THE UV–MID-IR SPECTRAL ENERGY DISTRIBUTION OF A $z = 1.7$ QUASAR HOST GALAXY

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ABSTRACT

We have measured the spectral energy distribution (SED) of the host galaxy of the $z_s = 1.7$ gravitationally lensed quasar SDSS J1004+4112 from 0.44–8.0 μm (0.16–3.0 μm in the rest frame). The large angular extent of the lensed images and their separation from the central galaxy of this cluster lens allows the images to be resolved even with the Spitzer Space Telescope. Based on the SED, the host galaxy is a mixture of relatively old and intermediate age stars with an inferred stellar mass of $\log(M_*/M_\odot) = 11.09 \pm 0.28$ and a star-formation rate of $\log(M_{\text{HI}}/M_\odot \text{ yr}^{-1}) = 1.21 \pm 0.26$. Given the estimated black hole mass of $M_{\text{BH}} \approx 10^{8.6} M_\odot$ from locally calibrated correlations of black hole masses with line widths and luminosities, the black hole represents a fraction $\log(M_{\text{BH}}/M_*) = -2.49 \pm 0.28$ of the stellar mass and it is radiating at 0.24 ± 0.05 of the Eddington limit. The ratio of the host stellar mass to the black hole mass is only marginally consistent with the locally observed ratio.

Key words: galaxies: evolution – quasars: individual (SDSS J1004+4112)

Online-only material: color figure

1. INTRODUCTION

In the local universe, the host galaxies of active, luminous black holes tend to be bluer star-forming galaxies with a roughly 1000:1 ratio between the star formation and accretion rates (Kauffmann & Heckman 2005). More luminous active galactic nuclei (AGNs) also show younger stellar populations. Moreover, the relative growth rates match the observed local ratio of stellar to black hole mass (Kauffmann & Heckman 2005; Marconi & Hunt 2003). At higher redshifts, $z > 1$, the picture is less clear because the greater distances and higher typical AGN luminosities make it increasingly difficult to study host galaxies. Studies by Peng et al. (2006a, 2006b) argue that the relationship is shifted and that at this epoch ($z > 1$) the black hole mass grows faster relative to the stellar mass than is observed locally, while Lauer et al. (2007) and Di Matteo et al. (2008) argue for little change.

There is also considerable interest in the star-formation rates (SFRs) of the hosts at these redshifts. With the now prevalent view that the black holes and stars grow in a self-regulating process (see, e.g., Hopkins et al. 2005a, 2005b, 2006a, 2006b, 2008; Sijacki et al. 2007; Di Matteo et al. 2008), particularly during major mergers, it is of considerable importance to be able to estimate both the stellar mass and the SFR. In the Hopkins et al. (2005a, 2005b) scenario, the peak SFRs precede the peak quasar luminosity, and the quasar phase lasts about 10$^7$ yr. Unfortunately, estimating both stellar masses and SFRs at these redshifts not only requires a detection of the host but also a reasonably complete spectral energy distribution (SED).

Here, we make use of gravitational lensing to measure the SED of a $z_s = 1.73$ quasar host galaxy from 0.44–8.0 μm and infer its mass and SFR. As emphasized by Peng et al. (2006c), quasar lenses are ideal laboratories for studies of quasar hosts because the lens magnification "pulls" the host out from under the quasar to provide a $\sim 10^2$ improvement in contrast. Moreover, the arced shapes of the lensed hosts are easily distinguished from point-spread function (PSF) artifacts. Our target is the five-image lens SDSS J1004+4112 (Inada et al. 2003, 2005; Sharon et al. 2005; Ota et al. 2006; Fohlmeister et al. 2007, 2008; Inada et al. 2008). This lens is created by a $z_l = 0.68$ cluster of galaxies (Inada et al. 2003), giving it exceptionally large image separations (a $\sim 14$ arcsec Einstein ring diameter) that both leads to very large images of the host and places the quasar images well away from the lens galaxy emission. In fact, the host is so extended and well-separated from the lens that it can be resolved by the Spitzer Space Telescope with relative ease. There are also additional, higher redshift-lensed galaxies (Sharon et al. 2005) and time-delay measurements between the various lensed images of the quasar of $\Delta t_{\text{BA}} = 40.6 \pm 1.8$ days, $\Delta t_{\text{CA}} = 821.6 \pm 2.1$ days, and $\Delta t_{\text{AD}} > 1250$ days (Fohlmeister et al. 2008). In Section 2, we describe how we measure the SED of the host galaxy and the quasar. In Section 3, we use these estimates to determine the luminosity, stellar mass, and SFR of the host galaxy.

