1 | 0.420 | 18.82 | −23.24 | 2400 | Keck | HST |
| J105816.81+102414.5 | 0.275 | 18.29 | −22.63 | 3600 | KPNO | HST |
| J115159.59+673604.8 | 0.274 | 18.44 | −22.64 | 7200 | KPNO | HST |
| J115355.58+582424.3 | 0.319 | 18.29 | −22.88 | 3600 | KPNO | HST |
| J123043.41+614821.8 | 0.324 | 18.63 | −22.77 | 7200 | KPNO | HST |
| J124833.52+563507.4 | 0.266 | 17.45 | −23.46 | 3600 | KPNO | HST |
| J140513.75+625008.2 | 0.386 | 18.59 | −24.15 | 3600 | KPNO | ... |
| J145640.99+592702.3 | 0.277 | 18.14 | −22.84 | 3600 | KPNO | HST |
| J145658.15+593202.3 | 0.326 | 18.58 | −22.86 | 2400 | SDSS | HST |
| J154534.55+573625.1 | 0.268 | 18.07 | −22.88 | 3600 | KPNO | HST |
| J155214.85+659169.9 | 0.335 | 18.49 | −22.97 | 3600 | KPNO | ... |
| J164444.92+423304.5 | 0.317 | 18.98 | −22.16 | 7200 | KPNO | HST |
| J170046.95+622056.4 | 0.276 | 18.58 | −22.51 | 3600 | KPNO | HST |
| J170819.80+603759.4 | 0.289 | 18.92 | −22.19 | 1200 | KPNO | ... |
| J210200.42+000501.8 | 0.329 | 18.16 | −23.38 | 2400 | Keck | HST |
| J211343.20—075017.6 | 0.420 | 18.44 | −23.96 | 1200 | Keck | HST |
| J211838.12+055640.6 | 0.384 | 18.49 | −23.72 | 1200 | Keck | HST |
| J212843.42+003435.6 | 0.346 | 18.78 | −22.92 | 1200 | Keck | HST |
| J230614.18—010024.4 | 0.267 | 17.77 | −23.22 | 1200 | Keck | HST |
| J231055.50—090107.6 | 0.364 | 18.50 | −23.40 | 3600 | Keck | HST |
| J231317.85—082238.4 | 0.366 | 18.40 | −23.09 | 1200 | Keck | ... |
| J233430.89+140649.7 | 0.363 | 18.57 | −23.26 | 1200 | Keck | HST |
| J234335.48—005758.1 | 0.341 | 18.00 | −23.74 | 1200 | Keck | ... |
| J234403.55+154214.0 | 0.288 | 18.33 | −22.92 | 920 | Keck | HST |

Notes.

a SDSS DR7 $r$ AB magnitudes (modelMag_r).
b SDSS DR7 dereddened $r$-corrected $r$ absolute AB magnitudes.
c Denotes whether morphological data are available from HST ACS/WFC imaging.
Figure 1. Examples of our spectral decomposition of AGNs and post-starburst stellar population highlighting the (a) Mg \textsc{ii}, (b) Balmer break, (c) H\textbeta, and (d) H\textalpha regions. The red line is the data. The blue lines make up the components used in the fitting. For ease of interpretation, we plot the emission lines and Fe \textsc{ii} templates above the power law. The black line is the model fit to the data.

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

2.4. Finalized Spectra and Uncertainties

Since we chose to orient the slit to also observe neighboring objects we did not observe at parallactic angle. We used the SDSS spectra to correct for atmospheric diffraction slit losses. First, we divide our spectra by the corresponding SDSS spectra and fit the result by a low-order Legendre polynomial. We then corrected our spectra by dividing by the fitted polynomial. The resulting corrected spectra were well matched to the flux calibration of the SDSS spectra.

We corrected for Galactic extinction using the Schlegel et al. (1998) maps and the IRAF task \texttt{deredden} which utilizes the Cardelli et al. (1989) extinction curves. We converted the spectra to rest frame using the IRAF \texttt{dopcor} task using SDSS redshifts. We note that we retained observed fluxes.

We have used a single uniform method to estimate the noise for each spectrum. For each pixel, we compute the root-mean-square value of the difference between the signal and the average using nine pixels centered on the input pixel. We use this estimated noise spectrum to weight individual points in the fitting procedure we describe below.

3. STELLAR POPULATION SYNTHESIS AND AGN COMPONENT MODELING

We utilized the IRAF task \texttt{specfit} (Kriss 1994) to model the starburst populations and AGN contributions to the PSQs. The $\chi^2$ minimization technique of \texttt{specfit} simultaneously models multiple components. We characterized the AGN contribution of the PSQs using a power law, UV and optical iron emission line blends, as well as multiple Gaussian emission lines from the AGN broad- and narrow-line regions. A Charlot & Bruzual (S. Charlot & G. Bruzual 2007, private communication) instantaneous starburst (ISB) varying in age and mass describes the post-starburst component to the PSQs. We characterize the multiple fit components as originating either from the (1) AGN, (2) narrow-line regions, or (3) starburst, and we discuss these components in that order for the remainder of the paper.

We used the same initial guess parameters for each PSQ while changing the step sizes of the power-law index (0.02, 0.05, and 0.08) and starburst age (50, 100, and 200 Myr) corresponding to five runs for each object. We give plots of the runs corresponding to the best fits in the Appendix as well as zoom in on the broad lines and Balmer break for a few of our objects in Figure 1.

Table 2 gives the fitting results for the AGN power law, Fe \textsc{ii} templates, and broad lines. The AGN power-law contribution is described by a normalization factor at 1000 Å and the power-law index, $\alpha$: $f_{\lambda} \propto \lambda^{-\alpha}$. The UV and optical iron emission line blends are modeled using the UV and optical Fe \textsc{ii} templates derived from I Zw 1 (Vestergaard & Wilkes 2001; Boroson & Green 1992). We convolved a Gaussian with the Fe \textsc{ii} templates to simulate different velocity widths. The \texttt{specfit} task velocity-weight interpolates between the these templates and is also allowed to vary in intensity for each object.

Gaussian emission lines are described by the flux under the profile, line centroid, FWHM, and an asymmetry parameter. We found fitting two broad-line Gaussians to be satisfactory in matching the asymmetries and wings of emission lines.
originating from the broad-line region (i.e., Mg II, Hβ, and Hα). Thus, we held the asymmetry parameter at “symmetric” and include two broad Gaussians in order to better model the line asymmetries. We obtain a single broad-line FWHM by task age-weight interpolates and include two broad Gaussians in order to better model Hii region where degeneracies and a Chabrier (2003) initial mass function (IMF) to model the starburst contribution and find the best fit by varying the starburst age and intensity. The specfit task age-weight interpolates between the stellar population ages of 56, 75, 100, 133, 177, 237, 316, 422, 562, 750, 1000, 1330, 1770, and 2370 Myr. Our age estimates are insensitive to changes in the IMF. We discuss starburst mass calculations in Section 3.3. Table 5 gives fitting results for the post-starburst stellar populations.

