THE HOST GALAXY OF THE QUASAR HE 0450–2958

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ABSTRACT

A recent study suggests that the quasar HE 0450–2958 is hosted by a galaxy substantially fainter than that inferred from the correlation between black hole mass and bulge luminosity. As this result has significant bearings on galaxy and black hole evolution, we revisit the issue by performing an independent analysis of the data, using a two-dimensional image fitting technique. We indeed find no evidence of a host galaxy either, but, due to the brightness of the quasar and uncertainties in the point-spread function, the limits are fairly weak. To derive an upper limit on the host galaxy luminosity, we perform simulations to deblend the quasar from the host under conditions similar to those actually observed. We find that the host galaxy has an absolute magnitude upper limit of \(M_V \lesssim -21\), in good agreement with the previous determination. Since this limit is consistent with the value predicted from the current best estimate of the black hole mass, there is no compelling evidence that the quasar HE 0450–2958 has an abnormally underluminous host galaxy. We also show that, contrary to previous claims, the companion galaxy to HE 0450–2958 should not be regarded as an ultraluminous infrared galaxy.

Subject headings: galaxies: active — galaxies: bulges — galaxies: fundamental parameters — quasars: individual (HE 0450–2958)

1. INTRODUCTION

It is widely accepted that central black holes commonly exist in massive galaxies and that they play an important role in their evolution (see reviews in Ho 2004). This view is in large part motivated by the strong empirical correlations that exist between black hole mass and host galaxy properties, in particular the bulge luminosity (\(M_* - L_{\text{bul}}\) relation; Kormendy & Richstone 1995; Magorrian et al. 1998) and bulge stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000). An intriguing recent observation has posed a challenge to this picture. From analysis of high-angular resolution data on the bright, relatively nearby quasar HE 0450–2958, Magain et al. (2005; hereinafter M05) were not able to detect a host galaxy associated with this system. They claim that the black hole in HE 0450–2958 is hosted by an exceptionally faint galaxy, in apparent violation of the \(M_* - L_{\text{bul}}\) relation. The results of M05 have stimulated lively debate as to the cause of this apparent anomaly, including the possibility of the black hole in HE 0450–2958 having been ejected from its companion galaxy in the aftermath of a merger event, either by gravitational radiation recoil or the slingshot effect from a three-body interaction. Either of these explanations, if correct, would have important implications for theories concerning the dynamics and evolution of binary massive black holes.

The analysis of M05, both for their Hubble Space Telescope (HST) images and ground-based spectra, rely on highly specialized deconvolution methods developed by these authors (Magain et al. 1998; Courbin et al. 2000). While we do not call into question the reliability of M05’s analysis, given the widespread interest that their results have generated, it would be necessary to confirm them independently, preferably using a different technique. This is the main purpose of this paper, where we attempt to constrain the luminosity of the host of HE 0450–2958 using a two-dimensional image fitting program.

HE 0450–2958 is a luminous (\(M_V = -25.8\) mag) radio-quiet quasar located at a redshift \(z = 0.285\). Originally discovered by de Grijp et al. (1987), it has previously been noted for being a prominent infrared source (de Grijp et al. 1987; Low et al. 1988) with characteristics intermediate between those of starburst galaxies and quasars, prompting Canalizo & Stockton (2001) to speculate that the system is undergoing a transition between these two evolutionary phases, plausibly triggered by tidal interaction with a companion located only \(\sim 1''5\) away. The field surrounding HE 0450–2958 is quite complex (see Fig. 1 and M05). In addition to the nearby, distorted companion, a bright foreground star sits \(2''\) in the opposite side of the quasar, and immediately adjacent to the quasar lies a blob of ionized gas. Given these complications and the large brightness contrast between the quasar and any putative underlying host galaxy, we can anticipate that any robust estimate of the host will be nontrivial (e.g., Schade et al. 2000). Nevertheless, our analysis indicates that the current limits cannot exclude the possibility that HE 0450–2958 has a normal host galaxy.