2. DATA

We use Hubble Space Telescope (HST) and Spitzer Space Telescope observations of SDSS J1004+4112 in eight bands covering the visual to mid-infrared wavelengths. The HST data consist of ACS/WFC Br(F435W), V(F555W), I(F814W) observations and NICMOS/NIC2 H(F160W) observations. The Spitzer/IRAC (Infrared Array Camera) data consist of 3.6, 4.5, 5.8, and 8.0 μm observations. For the V, I, H, and IRAC bands, we have multiple observational epochs. A summary of the observations is given in Table 1. Each HST observation consists of several (typically four) subexposures, drizzled together (Fruchter et al. 2002) to create one background-subtracted image. Each IRAC epoch consists of 36 dithered 96.8 s images in each of the IRAC channels. Starting with the Basic Calibrated Data frames, the mosaic is oversampled by a factor of 4 using MOPEX (Mosaicking and Point Source Extraction), with outlier rejection to remove cosmic rays. Typical image depths (in Vega magnitudes) are given in Table 1.

We first used a parametric model to fit the images using a combination of point sources for the quasars, exponential
disks, and de Vaucouleurs models for the cluster galaxies and Gaussians for the images of the host galaxies, all convolved with PSF models, as in Lehár et al. (2000). These have problems for Gaussians for the images of the host galaxies, all convolved with disks, and de Vaucouleurs models for the cluster galaxies and Gaussians for the images of the host galaxies, all convolved with PSF models, as in Lehár et al. (2000). These have problems for estimating the flux of the host galaxy due to the fact that the PSF, generated by TinyTim for the HST bands and obtained from Spitzer for the IRAC bands, has significant fractional errors at the peak of the quasar, exactly where the model for the host galaxy also peaks. The parametric models tend to overestimate the flux of the host galaxy in order to reduce the residuals at the position of the quasar. We will use these models only to correct aperture magnitudes for the effects of the PSF.

We next created a series of masks that isolate regions on the images where the flux is dominated by either the host galaxy or the quasar, in both cases excluding flux from objects in the field. These masks have regions with value either 0 or 1 in order to exclude or include flux, respectively, in specific pixels when multiplied into the original images. We keep the masks consistent across all bands by geometrically transforming a master copy to the appropriate centering, pixel scale, and the orientation of each observation. We defined three types of masks. Host masks exclude flux both near the quasars and away from the host images seen in the I/H data. Quasar masks include only flux near the peak of the quasar images. Background masks include a region outside the host mask that we use to estimate any residual background flux. Joint masks combine the host and the quasar masks to estimate the total flux of both components. Figure 1 superposes these masks on an H-band image.

When we apply a mask to a region, we calculate the flux \( f_{\text{mask}} \) under the mask. This flux is a combination of the true flux in the masked region \( f \) with contamination \( f_{\text{cont}} \) spread into the masked region by the PSF, losses \( f_{\text{loss}} \) out of the region due to the PSF, and \( f_{\text{back}} \) due to any misestimation of the background during the image reduction process. For example, we estimate \( f_{\text{cont}} \) and \( f_{\text{loss}} \) for our host mask as follows. We start from the model of the image without PSF convolution. We then mask this image, convolve it with the PSF, and measure the flux under the second mask. Thus, the contamination, \( f_{\text{cont}} \), of the host mask region due to the PSF spreading flux out of the quasar mask region is found by first masking the unconvolved model image with the quasar mask, convolving this masked image with the PSF, and then measuring the flux found in the host mask region, while \( f_{\text{loss}} \) is found by masking with the host mask, convolving with the PSF, and then measuring the flux outside the host mask. Since these corrections are modest, we are not very sensitive to the problems in the model image. We estimate the background by subtracting the model from the data and measuring the residuals in the background mask. The resulting flux for any region is then

\[
 f = f_{\text{mask}} - f_{\text{cont}} + f_{\text{loss}} - f_{\text{back}}.
\]