After choosing the fit corresponding to the best χ², we analyzed the goodness of fit by eye for each object and interactively made adjustments to the fit parameters as necessary. We discarded components where the S/N was low (≤5; particularly troublesome for Mg II and in some objects the UV Fe II templates) and in the complicated Hβ region where degeneracies and a Chabrier (2003) initial mass function (IMF) to model the starburst contribution and find the best fit by varying the starburst age and intensity. The specfit task age-weight interpolates between the stellar population ages of 56, 75, 100, 133, 177, 237, 316, 422, 562, 750, 1000, 1330, 1770, and 2370 Myr. Our age estimates are insensitive to changes in the IMF. We discuss starburst mass calculations in Section 3.3. Table 5 gives fitting results for the post-starburst stellar populations.

After choosing the fit corresponding to the best χ², we analyzed the goodness of fit by eye for each object and interactively made adjustments to the fit parameters as necessary. We discarded components where the S/N was low (≤5; particularly troublesome for Mg II and in some objects the UV Fe II templates) and in the complicated Hβ region where degeneracies and a Chabrier (2003) initial mass function (IMF) to model the starburst contribution and find the best fit by varying the starburst age and intensity. The specfit task age-weight interpolates between the stellar population ages of 56, 75, 100, 133, 177, 237, 316, 422, 562, 750, 1000, 1330, 1770, and 2370 Myr. Our age estimates are insensitive to changes in the IMF. We discuss starburst mass calculations in Section 3.3. Table 5 gives fitting results for the post-starburst stellar populations.

After choosing the fit corresponding to the best χ², we analyzed the goodness of fit by eye for each object and interactively made adjustments to the fit parameters as necessary. We discarded components where the S/N was low (≤5; particularly troublesome for Mg II and in some objects the UV Fe II templates) and in the complicated Hβ region where degeneracies and a Chabrier (2003) initial mass function (IMF) to model the starburst contribution and find the best fit by varying the starburst age and intensity. The specfit task age-weight interpolates between the stellar population ages of 56, 75, 100, 133, 177, 237, 316, 422, 562, 750, 1000, 1330, 1770, and 2370 Myr. Our age estimates are insensitive to changes in the IMF. We discuss starburst mass calculations in Section 3.3. Table 5 gives fitting results for the post-starburst stellar populations.

After choosing the fit corresponding to the best χ², we analyzed the goodness of fit by eye for each object and interactively made adjustments to the fit parameters as necessary. We discarded components where the S/N was low (≤5; particularly troublesome for Mg II and in some objects the UV Fe II templates) and in the complicated Hβ region where degeneracies and a Chabrier (2003) initial mass function (IMF) to model the starburst contribution and find the best fit by varying the starburst age and intensity. The specfit task age-weight interpolates between the stellar population ages of 56, 75, 100, 133, 177, 237, 316, 422, 562, 750, 1000, 1330, 1770, and 2370 Myr. Our age estimates are insensitive to changes in the IMF. We discuss starburst mass calculations in Section 3.3. Table 5 gives fitting results for the post-starburst stellar populations.
Table 3
Narrow-line Fitting Results—A

| Object                  | [Ne v] | [O iii] | Hβ     | [O iii] λ4959 | [O iii] λ5007 |
|-------------------------|--------|---------|--------|--------------|--------------|
| SDSSJ                   | Fluxa  | FWHMb  | Flux   | FWHMb        | Flux         |
| J003043+103517          | 9.29   | 798     | 51.62  | 731          | 21.77        |
| J005739+010044          | 6.95   | 469     | 24.64  | 411          | 11.47        |
| J012559+142738          | 33.24  | 898     | 41.37  | 449          | 32.15        |
| J020258+020807          | 7.93   | 590     | 152.68 | 562          | –1.13        |
| J021447+032250          | 13.65  | 752     | 28.59  | 440          | 15.42        |
| J023253+082832          | 15.32  | 699     | 36.25  | 754          | 21.02        |
| J023700+010130          | 13.42  | 803     | 81.27  | 523          | 3.20         |
| J025735+001631          | 19.29  | 517     | 28.07  | 458          | 11.16        |
| J032143+065157          | 9.26   | 621     | 7.73   | 792          | 16.88        |
| J040210+054630          | 3.55   | 348     | 32.00  | 586          | 9.23         |
| J074621+335040          | 31.47  | 612     | 32.46  | 449          | 22.90        |
| J075045+212546          | 15.45  | 608     | 30.39  | 389          | 11.46        |
| J075521+292039          | 7.60   | 398     | 55.86  | 426          | 4.64         |
| J075549+321704          | 16.08  | 695     | 19.61  | 736          | 10.84        |
| J081018+250921          | 23.93  | 532     | ...    | ...          | ...          |
| J090107+282238          | 13.79  | 429     | 38.29  | 943          | 15.22        |
| J115159+637604          | 9.49   | 584     | 23.87  | 507          | 6.38         |
| J115355+582442          | 18.44  | 659     | 58.94  | 572          | 5.89         |
| J123043+314821          | 8.49   | 449     | 41.79  | 553          | 10.41        |
| J124833+563507          | ...    | ...     | 17.68  | 440          | ...          |
| J140513+625008          | 22.15  | 798     | 30.04  | 617          | 14.63        |
| J145640+242727          | ...    | ...     | 23.00  | 490          | ...          |
| J145658+393202          | 11.02  | 384     | 50.49  | 516          | 7.15         |
| J154534+573625          | 43.09  | 561     | 157.47 | 728          | 28.11        |
| J155214+565916          | 4.42   | 328     | 34.27  | 606          | 3.84         |
| J164444+423304          | ...    | ...     | 28.66  | 779          | 1.55         |
| J170046+62056           | 23.89  | 753     | 41.60  | 1144         | 16.56        |
| J170819+603759          | ...    | ...     | ...    | ...          | ...          |
| J201020+005051          | 23.88  | 814     | 50.77  | 631          | 2.93         |
| J211343+075017          | 38.08  | 688     | 55.43  | 538          | 25.91        |
| J211838+056540          | 19.99  | 671     | 22.14  | 450          | 11.42        |
| J212843+002435          | 11.07  | 642     | 14.59  | 693          | 10.13        |
| J230614+010024          | 11.91  | 344     | 61.32  | 473          | 6.99         |
| J231055+090107          | 17.28  | 674     | 56.33  | 627          | 10.46        |
| J231317+082328          | 9.32   | 794     | 9.00   | 300          | 5.34         |
| J233430+140649          | 30.54  | 689     | 140.41 | 525          | 15.50        |
| J234335+035758          | 8.37   | 603     | 42.66  | 818          | 6.16         |
| J234403+152414          | ...    | ...     | 10.98  | 729          | ...          |

Notes. The FWHM of the narrow emission lines should not be considered physical due to the low spectral resolution of our KPNO and Keck spectra.

a Scaling for the Gaussian emission lines corresponds to the integrated area under the curve as flux in units of 10^{-17} erg s^{-1} cm^{-2}.