2. DATA REDUCTION AND IMAGE FITTING

The data analyzed in this study were retrieved from the HST archive. The images were taken on 2004 October 1 (GO 10238; PI: Courbin) with the High Resolution Channel of the Advanced Camera for Surveys (ACS) through the F606W filter. Three short exposures of 30 s and three long exposures of 330 s were taken with dithering. To construct a reliable point-spread function (PSF), several stars, of unknown spectral type selected from the HST Guide Star Catalog, were also observed with the same observing strategy. One of the stars was observed during the same orbit as the science target, while the others were ob-

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5We adopt the following cosmological parameters: \(H_0 = 100 h = 71\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.27\), and \(\Omega_{\Lambda} = 0.75\) (Spergel et al. 2003).
Fig. 1.— GALFIT decomposition of the HST/ACS F606W image of HE 0450–2958. Each panel is $10'' \times 10''$, with $1''$ denoted by the horizontal bar. The original, model, and residual images are shown in the left, middle, and right columns, respectively. In panel (a), the model contains the quasar, a host galaxy (modeled with a Sérsic index $n = 1.8$) centered on the quasar, and the foreground star; the companion galaxy was masked out. The residual image clearly shows the “blob” adjacent to the quasar. In panel (b), the fit includes both the companion galaxy and the blob, each modeled with Sérsic components of arbitrary shape described by Fourier modes.
served during different orbits; hereinafter we will refer to these as the “optimal” PSF and the “alternative” PSFs, respectively. Standard data reduction steps, including bias subtraction, flat fielding, and flux calibration were done by the HST pipeline.

We experimented with different ways to combine the drizzled subexposures, by iteratively applying manual shifts to the PSF images. In the end, we found that the best results were achieved using the Pyraf-based script MULTIDRIZZLE, using the default coordinate information in the image headers. After applying MULTIDRIZZLE to each exposure subset, the saturated cores of the deep image were replaced by the unsaturated cores of the short-exposure image.

We analyzed the images using an updated version (3.0) of GALFIT (Peng et al. 2002; C. Y. Peng et al., in preparation), a program designed to perform two-dimensional fits to HST images of galaxies. GALFIT finds an optimal decomposition of a galaxy image into multiple components, each described by a user-specified parametric model properly convolved with an input PSF. The choice of input PSF is critical. For objects such as HE 0450−2958, where the contrast between the active galactic nucleus (AGN) and the host galaxy is large, tiny mismatches of the PSF core will result in large mismatches in the PSF wings, and hence lead to erroneous inferences on the properties of the host. To bracket the systematics induced by PSF variations, we perform our fits using not only the optimal PSF, but also the three additional alternate PSFs.

The variance among the PSFs at the peak is 20%, which is consistent with the genuine PSF variance of ACS (Jahneke et al. 2004). Note that we do not use synthetic TinyTim (Krist 1995) PSFs, as these do not give a sufficiently accurate representation of the true PSF for the present application.

In our first attempt, we masked out the companion galaxy during the fit. We assumed that the luminosity profile of the host galaxy can be described by a single-component Sérsic (1968) function. We experimented with three cases: (1) Sérsic index $n = 1$, which is equivalent to an exponential profile; (2) $n = 4$, which is equivalent to a de Vaucouleurs (1948) profile; and (3) $n$ was allowed to be a free parameter. We let the program fit for all of the other free parameters: for the host galaxy, these are its position, luminosity, effective radius, axis ratio, and position angle; for the quasar core and foreground star, these are their positions and luminosities. The case with free $n$ is shown in Figure 1a. In the residual image, the peak of the AGN component tends to be oversubtracted, and the blob clearly shows up adjacent to the AGN. The best-fit component for the host galaxy has a very small effective radius (less than one pixel). This indicates that the fit is unphysical, and is a symptom of GALFIT trying to assign the residual flux from the PSF mismatch to the host galaxy component. Varying the input PSF did not help.