The measurements are summarized in Table 2. We first estimate statistical uncertainties in the magnitudes using a bootstrap resampling of the images. The bootstrap resampling technique creates an ensemble of trial images by sampling with replacement from the subimages (dithers, CR Splits, etc.) that were averaged together for each observation. We analyze each trial image in the same manner as the true images and estimate error bars from the variance of the results over the trials. The remaining uncertainty arises from the background subtraction. We recomputed all the estimates using two different regions for estimating the background flux, as well as a background estimate generated by the model fits. The dispersion of these background estimates, multiplied by the number of pixels in a given mask region, gives an estimate of the background uncertainties in each mask region. Small changes in the estimated background can have significant effects on the flux measured for the host because of the large number of pixels in both the host mask and the joint mask. The uncertainties we present in Table 2 are a combination of these statistical and background uncertainties, added in quadrature.

We use data from the ongoing monitoring of SDSS J1004+4112 (Fohlmeister et al. 2008) to correct for time variability of the quasar in the QSO and joint masks. We chose 2005 December 13 as the reference date, as many of our observations were made close to this date (see Table 1). We estimate the time-delay corrections by comparing the flux measured in the monitoring project on or within ~2 days of the observation with the flux measured in the monitoring project on or within ~2 days of the reference date. These time-delay corrections range from about 0.05 to ~0.44 magnitudes. We use these...
time-delay corrections only for the optical to near-IR observations of the quasar because the observations in the mid-IR show much less variability, as one would expect from the general trend of reduced variability at longer wavelengths (e.g., Vanden Berk et al. 2004). We do not correct for the time delays between the lensed images because the image D time delay is not known (see Fohlmeister et al. 2008). Essentially, we will “time average” the properties of the quasar in our final results.

3. ANALYSIS

We used an extended version of the SED template models presented by Assef et al. (2008) to fit the data for each lensed image. These templates consist of early-type, Sbc, Irr and QSO templates empirically derived by fitting the GALEX UV through Spitzer/MIPS 24 μm SEDs of 13623 “pure” galaxies (with no obvious signatures of nuclear activity) and 4242 quasars and galaxies with AGN activity in the NDWFS Boötes field (Jannuzi & Dey 1999), with redshifts measured by the AGN and Galaxy Evolution Survey (AGES; C. S. Kochanek et al. 2009, in preparation). Assef et al. (2008) give details of the procedure used to derive these templates, which will be discussed in more detail by R. J. Assef et al. (2009, in preparation). A fit is produced by multiplying each template by a coefficient and finding the $\chi^2$ minimizing fit to the data over these coefficients, with the added constraint that all template coefficients must be nonnegative, as subtracting a template is unphysical (see the discussion by Assef et al. (2008) and R. J. Assef et al. (2009, in preparation).

For images A, B, and C we separately fit the host, QSO, and joint SEDs, while for image D we only fit the joint SED. Figures 2–4 show examples of the template fits and Table 3 lists the host luminosities derived from the template fits to the host, QSO, and joint mask data. These luminosities are corrected for magnification by the lens using magnifications of 28.5, 19.1, 9.8, 7.8 for the A, B, C, and D images, respectively, from the models of Inada et al. (2008; M. Oguri 2008, private communication).

We used several methods to estimate our systematic uncertainties in determining the properties of the host galaxy. First, we fit the host mask data both with and without the $B$-, $V$-, and $I$-band data in order to examine whether eliminating the data points with the worst signal-to-noise ratios would produce any difference in the fits. These fits produced significant variations on an image-by-image basis, but showed little effect on the averages, which is unsurprising, considering that these data points are already heavily downweighted by their large uncertainties during the fitting process. Next, we fit the QSO and joint mask data once by allowing all template components to vary and once by fixing the ratios of the galaxy templates using the results of the host mask fits. These fits produced different results for the template ratios (although the Irr template was never favored) and