b FWHM is given in rest frame km s^{-1}.
Table 4
Narrow-line Fitting Results—B

| Object            | [N ii] λ6548 Flux | [N ii] λ6548 FWHM | Hα Flux | Hα FWHM | [N ii] λ6583 Flux | [N ii] λ6583 FWHM |
|-------------------|------------------|------------------|--------|--------|------------------|------------------|
| SDSSJ             |                  |                  |        |        |                  |                  |
| J003043−103517     | 37.67            | 694              | 122.86 | 694    | 113.01           | 694              |
| J005739+010044     | 33.70            | 469              | 224.43 | 469    | 101.10           | 469              |
| J015259+142738     | 26.10            | 493              | 32.62  | 354    | 78.29            | 493              |
| J020258−002807     |                  |                  |        |        |                  |                  |
| J021447−003250     |                  |                  |        |        |                  |                  |
| J023253−082832     | 21.08            | 699              | 102.62 | 699    | 63.24            | 699              |
| J023700−010130     |                  |                  |        |        |                  |                  |
| J025735−001631     |                  |                  |        |        |                  |                  |
| J032437−064517     |                  |                  |        |        |                  |                  |
| J040210−054630     | 11.00            | 456              | 130.00 | 456    | 37.00            | 456              |
| J041250−062952     |                  |                  |        |        |                  |                  |
| J074621+335040     | 46.50            | 612              | 117.05 | 612    | 139.49           | 612              |
| J075045+212546     |                  |                  |        |        |                  |                  |
| J075521+295039     |                  |                  |        |        |                  |                  |
| J081018+250921     | 17.00            | 532              | 11.33  | 532    | 51.01            | 532              |
| J105816+102414     | 20.33            | 429              | 49.17  | 429    | 60.98            | 429              |
| J111519+673604     | 12.48            | 295              | 41.61  | 295    | 37.44            | 295              |
| J115355+582442     | 35.49            | 659              | 88.45  | 659    | 106.48           | 659              |
| J123034−614821     | 41.68            | 449              | 217.61 | 449    | 125.04           | 449              |
| J124833+563507     | 25.94            | 513              | 83.91  | 513    | 77.81            | 513              |
| J140513+625008     | 18.78            | 798              | 37.76  | 798    | 56.34            | 798              |
| J145660+524727     | 9.42             | 200              | 44.01  | 200    | 28.26            | 200              |
| J145658+593202     | 17.87            | 384              | 97.65  | 384    | 53.62            | 384              |
| J154534+573625     | 92.60            | 561              | 211.54 | 561    | 277.80           | 561              |
| J155214+565916     | 16.43            | 328              | 63.16  | 328    | 49.28            | 328              |
| J164444+433034     | 11.53            | 691              | 93.17  | 691    | 34.59            | 691              |
| J170046+62056      | 11.11            | 455              | 49.99  | 455    | 33.32            | 455              |
| J170819+603759     |                  |                  |        |        |                  |                  |
| J210200+000501     |                  |                  |        |        |                  |                  |
| J211343−075017     |                  |                  |        |        |                  |                  |
| J211838+005640     |                  |                  |        |        |                  |                  |
| J212843+002435     |                  |                  |        |        |                  |                  |
| J230614−010024     | 31.65            | 344              | 202.85 | 344    | 94.96            | 344              |
| J231055−090107     |                  |                  |        |        |                  |                  |
| J231317−082238     |                  |                  |        |        |                  |                  |
| J233430+140649     |                  |                  |        |        |                  |                  |
| J234335−005758     |                  |                  |        |        |                  |                  |
| J234403+154214     | 9.56             | 406              | 42.66  | 406    | 28.67            | 406              |

Notes. The FWHM of the narrow emission lines should not be considered physical due to the low spectral resolution of our KPNO and Keck spectra.

a Scaling for the Gaussian emission lines corresponds to the integrated area under the curve as flux in units of 10^{-17} erg s^{-1} cm^{-2}.
b FWHM is given in rest frame km s^{-1}.

While our fits do not require reddening, dust may be present along the line of sight to the AGN and/or stellar component of our PSQs. Dust reddening makes a stellar population appear less luminous and older. Therefore, if significant dust is present the true stellar population age would be younger and the mass larger than our reported measurements. For a visual extinction of 0.1 mag a 422 Myr population appears both older and less luminous by ~10%. The differences are less for older populations. The dust reddening laws toward AGNs and starbursts typically differ further complicating more detailed modeling (Calzetti et al. 1994; Richards et al. 2003).

Our selection criteria ensure that an intermediate-age population is present and strong, but we also know that a more complex stellar population is likely present that includes both older and younger stars. We know that a few of the PSQs have morphologies that show knots of ongoing star formation (C11), suggesting that young stellar populations may be present. A similarly simple model, AGN+instantaneous burst, of the prototype PSQ, UN J1025-0040 (Brotherton et al. 1999) required revising to include a younger stellar population when high-resolution blue Hubble Space Telescope (HST) images were obtained (Brotherton et al. 2002). Because younger stellar populations have relatively weak spectral signatures and are difficult to identify with spectra alone in the presence of post-starburst populations, we want to suggest that this issue be kept in mind when interpreting spectral fitting results.

The imaging also shows galaxies that appear to be spirals with bulges, which typically have older populations, and ellipticals that appear to be post-merger remnants. The dominant intermediate age populations are most likely created as part of the merging process, but the older remain present. Older populations do have spectral signatures that are distinct (e.g., Mg i b absorption, larger Ca ii H & K ratios relative to Balmer line absorption), so we have a better chance of identifying objects that require a more complex stellar population in our fitting. Mg i b absorption is not readily apparent in individual spectra,
We quantitatively investigated this effect ourselves with our own techniques by simulating spectra of a post-starburst plus old stellar component for a range of flux/mass ratios. We created our simulated spectra by combining ratios of 422 Myr old and 5.6 Gyr old Charlot & Bruzual instantaneous burst models and adding artificial noise consistent with our data. We then fit the resulting simulated spectra with a single-aged stellar component. The intermediate stellar age and mass were recovered to better than 10% as long as the older population was less than 70% of the stellar mass. At higher mass fractions, the intermediate age population fit was compromised and skewed the results to indicate older, more massive populations. The AGN component additionally greatly complicates the task and can mask the presence of different-aged stellar components. We conclude that our results are robust as long as the post-starburst population is massive enough to be dominant in flux, as it is at least in some cases (e.g., Hiner et al., 2012), but that higher S/N spectra (letting us measure the Mg II feature more reliably) or another waveband of high-resolution imaging (e.g., Brotherton et al., 2002) will be required to definitively resolve this issue.

We additionally note that in our simulations, when a fit overestimates a post-starburst stellar population age, the equivalent widths of the Balmer lines are greatly overestimated (at least ~30%), although as a complication the AGN component can dilute the equivalent widths. In our single intermediate-age population fits, the Balmer lines of the data are well characterized by our model and for only one object (SDSS J023700.30–010130.5) we note that there might be a significant overestimation. The good fits overall and the fact that we have used a single, consistent approach to fitting all objects suggests that even in the presence of some systematic issues, relative measurements are still likely meaningful and correlation analysis is of interest.

The issue of how to robustly fit complex spectra involving multiple stellar components of unknown metallicity, an AGN, and unknown and perhaps complex dust reddening, at a range of S/Ns, is complicated and deserving of additional deeper investigation and is beyond the scope of the present work. Our existing data are well and consistently fit by our simple model, and to investigate these more sophisticated models would require additional data. Even with more data, degeneracies may make it extremely difficult to find unique and perfect solutions. Again, our fits appear good and likely provide useful information about the PSQs, but keep in mind these caveats and how they may bias the results when interpreting our measurements.