Given the proximity of the companion galaxy and the blob to the quasar, they are likely to have a significant effect on the fit. Thus, we next performed the fit explicitly including these two features, using version 3.0 of GALFIT, which models the individual components using Fourier modes to allow for non-axisymmetric shapes. After some experimentation, we find that the bright knots and the extended halo of the companion can be described by four Sérsic components, whereas the blob can be fit with just a single Sérsic component. The fit using the optimal PSF is shown in Figure 1b, and the results are summarized in Table 1. The fit formally yields a host galaxy with $M_V \approx -19.8 \pm 1.5$ mag, depending on the choice of PSF, but we believe this result to be spurious, since the model has a tiny, physically unrealistic effective radius ($\lesssim 1$ pixel) and an axis ratio of nearly zero. The best fit, therefore, fails to yield

### Table 1

| Feature            | Function | $m_{F606W}$ | $M_V$   | Error | $R_E$ | $n$ | $b/a$ | Notes |
|--------------------|----------|-------------|---------|-------|-------|-----|-------|-------|
| Quasar             | PSF      | 15.18       | -25.46  | 0.48  | ...   | ... | ...   | ...   |
| Host Galaxy        | Sérsic   | 20.87       | -19.77  | 1.47  | 0.96  | 4.18| 0.03  | b     |
| Blob               | Sérsic   | 19.36       | -21.41  | 1.41  | 15.4  | 1.74| 0.43  |       |
| Companion Galaxy   | Sérsic   | 18.60       | -22.17  | 0.01  | 59.7  | 2.52| 0.47  | c     |
| Blob               | Sérsic   | 20.27       | -20.50  | 0.05  | 11.8  | 0.69| 0.53  |       |
| Blob               | Sérsic   | 20.28       | -20.49  | 0.04  | 10.8  | 0.47| 0.79  |       |
| Blob               | Sérsic   | 22.73       | -18.04  | 0.04  | 3.7   | 0.04| 0.54  |       |
| Foreground Star    | PSF      | 16.36       | ...     | ...   | ...   | ... | ...   | ...   |

Note.— Col. (1): Feature fitted. Col. (2): Function used in the fit. Col. (3): Apparent magnitude in the F606W filter, in the Vega system. Col. (4): V-band absolute magnitude, corrected for K-correction but not for Galactic extinction, which is negligibly small ($A_V = 0.05$ mag). For the quasar component, the K-correction and the transformation between F606W and $V$ were determined using the quasar composite spectrum of Vandenberg et al. 2001. In the case of the blob and companion galaxy, the corrections follow Fukuji et al. 1995 assuming an Sbc galaxy template; $M_V$ will be brighter by 0.25 mag if we assume an elliptical galaxy template. Col. (5): Uncertainty of the magnitude due to PSF variation. Col. (6): Effective radius of the S´ersic component, in units of pixels. Col. (7): S´ersic index. Col. (8): Axis ratio (minor/major axis). Col. (9): Notes: (a) $M_V = -25.47$ mag if include host galaxy. (b) Upper limit lies in the range $-19.2 < M_V < -20.2$ mag. The small effective radius and axis ratio suggests that this component is spurious. (c) Sum of all 4 components gives $M_V = -22.57$ mag.
Fig. 2. — Simulated images of HE 0450−2958 with an input host galaxy described by (a) $M_V = -24.2$ mag, $R_e = 3''/4$, Sérsic index $n = 4$, and $b/a = 1.0$ and (b) $M_V = -18.2$ mag, $R_e = 0''.1$, $n = 4$, and $b/a = 1.0$. Each panel is $10'' \times 10''$, with $1''$ denoted by the horizontal bar. The simulated image, nuclei subtracted image after the fit, and residual image are shown in the left, middle, and right columns, respectively. Both the simulations and the fits were performed using the optimal PSF.
convincing evidence for a host galaxy.