Figure 1. NICMOS/NIC2 $H$-band (F160W) image of SDSS J1004+4112 with mask outlines denoted by the solid black lines. The host galaxy is clearly seen stretched out from beneath the peak of the QSO. For image D we only use the joint mask.
## Table 2
SDSS J1004+4112 Magnitudes

| Filter | Date       | Image A          | Image B          | Image C          | Image D          |
|--------|------------|------------------|------------------|------------------|------------------|
|        |            | Host QSO Joint   | Host QSO Joint   | Host QSO Joint   | Host QSO Joint   |
| B      | 2005 Dec 13| 28.18 ± 0.81    | 23.44 ± 0.03    | 23.42 ± 0.01    | 23.24 ± 0.03    |
|        |            | 28.55 ± 0.67    | 23.24 ± 0.03    | 23.22 ± 0.01    | 23.26 ± 0.13    |
| V      | 2004 Jan 28| 27.93 ± 1.12    | 23.36 ± 0.15    | 23.34 ± 0.13    | 23.29 ± 0.15    |
|        |            | 27.39 ± 1.18    | 23.29 ± 0.15    | 23.26 ± 0.13    | 23.26 ± 0.13    |
| V      | 2005 Dec 12| 27.76 ± 1.11    | 23.29 ± 0.10    | 23.27 ± 0.08    | 23.27 ± 0.11    |
|        |            | 27.59 ± 1.19    | 23.27 ± 0.11    | 23.24 ± 0.08    | 23.24 ± 0.08    |
| I      | 2004 Apr 28| 25.52 ± 0.97    | 22.30 ± 0.16    | 22.26 ± 0.16    | 22.16 ± 0.16    |
|        |            | 25.39 ± 0.81    | 22.16 ± 0.16    | 22.11 ± 0.15    | 22.11 ± 0.15    |
| I      | 2005 Dec 12| 25.78 ± 0.73    | 22.42 ± 0.10    | 22.36 ± 0.04    | 22.27 ± 0.12    |
|        |            | 25.57 ± 0.72    | 22.27 ± 0.12    | 22.21 ± 0.04    | 22.21 ± 0.04    |
| H      | 2004 Apr 28| 22.43 ± 0.23    | 21.26 ± 0.10    | 21.02 ± 0.11    | 21.09 ± 0.11    |
|        |            | 22.36 ± 0.14    | 21.09 ± 0.11    | 20.86 ± 0.11    | 20.86 ± 0.11    |
| H      | 2004 Oct 9 | 22.41 ± 0.41    | 20.93 ± 0.08    | 20.66 ± 0.13    | 20.88 ± 0.09    |
|        |            | 21.89 ± 0.40    | 20.88 ± 0.09    | 20.47 ± 0.14    | 20.47 ± 0.14    |
| H      | 2006 Oct 22| 22.38 ± 0.15    | 21.16 ± 0.10    | 20.87 ± 0.09    | 20.86 ± 0.10    |
|        |            | 21.94 ± 0.33    | 20.86 ± 0.10    | 20.48 ± 0.13    | 20.48 ± 0.13    |
| 3.6 µm | 2005 Dec 8 | 19.94 ± 0.33    | 18.69 ± 0.01    | 18.30 ± 0.05    | 18.60 ± 0.03    |