### 3.2. AGN Properties

From the fitting results, we were able to estimate two fundamental physical AGN properties: the BH mass and Eddington ratio. We employed scaling relations that extend the reverberation mapping results of physical properties (i.e., $M_{\text{BH}}$ and radius of the broad-line region) to the observable quantities (i.e., continuum luminosity and broad line FWHM) of single-epoch data to calculate BH mass. We used Mg II, Hβ, Hα as well as estimated values of Hβ based on the measurements of Hα, being careful to discard data of low quality. All of our spectra have coverage at 5100 Å. We used the 5100 Å monochromatic luminosities based on the power-law components used in the fits as our AGN luminosities for the scaling relations below.

From the relation given by Vestergaard & Osmer (2009), we estimated $M_{\text{BH}}$ based on the Mg II broad line FWHM and the

### Table 5: Starburst Properties

| Object | Age (Myr) | Raw Scale | log Mass ($M_\odot$) | log $L_{\text{H}\alpha}$ (erg s$^{-1}$) | log $L_{\text{H}\beta}$ (erg s$^{-1}$) |
|--------|-----------|-----------|---------------------|---------------------------------|---------------------------------|
| J003043–103517 | 740 | 26.28 | 10.27 | 43.47 | 43.85 |
| J005739+010044 | 1180 | 34.19 | 10.41 | 43.41 | 43.76 |
| J015294+142738 | 1900 | 72.26 | 10.42 | 43.44 | 43.94 |
| J020258–002807 | 970 | 32.25 | 10.62 | 43.67 | 43.98 |
| J021447–003250 | 1090 | 22.17 | 10.54 | 43.54 | 43.98 |
| J023253–082832 | 1690 | 18.80 | 10.36 | 43.15 | 43.81 |
| J023700–010130 | 1230 | 36.26 | 10.79 | 43.74 | 43.92 |
| J025735–001631 | 280 | 30.05 | 10.13 | 43.70 | 44.06 |
| J032143–064517 | 2330 | 22.37 | 10.93 | 43.52 | 43.87 |
| J040210–054630 | 2400 | 25.11 | 10.66 | 43.26 | 43.55 |
| J046212+330400 | 620 | 48.50 | 10.41 | 43.68 | 44.04 |
| J075045+212546 | 2330 | 25.51 | 11.11 | 43.64 | 43.49 |
| J075521+290539 | 200 | 23.80 | 10.30 | 43.54 | 43.48 |
| J075549+321704 | 2310 | 21.06 | 11.06 | 43.64 | 44.14 |
| J105816+102414 | 1180 | 51.56 | 10.68 | 43.47 | 43.85 |
| J115196+673604 | 1490 | 31.75 | 10.57 | 43.44 | 43.63 |
| J115355+582442 | 760 | 38.21 | 10.52 | 43.71 | 43.97 |
| J220403+614821 | 1340 | 21.92 | 10.54 | 43.46 | 43.92 |
| J214833+563507 | 1400 | 67.30 | 10.83 | 43.75 | 43.97 |
| J214051+625008 | 830 | 34.36 | 10.73 | 43.85 | 44.05 |
| J215640+524727 | 1890 | 21.89 | 10.52 | 43.25 | 43.66 |
| J215658+593202 | 960 | 17.13 | 10.30 | 43.36 | 43.67 |
| J215434+573625 | 2380 | 44.53 | 10.89 | 43.51 | 43.95 |
| J215521+565916 | 1210 | 16.21 | 10.41 | 43.37 | 43.81 |
| J164444+423304 | 470 | 23.92 | 10.11 | 43.49 | 43.83 |
| J170046+622056 | 2670 | 28.28 | 10.78 | 43.34 | 43.66 |
| J170819+603759 | 1270 | 21.97 | 10.37 | 43.32 | 43.68 |
| J210200+000501 | 790 | 54.88 | 10.73 | 43.89 | 44.11 |
| J211343–070517 | 750 | 52.55 | 10.97 | 44.12 | 44.34 |
| J211838+005640 | 1160 | 41.20 | 10.95 | 43.91 | 44.18 |
| J212843+002435 | 1690 | 18.88 | 10.65 | 43.42 | 43.88 |
| J230614–010024 | 890 | 48.31 | 10.50 | 43.62 | 43.95 |
| J231055–090107 | 2230 | 31.48 | 10.65 | 43.67 | 43.90 |
| J231317–082238 | 1500 | 26.73 | 10.85 | 43.69 | 44.07 |
| J233403+140649 | 240 | 18.19 | 9.84 | 43.49 | 44.12 |
| J234335–005758 | 1400 | 36.17 | 10.83 | 43.73 | 43.95 |
| J234403+154214 | 2570 | 34.88 | 10.90 | 43.47 | 43.64 |

**Notes.**

- Scale directly from fitting.
- Total integrated light of the starburst component from 3000 Å to 6000 Å.
- Total integrated light (AGNs plus starburst components) from 3000 Å to 6000 Å.
5100 Å monochromatic luminosity:

$$\frac{M_{BH}(Mg\,\,\alpha)}{M_\odot} = 10^{6.96} \left(\frac{\text{FWHM Mg}\,\,\alpha}{1000 \text{ km s}^{-1}}\right)^2 \left(\frac{\lambda L_\lambda(5100 \text{ Å})}{10^{44} \text{ erg s}^{-1}}\right)^{0.5}.$$  \hspace{1cm} (1)

The scatter in the zero point of the relation is given to be 0.55 dex.

We used the relation

$$\frac{M_{BH}(H\beta)}{M_\odot} = 10^{6.91\pm0.02} \left(\frac{\text{FWHM H}\beta}{1000 \text{ km s}^{-1}}\right)^2 \left(\frac{\lambda L_\lambda(5100 \text{ Å})}{10^{44} \text{ erg s}^{-1}}\right)^{0.5}$$  \hspace{1cm} (2)

to calculate the BH mass based on the H\beta broad line FWHM and the 5100 Å AGN monochromatic luminosity (Vestergaard & Peterson 2006). The intrinsic scatter in the sample is described by 0.43 dex. We have given the relation in linear space as opposed to log space for ease of reading. We note that the relations given for Mg\,\alpha and H\beta are on the same mass scale.

We estimated the BH masses using H\alpha broad line FWHM and the 5100 Å AGN monochromatic luminosity according to the Greene et al. (2010) scaling relation:

$$\frac{M_{BH}(H\alpha)}{M_\odot} = (9.7 \pm 0.5) \times 10^6 \left(\frac{\text{FWHM H}\alpha}{1000 \text{ km s}^{-1}}\right)^{2.06\pm0.06} \times \left(\frac{\lambda L_\lambda(5100 \text{ Å})}{10^{44} \text{ erg s}^{-1}}\right)^{0.519\pm0.07}.$$  \hspace{1cm} (3)

Though the scatter in this relation is not reported, typical values are \textasciitilde0.4–0.5 dex.

Since stellar absorption from the post-starburst population contaminates broad emission in H\beta, making the fits less reliable, and this stellar contamination is negligible for H\alpha we used H\alpha as a proxy for H\beta when H\alpha is present in the spectrum (Shen et al. 2011)

$$\log \left(\frac{\text{FWHM H}\beta}{\text{km s}^{-1}}\right) = (-0.11 \pm 0.03) + (1.05 \pm 0.01) \times \log \left(\frac{\text{FWHM H}\alpha}{\text{km s}^{-1}}\right).$$  \hspace{1cm} (4)

We then used the estimated H\beta values in conjunction with Equation (2) to calculate BH measurements for H\beta based on H\alpha. There are slight differences between the two formalisms of Greene et al. (2010) and Vestergaard & Peterson (2006); most notably between the prefactors and radius–luminosity (scaling of \lambda L_\lambda) relations. However, the differences are small; for our sample the difference is less than 8\%, much less than the intrinsic scatter.