3. SIMULATIONS

We first ran purely idealized simulations to determine a robust upper limit for the luminosity of the undetected host galaxy. Using GALFIT, we generated a set of images wherein, using the optimal PSF, the quasar and the foreground star were placed at their respective locations. Then, artificial single-component host galaxies with realistic parameters were added on top of the quasar. Specifically, the galaxies spanned a wide range in absolute magnitude ($-18.2 \leq M_V \leq -24.2$, $\Delta M_V = 1.0$), axis ratio ($b/a = 0.7, 0.85, 1.0$), and Sérsic index ($n = 1, 2.5, 4$). The effective radius of each galaxy was assigned using the $r$-band size-luminosity relation of local early-type galaxies given by McIntosh et al. (2005), which we assume reasonably approximates the F606W band. This idealization represents the absolute detection limit given signal-to-noise considerations in the absence of complications, such as PSF mismatches or other non-random structures in the image.

We simulated a 990 s exposure by adding in an appropriate average sky background, as given in the ACS Instrument Handbook, readout noise, and Poisson noise. Since in the real observation the bright core was saturated in deep (990 s) image and replaced by the short-exposure (90 s) image, we increased the noise in the core by a factor of $\sqrt{10}$. Finally, we use GALFIT to fit the artificial images to recover the host galaxy, again using the optimal PSF. Figure 2 shows two examples at the extremes of the luminosity sequence we simulated. The results of our idealized simulations are summarized in Figure 3, where we show, as a function of input host galaxy absolute magnitude, the output residuals in absolute magnitude, effective radius, and Sérsic index. As expected, the magnitude residuals grow increasingly larger as the input galaxy becomes fainter. When GALFIT fails to detect the host, the Sérsic host component competes for the flux from the AGN core itself, resulting in a component that is more luminous (Fig. 3a) and more compact (Fig. 3b) than the input model. Such a spurious object would also tend to have a strong central peak, as evidenced by the large output Sérsic index (Fig. 3c).

How do we establish an upper limit on the host galaxy luminosity? As mentioned above, when GALFIT cannot detect a host, the host component competes for the flux from the central AGN core by shrinking in size to mimic a PSF. Thus, the plot for the residual of the effective radius provides an important diagnostic. Based on this observation, we estimate that the host galaxy has a likely upper limit of $M_V \approx -20.2 \pm 1.0$ mag due to purely signal-to-noise considerations. Changing the input PSF to simulate PSF mismatch does not appreciably change the qualitative behavior of the fit.

The above set of simulations, however, is highly idealized. In order to make the calculations more realistic, we added the artificial galaxy model directly on top of the quasar in the real science image. For simplicity, we assumed an elliptical-like galaxy with $n = 4$, whose size, as above, is specified by the size-luminosity relation. For the fit, we used the optimal PSF plus two of the alternate PSFs. We held fixed all the parameters for the other components (quasar, blob, companion galaxy, and foreground star), with the exception of their amplitude, based
on the best-fitting results from the original image (Table 1). The trends in the residuals for this set of simulations (Fig. 4) qualitatively resemble those for the idealized set, but in detail they differ due to added complexities in the image. In particular, the optimal PSF is somewhat better than one of the alternate PSFs at recovering the input model, thereby showing how sensitive the results are to PSF assumptions under high-contrast imaging.

Using again the criterion of $R_\text{out}/R_\text{in} \rightarrow 0$ to gauge when the recovered galaxy parameters appear improbable, we estimate the upper limit of the host’s absolute magnitude to be $M_V \approx -21.2 \pm 1.0$, roughly 1 magnitude brighter than in the idealized simulations.

4. RESULTS AND DISCUSSION

4.1. The Luminosity of the Host Galaxy

This study provides a new, independent analysis of the HST/ACS images of the quasar system HE 0450–2958. Our analysis is based on direct two-dimensional fitting of the images. Consistent with the findings of M05, we also failed to detect the galaxy presumably hosting the black hole. We performed extensive simulations in order to place a robust upper limit on the brightness of the undetected host. Depending on the assumptions adopted, our upper limit of the absolute magnitude of the host galaxy lies in the range $M_V \approx -20$ to $-21$ mag. These limits are similar to those found by M05, based on a very different method of analysis.