|        |            | 19.42 ± 0.21    | 18.60 ± 0.03    | 18.07 ± 0.09    | 18.07 ± 0.09    |
| 3.6 µm | 2005 Dec 26| 19.80 ± 0.17    | 18.72 ± 0.02    | 18.29 ± 0.07    | 18.65 ± 0.02    |
|        |            | 19.41 ± 0.33    | 18.65 ± 0.02    | 18.10 ± 0.10    | 18.10 ± 0.10    |
| 3.6 µm | 2006 Nov 25| 19.80 ± 0.22    | 18.86 ± 0.06    | 18.42 ± 0.10    | 18.67 ± 0.06    |
|        |            | 19.37 ± 0.32    | 18.67 ± 0.06    | 18.10 ± 0.07    | 18.10 ± 0.07    |
| 4.5 µm | 2005 Dec 8 | 19.12 ± 0.23    | 17.87 ± 0.01    | 17.46 ± 0.06    | 17.74 ± 0.02    |
|        |            | 18.90 ± 0.11    | 17.74 ± 0.02    | 17.32 ± 0.03    | 17.32 ± 0.03    |
| 4.5 µm | 2005 Dec 26| 19.01 ± 0.22    | 17.92 ± 0.02    | 17.47 ± 0.03    | 17.81 ± 0.02    |
|        |            | 18.86 ± 0.08    | 17.81 ± 0.02    | 17.36 ± 0.03    | 17.36 ± 0.03    |
| 4.5 µm | 2006 Nov 25| 19.04 ± 0.22    | 18.01 ± 0.05    | 17.59 ± 0.05    | 17.85 ± 0.05    |
|        |            | 18.89 ± 0.04    | 17.85 ± 0.05    | 17.43 ± 0.05    | 17.43 ± 0.05    |
| 5.8 µm | 2005 Dec 8 | 18.92 ± 0.32    | 17.03 ± 0.01    | 16.71 ± 0.03    | 16.96 ± 0.02    |
|        |            | 18.60 ± 0.15    | 16.96 ± 0.02    | 16.62 ± 0.06    | 16.62 ± 0.06    |
| 5.8 µm | 2005 Dec 26| 19.08 ± 0.40    | 17.06 ± 0.01    | 16.76 ± 0.04    | 16.96 ± 0.01    |
|        |            | 18.87 ± 0.18    | 16.96 ± 0.01    | 16.65 ± 0.03    | 16.65 ± 0.03    |
| 5.8 µm | 2006 Nov 25| 18.95 ± 0.40    | 17.12 ± 0.04    | 16.90 ± 0.06    | 16.91 ± 0.04    |
|        |            | 18.77 ± 0.22    | 16.91 ± 0.04    | 16.70 ± 0.05    | 16.70 ± 0.05    |
| 8.0 µm | 2005 Dec 8 | 18.53 ± 0.17    | 15.93 ± 0.01    | 15.89 ± 0.01    | 15.85 ± 0.01    |
|        |            | 18.27 ± 0.48    | 15.85 ± 0.01    | 15.80 ± 0.02    | 15.80 ± 0.02    |
| 8.0 µm | 2005 Dec 26| 18.51 ± 0.18    | 16.07 ± 0.04    | 15.88 ± 0.02    | 16.00 ± 0.01    |
|        |            | 18.45 ± 0.30    | 15.88 ± 0.02    | 15.85 ± 0.03    | 15.85 ± 0.03    |
| 8.0 µm | 2006 Nov 25| 18.46 ± 0.08    | 15.87 ± 0.03    | 16.02 ± 0.03    | 15.73 ± 0.03    |
|        |            | 18.27 ± 0.23    | 15.73 ± 0.03    | 15.91 ± 0.04    | 15.91 ± 0.04    |