We have given several measurements of the BH mass. Each line has its own particular issue. The blue side of the spectra suffer from S/N degradation which sometimes gives unreliable measurements for Mg\,\alpha. Occasionally, up to \textasciitilde50\% of the H\beta broad emission can be contaminated by stellar absorption. Due to the redshift range of our sample, sometimes H\alpha is out of our observing window. In subsequent sections, we make comparisons using these values individually. However, we also give an adopted \textit{M_{BH}} by applying the following prescription. When we have three reliable measurements we adopt the median of these values. For two good measurements, we give the mean of the values. If there is only one reliable value, we adopt this as our \textit{M_{BH}}. There is one object (SDSS J020258.94−002807.5) for which H\alpha was not covered and both Mg\,\alpha and H\beta were unreliable.

We estimated the AGN bolometric luminosity using the measured rest-frame flux at 5100 Å from the fit to the power-law continuum and convert it into a total emitted luminosity using luminosity distances for our cosmology and an appropriate bolometric correction (f = 8.1; Runnoe et al. 2012):

$$L_{bol} = 4\pi D_L^2 f (1 + z) \lambda F_\lambda(5100 \text{ Å}).$$  \hspace{1cm} (5)

The Eddington ratio is given by $L_{bol}/L_{Edd}$ where we use $L_{Edd} = 1.51 \times 10^{38} (M_{BH}/M_\odot) \text{ erg s}^{-1}$ (Krolik 1999). Table 6 gives BH masses for each broad line measurement and their Eddington ratios.

Figure 2 shows where the different broad line width measurements (i.e., Mg\,\alpha, H\beta, H\alpha, and predicted H\beta) lie as a function of $\lambda L_\lambda(5100 \text{ Å})$. For reference we indicate lines of constant \textit{M_{BH}} and $L_{bol}/L_{Edd}$ based on Mg\,\alpha. Constant lines of \textit{M_{BH}} and $L_{bol}/L_{Edd}$ based on H\beta and H\alpha will vary slightly in slope and intercept.

3.3. Post-starburst Properties

The post-starburst stellar populations can be described using two fundamental physical parameters, starburst age and mass. The post-starburst ages are known directly from the fitting results. The scale factor is a function of the mass and age of the starburst. The inputted PSQ spectra are in units of $10^{-17} \text{ erg s}^{-1} \text{ cm}^2 \text{ Å}^{-1}$ while the template spectra are in units of $L_\odot/\text{ Å}$ and scaled up by their age in Myr. Thus, we can derive the total starburst mass by using the scale factor and the
Section 4. Results and Discussion

We seek to explore joint AGNs and starburst activity by investigating the interplay between the fundamental properties of PSQs and their morphological subpopulations. In Section 4.1, we investigate the relationships between the fundamental properties of PSQs. We investigate the fundamental properties of PSQs in relation to their morphological subpopulations in Section 4.2. Finally, in Section 4.3, we give a simple prescription to reliably classify the morphology of PSQs based on spectral properties.

4.1. Correlations Based on Fundamental PSQ Properties

We calculate Spearman-rank correlation coefficient matrices involving several hundred correlation tests between fitted and derived parameters for (1) the total sample, (2) the early-type and spiral morphological classifications, and (3) the disturbed and undisturbed classifications. We compute the probability of the correlations arising by chance and list those less than 1% in Table 7.

We find a number of strong correlations among quasar and starburst properties; however, many of these are due to selection effects which we will discuss below. Some merger
be comparable in luminosity in order for one not to swamp out between parameters. For example, the starburst and AGN must find very few additional correlations of this type.

properties of a more physical origin (Di Matteo et al. 2005). We induced evolutionary scenarios predict correlations among these properties. The starburst and AGN must be comparable in luminosity in order for one not to swamp out light from the other, thus giving rise to a significant correlation of the luminosities of both. We note that the mean AGN-to-total light, \( f_{\text{AGN}} \), is 0.55 with only a standard deviation of 0.13. This leaves us with a limited parameter space to explore.

### 4.1. Derived AGN Properties

Figure 3 shows our strongest correlation among AGN properties. The \( M_{\text{BH}} \) increases as \( L/L_{\text{Edd}} \) decreases, which probably arises as a result of two effects. The first effect is the dearth in massive BHs with high accretion rates at this redshift, which is the result of cosmic downsizing (Heckman et al. 2004). The second cause is the lack of lower mass black holes with low accretion rates which fail to make the luminosity cut. The combination of these two effects, demographics plus selection effects, leads to a strong inverse correlation. However, this does not rule out the possibility that there is an underlying physical correlation, but confirming this would require a more sophisticated sample selection.

### 4.1.2. Narrow-line Ratios

Narrow emission lines can be powered by several sources of photoionizing radiation, including young O and B stars and the central AGN. Comparing the relative strengths between lines with high- and low-ionization potentials tells us about the shape of the photoionizing continuum and thus diagnoses the source. AGNs have harder continua (relatively more high-energy photons) while star-forming continua are softer (relatively more low-energy photons).

We find a number of strong correlations among narrow-line ratios that can be interpreted in terms of the relative contributions of AGNs and star formation. In particular, the highly ionized \([\text{O iii}]\) \( \lambda 5007 \) emission line is more prominent in AGN spectra but other lines may also be diagnostic. For example, Figure 4