How luminous do we expect the host galaxy to be? This can be estimated from the $M_* - L_{\text{bul}}$ relation, given a black hole mass. Assuming that the quasar is radiating at 50% of its Eddington limit, M05 estimated $M_* \approx 8 \times 10^8 M_\odot$. This value, however, is about a factor of 10 too large. Merritt et al. (2006) show that HE 0450–2958 shares many of the properties of narrow-line Seyfert 1 galaxies, which are thought to be relatively low-mass black holes radiating near or perhaps even greater than their Eddington limit (e.g., Collin & Kawaguchi 2004). From an analysis of the optical spectra taken by M05, Merritt et al. obtained a new estimate of the black hole mass using the virial method (e.g., Kaspi et al. 2000) as presented by Greene & Ho (2005b). Depending on the formalism used, they find $M_* \approx (6-9) \times 10^7 M_\odot$. Choosing, for concreteness, $M_* = 7.5 \times 10^7 M_\odot$, the $B$-band $M_* - L_{\text{bul}}$ relation of Marconi & Hunt (2003) for inactive galaxies predicts a bulge absolute magnitude of $M_R = -18.9$, or $M_V \approx -19.9$ assuming $B-V = 0.96$ mag for early-type galaxies (Fukugita et al. 1995). Alternatively, if we adopt the $R$-band $M_* - L_{\text{bul}}$ relation of McLure & Dunlop (2002) for active galaxies, properly adjusted to our cosmology, we obtain $M_R = -21.2$ mag, or $M_V \approx -20.6$ if $V-R = 0.61$ mag (Fukugita et al. 1995). Considering the allowed range of black hole masses, the current uncertainty on the zeropoint of the virial mass estimator for AGNs ($\sim 0.5$ dex; Nelson et al. 2004; Onken et al. 2004; Greene & Ho 2006), and the intrinsic scatter of the $M_* - L_{\text{bul}}$ relation ($\sim 0.3$ dex; McLure & Dunlop 2002; Marconi & Hunt 2003), the predicted host luminosity is consistent with the observed upper limits.

The above conclusion is subject to three caveats. First, most nearby narrow-line Seyfert 1 galaxies have a disk component in addition to a bulge (Crenshaw et al. 2003). Our luminosity limit for the host, therefore, is uncertain by its unknown bulge-to-total luminosity ratio, which for early-type spirals is $\sim 0.5$. Second, we have assumed that narrow-line Seyfert 1 galaxies obey the same black hole-bulge scaling relations as do inactive galaxies and other classes of AGNs. Despite claims to the contrary (e.g., Wandel 2002; Mathur & Grupe 2005), however, recent studies that directly probe the stellar component of the host (Barth et al. 2005; Botte et al. 2005; Greene & Ho 2005a, 2006) give little reason to suspect that narrow-line Seyfert 1 galaxies behave abnormally. Finally, given the quasar-like luminosity of HE 0450–2958, we should bear in mind that any direct analogy with the typically much less luminous narrow-line Seyfert 1 galaxies is necessarily speculative.

4.2. The Companion Galaxy is Not a ULIRG

In the recent literature (e.g., M05; Haehnelt et al. 2006; Hoffman & Loeb 2006; Merritt et al. 2006), the companion is often referred to as an ultraluminous infrared galaxy (ULIRG), by which is meant a highly obscured system experiencing a high level of ongoing star formation. This perception appears to be driven by the association of the HE 0450–2958 system with an infrared-bright source, with the implicit assumption that most of the infrared emission arises from stellar heating intrinsic to the companion galaxy, by the fact that the companion has a young stellar population (Canalizo & Stockton 2001; M05; Merritt et al. 2006), and the suggestion, based on its apparently large Balmer decrement, that the companion appears to be highly extincted (M05).

We disagree with this assessment, for the following reasons. Although the HE 0450–2958 system indeed is infrared-bright, we believe that most of the dust emission is associated with and heated by the quasar itself rather than the companion galaxy. (The spatial resolution of the infrared observations is insufficient to separate the companion from the quasar.) From the Infrared Astronomical Satellite (IRAS) measurements given in the IRAS Point Source Catalog, the infrared flux density ratios of HE 0450–2958 ($S_{25}/S_{60} = 0.32$, $S_{60}/S_{100} = 0.81$) lie in the regime of AGNs (de Grijp et al. 1987; Low et al. 1988). This indicates that the dust temperature is generally hotter than in typical starbursts and is more characteristic of AGN heating.