Notes. These are Vega magnitudes corrected for magnification by the lens based on the models of Inada et al. (2008; M. Oguri 2008, private communication). The fluxes in the QSO mask contain a portion of the host galaxy. The QSO and joint fluxes are adjusted to account for time-dependent variability in the quasar using corrections from the monitoring data of Fohlmeister et al. (2008). The 2004 April 28 NICMOS H-band observation included only images A and B.
between the 8.0 μm flux and LIR, while Kennicutt (1998a) yields a very flat SED in the UV region used in their template fits, which is then used to estimate the unobscured SFR. The SFRs derived from our template fits are given in Table 3, where uncertainties in the UV SFRs are dominated by uncertainties in the template fits, while those in the IR SFRs are dominated by the scatter in the scaling relations. Kennicutt (1998a) note that this UV–SFR relation has the benefit of directly tracking emission from young stellar atmospheres, but would also be quite sensitive to both the extinction and variation of the IMF. The Kennicutt (1998b) relation between the IR luminosity and the SFR likewise assumes a Salpeter IMF with continuous star formation, but it also assumes that all of the bolometric luminosity is reprocessed in the infrared.

We combined the template models with the results of Bell et al. (2003) to estimate the stellar mass of the host galaxy. Bell et al. (2003) assumed a universal “diet Salpeter” IMF and a variety of star-formation histories to simulate SED templates, which then fit to a large sample of Sloan Digital Sky Survey (SDSS) galaxies to estimate mass-to-light ratios, log(M/L) ratios, in combination with the measured colors of the galaxies, to derive relationships between colors and mass-to-light ratios, log(M/L) = a_0 + (b_0 × color), as detailed by Bell et al. (2003, Table 7). We assume a Kroupa IMF, which better represents a normal stellar population, and this introduces a –0.15 dex

Figure 2. Host mask SED for images A (top), B (middle), and C (bottom). Observation bands are from left to right: ACS/WFC (F435W), V(F555W), I(F814W), NICMOS/NIC2 (H(F160W), IRAC 3.6, 4.5, 5.8, and 8.0 μm). The results for all observation epochs are shown. The solid, dot-dashed, long-dashed, and short-dashed lines correspond to the total SED and the contribution from the E, Sbc, and Irr templates, respectively. The open circles are the measured fluxes, while the closed squares are the best-fit values given the template fits. The contribution from the Irr template is too small to be seen on this scale. The SEDs are corrected for magnification by the lens based on the models of Inada et al. (2008; M. Oguri 2008, private communication).

Figure 3. QSO mask SED for images A (top), B (middle), and C (bottom). The galaxy templates and data points are the same as described in Figure 2, while the dotted line shows the QSO template and the solid line shows the sum of all templates. The contribution from the Irr template is too small to be seen on this scale. The changes in the optical continuum slope are due to the variations in the QSO extinction estimates.
correction to the value of $a_{\lambda}$. We estimate the rest frame $(g - r)$ color and $K$-band luminosity from our template fits, and then use the Bell et al. (2003) $K$-band parameters ($a_K = -0.359$ and $b_K = 0.197$) to estimate the mass-to-light ratio. This leads to an estimated host $K$-band $\log(M/L) = (-0.19 \pm 0.28)(M/L)_\odot$, with uncertainties dominated by random scatter in the Bell et al. (2003) calibration and in the color derived from the template fits. The estimated rest frame $(g - r) \simeq 0.85$ color of the host puts it in the “green valley” between the star-forming “blue cloud” and the “red sequence” (see, e.g., Strateva et al. 2001; Blanton et al. 2003), as seen in Figure 5.

The estimated Mg $\text{II}$ and C[IV] line FWHM are 49 and 21 Å, respectively (Fohlmeister et al. 2008; C. W. Morgan 2009, private communication). Both indicate a black hole mass of $\log(M_{\text{BH}}/M_\odot) \simeq 8.6$ based on the scalings of McLure & Jarvis (2002) for Mg $\text{II}$ and Vestergaard & Peterson (2006).
for C[IV]. We have also applied the revised normalization of Onken et al. (2004) to the Mg II estimate. The estimated magnification-corrected luminosity at rest frame at 1350 Å is $2.0 \times 10^{43}$ erg s$^{-1}$ based on power-law fits to the B, V, and I HST images. The uncertainties in the $M_{\text{BH}}$ estimate are dominated by systematics, principally the 0.3 dex uncertainty typical of $M_{\text{BH}}$ estimates from line widths and 0.15 dex from the magnification uncertainties. Nonetheless, the excellent agreement between the Mg II and C[IV] mass estimates ($\log(M_{\text{BH}}/M_\odot) = 8.62$ and 8.56, respectively) is reassuring. If we estimate a black hole mass from the rest-frame V-band host luminosity of $(2.07 \pm 0.03) \times 10^{43}$ erg s$^{-1}$, using the relation of Gültekin et al. (2009), we find a black hole mass of $(M_{\text{BH}}/M_\odot) = 8.74 \pm 0.21$ that agrees well with the estimates from the line widths. Note, however, that we have no estimate of the fraction of the galactic luminosity that comes from the host’s bulge, as used in the Gültekin et al. (2009) relation, since decomposing the host galaxy into bulge and disk components is made impossible by the geometry of the lensing of the host and the high luminosity of the quasar. The Eddington luminosity for such a black hole is

$$L_{\text{Edd}} = 5.7 \times 10^{42} \left( \frac{M_{\text{BH}}}{10^{8.6} M_\odot} \right) L_\odot.$$  

From our template models, we can estimate the 0.1–24 μm luminosity of the black hole (see Table 3). We use the 3 μm to L$_{\text{IR}}$ analysis from Section 2.6 of Gallagher et al. (2007), applied to the Boötes field AGNs to estimate a bolometric correction of BC $\simeq 1$ between this luminosity and the bolometric luminosity (for an in depth discussion, see R. J. Assef et al., 2009, in preparation).