| Property 1 | Property 2 | \( \rho \) | \( P(\%) \) | Number |
|------------|------------|----------|-------------|--------|
| Total Population |
| \( z \) | \( L_{\text{Tot}} \) | 0.518 | 0.086 | 38 |
| \( z \) | \( L_{SB} \) | 0.494 | 0.161 | 38 |
| \( z \) | SB Mass | 0.428 | 0.737 | 38 |
| \( \lambda L_e(5100 \text{ Å})^a \) | \( L_{\text{Edd}} \) | 0.433 | 0.074 | 37 |
| \( \lambda L_e(5100 \text{ Å}) \) | [O iii]/[H\beta] | 0.481 | 0.527 | 32 |
| \( \lambda L_e(5100 \text{ Å}) \) | [O ii]/[O iii] | 0.476 | 0.508 | 33 |
| \( \alpha \) | SB Mass | 0.479 | 0.237 | 38 |
| \( L_{\text{Tot}} \) | [O iii]/[H\beta] | 0.509 | 0.292 | 32 |
| \( L_{\text{Tot}} \) | [N ii]/H\alpha | 0.678 | 0.073 | 21 |
| \( L_{\text{AGN}} \) | L\( _{SB} \) | 0.441 | 0.553 | 38 |
| \( L_{\text{AGN}} \) | \( L/L_{\text{Edd}} \) | 0.424 | 0.890 | 37 |
| \( L_{\text{AGN}} \) | [O iii]/[H\beta] | 0.563 | 0.079 | 32 |
| \( L_{\text{AGN}} \) | [O ii]/[O iii] | 0.493 | 0.359 | 33 |
| \( L_{SB} \) | SB Mass | 0.452 | 0.438 | 38 |
| \( L_{SB} \) | [N ii]/H\alpha | 0.549 | 0.990 | 21 |
| \( L_{SB} \) | [Ne v]/[Ne iii] | 0.504 | 0.276 | 33 |
| \( M_{\text{BH}} \) | [Mg ii] | 0.742 | 0.000 | 0 | 29 |
| \( M_{\text{BH}} \) | [H\beta] | 0.809 | 0.000 | 0 | 30 |
| \( M_{\text{BH}} \) | H\alpha | 0.739 | 0.013 | 21 |
| \( M_{\text{BH}} \) | [H\beta] | 0.739 | 0.013 | 21 |
| \( M_{\text{BH}} \) | Adopted | 0.724 | 0.000 | 37 |
| \( L_{\text{AGN}} \) | \( L_{\text{Edd}} \) | 0.747 | 0.033 | 13 |
| \( L_{\text{AGN}} \) | \( L_{\text{Edd}} \) | 0.747 | 0.033 | 13 |
| \( L_{\text{AGN}} \) | Adopted | 0.753 | 0.298 | 13 |
| \( L_{\text{AGN}} \) | Adopted | 0.813 | 0.072 | 13 |
| \( M_{\text{BH}} \) | [Mg ii] | 0.742 | 0.022 | 0 | 22 |
| \( M_{\text{BH}} \) | [H\beta] | 0.841 | 0.032 | 0 | 13 |
| \( M_{\text{BH}} \) | Adopted | 0.692 | 0.873 | 13 |
| \( L_{\text{AGN}} \) | \( L_{\text{Edd}} \) | 0.764 | 0.238 | 13 |
| \( L_{\text{AGN}} \) | Adopted | 0.753 | 0.298 | 13 |
| \( L_{\text{AGN}} \) | Adopted | 0.813 | 0.072 | 13 |
| \( \alpha \) | SB Mass | 0.824 | 0.005 | 0 | 17 |
| \( \alpha \) | SB Age | 0.764 | 0.238 | 13 |
| \( M_{\text{BH}} \) | Adopted | 0.753 | 0.298 | 13 |
| \( L_{\text{AGN}} \) | \( L_{\text{Edd}} \) | 0.650 | 0.871 | 15 |
| \( L_{\text{AGN}} \) | Adopted | 0.674 | 0.301 | 17 |
| \( L_{\text{AGN}} \) | Adopted | 0.674 | 0.301 | 17 |
| \( M_{\text{BH}} \) | [Mg ii] | 0.829 | 0.024 | 0 | 14 |
| \( M_{\text{BH}} \) | [H\beta] | 0.934 | 0.000 | 0 | 14 |
| \( M_{\text{BH}} \) | H\alpha | 0.800 | 0.311 | 11 |
| \( M_{\text{BH}} \) | [H\beta] | 0.800 | 0.311 | 11 |
| \( M_{\text{BH}} \) | Adopted | 0.814 | 0.007 | 17 |

Note. \( a \lambda L_e(5100 \text{ Å}) \) is the monochromatic AGN luminosity at 5100 Å in erg s\(^{-1}\).
The strongest correlation among starburst properties is between the age and mass of the post-starburst population (Figure 5). Just as in the case of AGN properties, Section 4.1.1, this correlation likely arises from a combination of demographics and selection effects. There is a lack of objects at large mass and young age. Such objects must exist and are likely dust enshrouded, seen in the infrared as luminous infrared galaxies (LIRGs; Sanders & Mirabel 1996) or may be found as post-starburst galaxies if there is a significant time delay before the onset of AGN activity (see, e.g., Wild et al. 2010; Schawinski et al. 2009). The envelope in the upper left is the result of a selection effect: our luminosity limit.

4.1.3. Starburst Properties

The strongest correlation among starburst properties is between the age and mass of the post-starburst population (Figure 5). Just as in the case of AGN properties, Section 4.1.1, this correlation likely arises from a combination of demographics and selection effects. There is a lack of objects at large mass and young age. Such objects must exist and are likely dust enshrouded, seen in the infrared as luminous infrared galaxies (LIRGs; Sanders & Mirabel 1996) or may be found as post-starburst galaxies if there is a significant time delay before the onset of AGN activity (see, e.g., Wild et al. 2010; Schawinski et al. 2009). The envelope in the upper left is the result of a selection effect: our luminosity limit.

4.1.4. AGN versus Starburst Properties

We find that higher spectral indices (bluer AGNs) correlate with larger starburst masses. This could be a result of a degeneracy between the spectral index and scaling of the starburst. As the spectral index increases it has the effect of taking away light, in which case the scaling of the starburst must make up the difference. Furthermore, if we assume a spectral index more typical of AGNs, we might expect a stronger correlation (e.g., Francis 1993 find $\alpha \sim 1.5$ with 0.5 scatter versus our 1.0). However, while the starburst template continuum guides our fitting, the Balmer region (i.e., Balmer break and absorption lines) of the spectra governs the quality of the starburst fit (see Figure 1).

Perhaps the most interesting result from this analysis is the lack of significant correlations between parameters which might have been suggested by merger-induced evolutionary scenarios (e.g., Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2006). Specifically, AGN luminosity (and/or Eddington ratio) should decline following a merger-triggered fueling event as the age of the starburst population increases. If there is a single mechanism driving both AGNs and starburst activity, naturally leading to correlations between their properties, then our results present a problem for such models. Our selection effects that limit parameter space could limit our ability to see correlations or there could be a delay in AGN triggering or multiple types of triggering events. For the latter reason, we also perform analysis by morphological classification.

4.2. Dependence on Morphological Class

We investigate the relationships among the morphology and fundamental (fitted and derived) properties of the AGN, narrow-line emission, and starburst. Visual classifications were
performed by three of the authors and the results are presented in Cales et al. (2011). Generally, arms and bars distinguish spiral galaxies while smooth, somewhat featureless (i.e., lacking arms/bars), light distributions identify early-type galaxies. We note that the early-type hosts are allowed to show tidal features although sometimes disturbances make classification difficult, resulting in an indeterminate classification. In Table 8, we list the mean, standard deviation, and number of objects for our basic properties for the total sample, and early-type and spiral (including “probable” spirals) sub-populations. When reliable statistical differences in sample means exist at P the Values below the 1% level (better than $P \leq 0.01$) we include the nonparametric Mann–Whitney statistic and its associated $P$-Value.