Our second, more compelling argument is based on the serious inconsistency between the predicted and actual emission-line strength of the object. The total ($8-1000 \mu m$) observed infrared luminosity, $\sim 5.3 \times 10^{12} L_\odot$ (Canalizo & Stockton 2001, adjusted to our adopted distance), if entirely attributed to star formation, would correspond to a star formation rate of $840 M_\odot$ yr$^{-1}$, using the calibration of Bell (2003). This estimate is severely at odds with the optical spectrum of the companion galaxy, which shows only weak emission lines superposed on a post-starburst spectrum (Canalizo & Stockton 2001; Merritt et al. 2006). According to the calibration of Kewley et al. (2004), and assuming solar abundances, a star formation rate of $840 M_\odot$ yr$^{-1}$ would generate a luminosity of $1.2 \times 10^{44}$ ergs s$^{-1}$ for the [O II] $\lambda 3727$ emission line, or a line flux of $f_{\text{[O II]}} = 4.8 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$ for a distance of 1452 Mpc. This value is over 800 times larger than the actual flux ($f_{\text{[O II]}} = 5.9 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$) we measured from the flux-calibrated spectrum published by Merritt et al. (2006), kindly sent to us by T. Storchi-Bergmann. Note that this value is probably an upper limit, since it is likely that there is some contamination from the narrow-line emission of the nearby quasar. One cannot appeal to high levels of extinction to hide the [O II] emission, because the Balmer decrement of the companion is actually rather modest, contrary to the assertion of M05. In the observed spectrum, the H$\beta$ line indeed does appear to be rather weak with respect to H$\alpha$, but this is partly due to dilution with strong H$\beta$ absorption.
from A stars. A proper measurement of the Balmer decrement requires careful decomposition of the starlight from the line emission (e.g., Ho et al. 1997). After subtracting a synthetic model for the starlight from the observed spectrum, Merritt et al. find Hα/Hβ = 4.6, which, for a standard Galactic extinction curve, corresponds to an extinction of AV ≈ 1.5 mag—certainly non-negligible, but not much larger than for late-type spirals. Correcting the [O II] line for this level of extinction would raise the inferred star formation rate by a factor of 8.8, to ~ 8.9 M⊙ yr⁻¹, but still far less than needed to match the value deduced from the observed infrared luminosity.

From the above considerations, one cannot escape the conclusion that the companion galaxy to HE 0450–2958 is most likely not a ULIRG. While the close proximity and distorted morphology of the companion galaxy certainly suggest that it is interacting with the quasar, the lack of any concrete evidence that it is a massive, gas-rich merger of the ULIRG variety diffuses some of the recent motivation for considering merger-driven scenarios to interpret this system.

5. SUMMARY

We perform the two dimensional fit to the HST/ACS image of the bright quasar HE 0450–2958 and several detailed simulations to investigate the extent to which this object lacks a surrounding host galaxy, as suggested in the recent literature. The host galaxy is not detected in our two-dimensional fitting. Our simulations indicate that the likely upper limit of the host galaxy luminosity is −20 ≲ M_V ≲ −21 mag, depending on the assumptions adopted. Our upper limits are very similar to the value of M_V ≈ −21.2 mag determined by M05, using a completely independent technique based on deconvolution. Considering the black hole mass for HE 0450–2958 revised by Merritt et al. (2006), M_*= (6–9) × 10^7 M☉, these limits are not in conflict with the luminosity of the host predicted from the M_*/L_ν relation, provided that the bulge-to-disk ratio of the host is not exceptionally unusual. There is no evidence that HE 0450–2958 contains a “naked” quasar or one hosted by an anomalously faint galaxy.

Lastly, we point out that the companion galaxy to the quasar is most likely not an ultraluminous infrared galaxy. The star formation rate inferred from the infrared emission far exceeds the amount estimated from the strength of the [O II] λ3727 line. We argue that most of the infrared emission is associated with the quasar itself.

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