Based on these scalings, a weighted average over the different lensed images and assuming a Kroupa IMF, we estimate that the total (obscured plus unobscured) SFR is $\log(M/M_\odot \text{ yr}^{-1}) = 1.21 \pm 0.26$ compared with a stellar mass of $\log(M_*/M_\odot) = 11.09 \pm 0.28$. The uncertainties in these quantities are dominated by the scatter in the IR scaling relations. Aside from the systematic and random uncertainties in the scalings used to determine the SFR (40%; Kennicutt 1998b; Babouzet et al. 2008) and the stellar mass (26%; Bell et al. 2003), the biggest uncertainties arise from the magnification estimates. The IRAC quasar flux ratios are probably a reasonable estimate of the intrinsic flux ratios because we expect (and observe) little variability at these wavelengths, as quasar variability diminishes to longer wavelengths (Vanden Berk et al. 2004), extinction effects will be negligible, and the mid-IR emission region is too large to be strongly microlensed (see, e.g., Pointdexter et al. 2007 for microlensing in HE 1104-1805). These IR flux ratios are B/A $\sim 0.76$, C/A $\sim 0.63$, and D/A $\sim 0.32$ compared with 0.67, 0.34, and 0.27 respectively from the Inada et al. (2008) models (M. Oguri, 2008, private communication). Much of this will be incorporated into the uncertainties estimated from the scatter between the various lensed images and masks. The host SED has roughly equal contributions from the E and Sbc templates and little contribution from the Irr template, independent of the image or region fit. While dust could obscure the optical/UV emission of young stars in the Irr template (see Figure 4), we would not find a good fit to the host using an obscured Irr template. Note that the inner (QSO mask) and the outer (Host mask) regions of the host galaxy seem to contain a similar number of stars and have similar specific SFRs.

We can also compare these inferences about the stars with those for the black hole. The black hole represents a mass fraction of $\log(M_{\text{BH}}/M_*) = -2.49 \pm 0.28$ compared with the stars, which is marginally inconsistent with local estimates of $\log(M_{\text{BH}}/M_*) = -2.85 \pm 0.12$ (Häring & Rix 2004). Our result is in better agreement with the Peng et al. (2006a) estimate that the $M_{\text{BH}}/M_*$ relation is $4^{+3}_{-1} (\pm 0.6$ dex) larger at $z = 1.7$ than locally (i.e., $\log(M_{\text{BH}}/M_*) \simeq -2.25$). Assuming that the evolution in this relationship found by Peng et al. (2006a) is correct, the agreement of the black hole masses estimated from the line widths and the host luminosity is then a coincidence in which the effect of evolution in the relation is balanced by our overestimation of the bulge luminosity. Finally, we note that after including our estimate of the bolometric correction, we find that $L_{\text{BH}}/L_{\text{Edd}} \simeq 0.24 \pm 0.05$, so the black hole is radiating at a significant fraction of its Eddington limit, as is typical of quasars at this epoch (e.g., Kollmeier et al. 2006). The quasar may be moderately extincted, as we find best fits where the quasar template is reddened by $E(B-V) \simeq 0.1, 0.1, 0.15$, and 0.0 magnitudes for the A–D images, respectively.

In summary, both the host galaxy and the quasar in SDSS J1004+4112 have relatively unremarkable properties. The one exception is that the host galaxy lies in the “green valley.” It is unclear from our template fits whether this galaxy is in transition from being a star-forming galaxy in the “blue cloud” to an old, red, and dead galaxy on the red sequence, or a red sequence galaxy with a recent burst of star formation that moved its color bluishward. This galaxy’s location in the color-magnitude diagram (CMD) is consistent with the observation of Hickox et al. (2009) that many X-ray AGNs with the X-ray luminosity of SDSS J1004+4112 ($\simeq 2 \times 10^{43}$ erg s$^{-1}$; Ota et al. 2006; Lamer et al. 2006) lie in the green valley, while radio AGNs tend to lie on the red sequence and mid-IR selected AGNs tend to lie in the blue cloud. The extreme extension of the host galaxy should also make it possible to obtain spectroscopic observations of the
host galaxy, potentially allowing measurement of the dynamical mass or metallicity.

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