| Property | Total | Early-type | Spiraals |
|----------|-------|------------|----------|
| $z$      | 0.32  | 0.33       | 0.31     |
| log $\lambda L_{\alpha}$ (5100 Å) | 43.94 | 44.11      | 43.77    |
| $\alpha$ | 1.00  | 1.11       | 1.06     |
| $f_{\text{sec}}$ | 0.55  | 0.57       | 0.51     |
| log $L_{\text{Tot}}$ | 43.93 | 44.08      | 43.81    |
| log $L_{\text{AGN}}$ | 43.65 | 43.82      | 43.51    |
| log $L_{\text{Edd}}$ | 43.57 | 43.69      | 43.50    |
| log $M_{\text{BH}}$ Mg II | 7.99  | 8.04       | 8.08     |
| $L/L_{\text{Edd}}$ Mg II | 0.07  | 0.08       | 0.05     |
| log $M_{\text{BH}}$ H$\beta$ | 8.27  | 8.28       | 8.49     |
| $L/L_{\text{Edd}}$ H$\beta$ | 0.04  | 0.05       | 0.02     |
| log $M_{\text{BH}}$ H$\alpha$ | 8.25  | 8.18       | 8.30     |
| $L/L_{\text{Edd}}$ H$\alpha$ | 0.03  | 0.04       | 0.02     |
| log $M_{\text{BH}}$ H$\alpha$–H$\beta$ | 8.28  | 8.21       | 8.34     |
| $L/L_{\text{Edd}}$ H$\alpha$–H$\beta$ | 0.03  | 0.04       | 0.02     |
| log $M_{\text{BH}}$ Adopted | 8.17  | 8.19       | 8.20     |
| $L/L_{\text{Edd}}$ Adopted | 0.05  | 0.06       | 0.03     |
| log $M_{\text{SB}}$ Mass | 10.58 | 10.53      | 10.65    |
| SB Age | 1321.75 | 967.60    | 1643.17  |
| [O iii]/H$\beta$ | 4.83  | 6.56       | 2.54     |
| [N ii]/H$\alpha$ | 1.06  | 1.57       | 0.73     |
| [O iii]/[O ii] | 2.31  | 2.79       | 1.59     |
| [Ne v]/[Ne iii] | 1.35  | 2.07       | 1.61     |
| Fe ii/[O iii] | 0.01  | 0.01       | 0.03     |

Notes.

a The mean of the population.
b The standard deviation of the population.
c The number of objects that were used to calculate mean, standard deviation, and/or population statistics.
d When statistical differences in sample means exist at below the 1% level we include the nonparametric Mann–Whitney statistic and its associated $P$-Value.

1. AGNs. The PSQs hosted in early-type galaxies have statistically significant higher total luminosities than spiral-hosted PSQs, and this appears to be somewhat more driven by differences in AGN luminosity although starburst luminosities also differ. This is supported by various methods of measuring the PSQ luminosity and its components (i.e., $L_{\text{Tot}}$, $L_{\text{AGN}}$, and $L_{\text{SB}}$; see Figures 6(a)–(c)). We note that AGN luminosity increases with BH mass and/or accretion rate. While there are no statistically significant differences between the subpopulations for Eddington fraction, BH mass, or starburst mass, it is possible that the AGN with early-type hosts tend to have higher luminosities because they have higher Eddington ratios (Figures 6(d)–(f)).

2. NLR. Figure 6(e) shows that the PSQs hosted in early-type galaxies have larger [O iii]/H$\beta$ than spiral-hosted PSQs, and we interpret this as differences in the hardness of the ionizing continuum reflecting the relative contributions of the AGN and star formation. The spiral PSQs have more ongoing star formation.

3. Starburst. The PSQs hosted in early-type galaxies tend to have younger starburst ages from our fitting results than the PSQs hosted by spirals (Figure 6(f)). This may be interpreted in different ways. Some possible explanations of this are: (1) the starburst luminosities are smaller in the spiral-hosted PSQs and our single age fits may be skewed by the presence of an older stellar population, (2) chance snapshot of unassociated starburst and AGN activity in spiral hosts with large starburst ages, or (3) longer timescales between triggering of the AGN and starburst in spiral PSQs. There may be no clear interpretation of this effect without additional data.

4.3. Spectral Diagnostics for Mode of Growth

PSQs appear to display both merger-driven and secular forms of galaxy evolution. They are a heterogeneous population hosted by both early-type and spiral galaxies, some of which...
Figure 6. (a)–(h) The solid histogram represents the total distribution, while the red horizontal and blue vertical hatched histograms indicate the early-type and spiral plus “probable” spiral morphology distributions, respectively. Early-type PSQs have more luminous AGNs and younger starburst populations, while PSQs with spiral hosts are consistent with ongoing star formation.

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

appear to be results of major mergers while others exist in isolated systems. C11 postulates that the early-type PSQs may be the low-z analogs of luminous merger-induced $z \sim 2$ quasars. Furthermore, at least some of the spiral PSQs are likely undergoing secular evolution. This conclusion is consistent with current theoretical frameworks which argue for two fundamentally different fueling mechanisms (i.e., merger-induced versus secular) responsible for mutual SMBH–bulge growth at the characteristic dividing line of quasar-Seyfert luminosities (Hopkins & Hernquist 2009).

We explored issues of the relative contributions of AGNs and star formation to powering narrow-emission lines previously in the context of the BPT diagram. We have also found differences between a number of properties and morphological subtype. We
can combine this information to create observational selection criteria to select PSQs as a function of galaxy host type without requiring high spatial resolution imaging. With the exception of a rare outlier, we can use a combination of \( \text{H}\beta/\text{[O}\text{iii}] \), \([\text{O}\text{iii}]/\text{[O}\text{ii}] \), and \( L_{\text{Tot}} \) to distinguish host galaxy type. Figure 7 shows several plots involving these quantities and where the objects of different classification fall. Using these we establish the following parameters to select PSQs by morphological subtype:

1. Early-type: \( L_{\text{Tot}} > 10^{43.85} \text{ erg s}^{-1} + \text{H}\beta/\text{[O}\text{iii}] < 0.4 \);
2. Spiral: \( L_{\text{Tot}} < 10^{43.95} \text{ erg s}^{-1} + [\text{O}\text{iii}]/\text{[O}\text{ii}] < 2.0 \).

While it has been suggested that major-mergers are not important drivers of AGN activity in the local downsized universe (Cisternas et al. 2011), such objects do exist primarily among quasars and may be valuable to study as analogs of luminous high-redshift quasars (Canalizo et al. 2007; Bennert et al. 2008, 2010). Studies of local AGNs \( (z \sim 0.05) \) have also found two modes of growth distinguished by morphology. Schawinski et al. (2010b) find that the least massive SMBH population of early-type hosts is growing while the most massive SMBH population of late-type hosts is growing. Furthermore, Schawinski et al. (2010a) trace a correlation between the merger fraction of early-type hosts and an evolutionary sequence involving starbursts and AGNs, such that, even in the local universe, early-type galaxies are still merger induced. This has important ramifications for future studies involving galaxy evolution and should guide the path of such studies.

5. SUMMARY
We performed AGN-host spectral decomposition of 38 PSQs, 29 of which have morphological classifications from C11. We characterized the host starburst masses and ages, and the AGN BH masses and Eddington fractions, with the aim of improving...
our understanding of the mutual evolution of luminous AGNs and their hosts.

1. Black hole properties. The PSQs have $M_{\text{BH}} \sim 10^{7.5-8.5} M_\odot$ which are accreting at $\sim1\%-10\%$ of Eddington luminosity.

2. Starburst properties. The PSQs have massive starbursts $\sim10^{10-11} M_\odot$ that span a range of ages $\sim$200–2000 Myr.

3. We find no strong correlations linking $M_{\text{BH}}$ and starburst properties.

4. The PSQ sample lacks young, massive starbursts that are likely obscured LIRGs that we cannot select optically or are seen as post-starburst galaxies.

5. Narrow-line emission. When plotted on traditional BPT diagrams, PSQs fall along and slightly above the mixing line showing a wide range in the relative contributions of AGNs and star formation.

6. Morphology. Early-type PSQs have significantly stronger AGN luminosities, younger ISB ages, and narrow-line ratios indicative of harder photoionizing continua when compared to spiral PSQs.

7. Morphological selection of PSQs. We determine that the selection criterion for (1) early-type PSQs of $L_{\text{Tot}} > 10^{43.85}$ erg s$^{-1}$ and $\text{H}_\beta/\text{[O} \text{iii}] < 0.4$ and (2) spiral PSQs of $L_{\text{Tot}} < 10^{43.95}$ erg s$^{-1}$ and $\text{[O} \text{iii}]/\text{[O} \text{ii}] < 2.0$ is efficient for determining morphology of the PSQ sample.

8. We conclude that the PSQ sample displays two distinct mechanisms for joint AGNs and starburst activity. The higher luminosity early-type PSQs appear to be the product of major mergers, show little current star formation, and may be identified as the low-$z$ analogs of the luminous and likely merger-induced high-redshift quasars. PSQs hosted in spirals likely represent a lower luminosity mode
of activity, such as “Seyfert mode” or secular activity, triggered by internal processes, e.g., bars, or external triggers, e.g., harassment.

In order to further explore possible correlations between AGNs and starburst properties, we intend to study a larger sample of PSQs with a broader range in AGNs and starburst strengths. For example, plotting PSQs on the $M_{\text{BH}}-\sigma_*$ relationship may be helpful in better understanding their role in massive galaxy evolution (Hiner et al., 2012). Another way to do this is to explore lower luminosity, lower redshift objects of the Brotherton et al. (2007) catalog in conjunction with morphologies from Galaxy Zoo and spectral fitting of only the highest quality SDSS spectra.

We acknowledge support from NASA through the LTSA grant NNG05GE84G. Z.S. acknowledges support from the National Natural Science Foundation of China through grant 10633040 and support by Chinese 973 Program 2007CB815405. G.C. acknowledges support from the National Science Foundation, under grant number AST 0507450. S. L. Cales was supported in part by NASA Headquarters under the NASA Earth and Space Science Fellowship Program (Grant NNX08AX07H), in part by the National Science Foundation GK-12 Program (Project 0841298), and also in part by ALMA-CONICYT program 31110020. A.D. acknowledges support from the Southern California Center for Galaxy Evolution, a multi-campus research program funded by the University of California Office of Research.

APPENDIX

SPECTRA OF FITTING RESULTS

Spectral decomposition of AGNs and post-starburst stellar population is shown in Figure 8. The red line is the data. The
Figure 8. (Continued)
Figure 8. (Continued)
Figure 8. (Continued)
Figure 8. (Continued)
Figure 8. (Continued)
blue lines make up the components used in the fitting. For ease of interpretation we plot the emission lines and Fe II templates above the power law. The black line is the model fit to the data.

REFERENCES

Abazajian, K., Adelman-McCarthy, J. K., Agers, M. A., et al. 2005, AJ, 129, 1755
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Bennert, N., Canalizo, G., Jungwiert, B., et al. 2008, ApJ, 677, 846
Bennert, V. N., Auger, M. W., Treu, T., Woo, J.-H., & Malkan, M. A. 2011, ApJ, 742, 107
Bennert, V. N., Treu, T., Woo, J., et al. 2010, ApJ, 708, 1507
Brotherton, M. S., Grabelsky, M., Canalizo, G., et al. 2002, PASP, 114, 593
Brotherton, M. S., van Breugel, W., Stanford, S. A., et al. 1999, ApJL, 520, 87
Brotherton, M. S., et al. 2007, BAAS, 39, 95
Cales, S. L., Brotherton, M. S., Shang, Z., et al. 2011, ApJ, 741, 106
Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582
Canalizo, G., Bennert, N., Jungwiert, B., et al. 2007, ApJ, 669, 801
Canalizo, G., Stockton, A., Brotherton, M. S., & van Breugel, W. 2000, AJ, 119, 59
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Charrier, G. 2003, PASP, 115, 761
Cisternas, M., Jahnke, K., Inskip, K. J., et al. 2011, ApJ, 726, 57
Dressler, A., & Gunn, J. E. 1983, ApJ, 270, 7
Falkenberg, M. A., Kotulla, R., & Fritze, U. 2009, MNRAS, 397, 1940
Greene, J. E., Peng, C. Y., & Ludwig, R. R. 2010, ApJ, 709, 937
Hasinger, G. 2008, A&A, 490, 905
Heckman, T. M., Kauffmann, G., Brinchmann, J., et al. 2004, ApJ, 613, 109
Hiner, K. D., Canalizo, G., Wold, M., Brotherton, M. S., & Cales, S. L. 2012, ApJ, 756, 162
Hopkins, P. F., & Hernquist, L. 2009, ApJ, 694, 599
Hopkins, P. F., Hernquist, L., Cox, T. J., Robertson, B., & Springel, V. 2006, ApJS, 163, 50
Kocevski, D. D., Lemaux, B. C., Lubin, L. M., et al. 2011, ApJ, 737, 38
Kocevski, D. D., Lubin, L. M., Lemaux, B. C., et al. 2009, ApJ, 700, 901
Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581
Kriss, G. A. 1994, in ASP Conf. Ser. 61, Astronomical Data Analysis Software and Systems III, ed. D. R. Crabtree, R. J. Hanisch, & J. Barnes (San Francisco, CA: ASP), 437
Krolik, J. H. 1999, Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment (Princeton, NJ: Princeton Univ. Press)
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
Massey, P., Strobel, K., Barnes, J. V., & Anderson, E. 1988, ApJS, 328, 315
Merritt, D., & Ferrarese, L. 2001, MNRAS, 320, L30
Oke, J. B., Cohen, J. G., Carr, M., et al. 1995, PASP, 107, 375
Richards, G. T., Hall, P. B., Vanden Berk, D. E., et al. 2003, AJ, 126, 1131
Richstone, D., Ajhar, E. A., Bender, R., et al. 1998, Natur, 395, A14
Runnoe, J. C., Brotherton, M. S., & Shang, Z. 2012, MNRAS, 422, 478
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 821
Schawinski, K., Dowlin, N., Thomas, D., Urry, C. M., & Edmondsion, E. 2010a, ApJL, 714, 108
Schawinski, K., Urry, C. M., Virani, S., et al. 2010b, ApJ, 711, 284
Schawinski, K., Virani, S., Simmons, B., et al. 2009, ApJL, 692, 19
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Serra, P., & Trager, S. C. 2007, MNRAS, 374, 769
Shen, Y., Richards, G. T., Strauss, M. A., et al. 2011, ApJS, 194, 45
Springel, V., Di Matteo, T., & Hernquist, L. 2005, ApJL, 620, 79
Trager, S. C., & Somerville, R. S. 2009, MNRAS, 395, 608
Vestergaard, M., & Osmer, P. S. 2009, ApJL, 701, 108
Vestergaard, M., & Peterson, B. M. 2006, ApJ, 641, 689
Wild, V., Heckman, T., & Charlot, S. 2010, MNRAS, 405, 933
Wild, V., Walcher, C. J., Johansson, P. H., et al. 2009, MNRAS, 395, 144
Yan, R., Newman, J. A., Faber, S. M., et al. 2006, ApJ, 648, 281