Carnegie Observatories Astrophysics Series, Vol. 1:
Coevolution of Black Holes and Galaxies, 2004
ed. L. C. Ho (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html)

Lensed Quasar Host Galaxies

C. Y. PENG[1], C. D. IMPEY[1], E. E. FALCO[2], C. R. KEETON[3], C. S. KOCHANEK[2],
J. LEHÁR[2], B. McLEOD[2], J. MUÑOZ[4], H.-W. RIX[5], and D. RUSIN[2]
(1) Steward Observatory, University of Arizona, AZ, USA
(2) Harvard-Smithsonian Center for Astrophysics, MA, USA
(3) University of Chicago, IL, USA
(4) Universidad de Valencia, Valencia, Spain
(5) Max-Planck Institut für Astronomie, Heidelberg, Germany

Abstract

Quasar host galaxies at $z \gtrsim 1.5$ are difficult to study because of their small angular size, large luminosity contrast with the central quasars, and cosmological surface brightness dimming. Gravitational lensing helps to overcome these challenges by stretching the host galaxy images into Einstein rings and long arcs, away from the unresolved quasar images. With lensing, the host morphology, structural properties, and color, can be studied in higher detail than previously possible using groundbased techniques (even with adaptive optics) and HST imaging of non-lensed quasars. We present results of host galaxy studies at $z \gtrsim 1.5$ using quasars from the CASTLES gravitational lensing survey. Analysis of luminous hosts shows that they have a mix of inner profiles ranging from steep (de Vaucouleurs-like) to shallow (exponential-like). Some host galaxies have resolved sub-structures. A large fraction of the hosts are significantly more luminous than passively evolving L^* galaxies, and are likely to be rare in the local universe. Some of the host colors are blue, suggesting star formation that is recent in the quasar rest frame.

1.1 Introduction

A number of low redshift ($z < 0.5$) quasar host galaxy studies (e.g. Disney et al. 1995; Taylor et al. 1996; Bahcall et al. 1996, 1997; Hooper, Impey, & Foltz 1997; McLeod, Rieke, & Storrie-Lombardi 1997; Hamilton, Casertano, Turnshek 2002) have now converged on a coherent picture of the hosts: the more luminous a quasar, the more likely it is to live in an early-type bulge that is massive, luminous and has an old stellar populations. These observations agree with the expectation that luminous bulges harbor black holes massive enough to sustain the most powerful quasars. There is little difference in the host galaxies of optically-luminous ($M_V < -23$) radio loud quasars (RLQ), radio quiet quasars (RQQ), and powerful radio galaxies. At lower luminosities, quasars are increasingly found in later Hubble types. The trend extends to even fainter luminosities, where AGNs (active galactic nuclei) such as Seyferts and LINERs, are commonly found in local galaxies of nearly all types (Ho, Filippenko, & Sargent 1997). In the range $0.5 \lesssim z \lesssim 1.0$, RLQ hosts on average are 0.5 mag brighter, and more similar to radio galaxies, than RQQ hosts, although the scatter is large.

At $z > 1$, data become much more scarce, as the contrast problem worsens between the luminous central quasar and the faint host galaxy. Quasars at high-z are intrinsically more luminous; the angular size of the hosts is small; the hosts are dimmed by factors of $(1+z)^4$

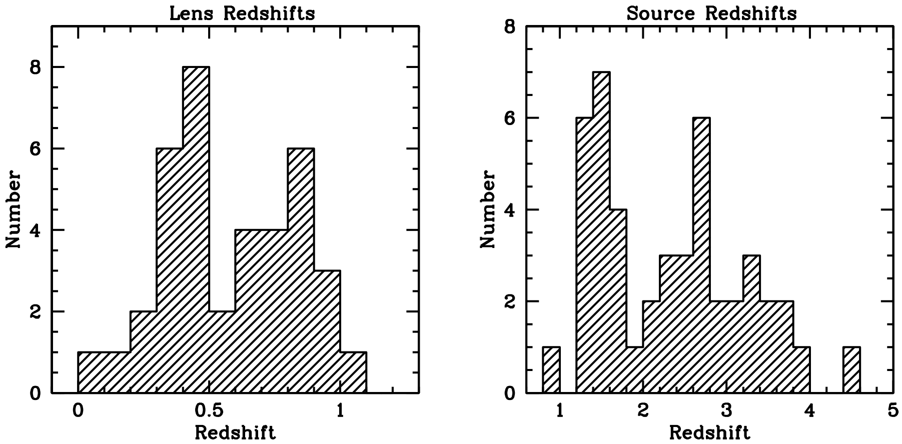

Fig. 1.1. Distribution of lensing galaxy (left) and background quasar (right) redshifts.

due to cosmological surface brightness dimming; and the atmospheric blurring entangles the host and quasar light. Despite these challenges, deep HST imaging studies by Kukula et al. (2001), Ridgway et al. (2001), and Hutchings et al. (2002), show that many of the hosts above the detection threshold are luminous as high a redshift as $z \approx 2$, suggesting the host galaxies may in fact be passively evolving.

Understanding the evolutionary connection between high-z quasar hosts and low-z galaxies requires overcoming several key roadblocks. Color information is needed to constrain the mass of the host at $z > 1$, but is hard to come by because the quasar/host contrast is worse in the optical than in the infrared. Obtaining faint galaxy counts in the quasar environment is important for evolutionary study, but it is observationally expensive to confirm the overdensity of the environment with spectroscopy. Even the task of detecting *luminous* hosts at $z > 1.5$ requires at least 4 orbits of HST NICMOS, and one would like to extend the luminosity function to much fainter quasar hosts. Morphology information is important as well, but it is currently difficult to get using adaptive optics because of PSF variability. Using HST NICMOS requires exposure times much longer than 4 orbits/object, thus the sample size is limited.

Gravitational lensing helps to overcome some of the obstacles. Lensing magnification draws out the host galaxy light into long arcs and Einstein rings, conserving the surface brightness, from underneath the luminous quasars. For the central quasar, lensing magnification increases the central flux, but it remains unresolved. The extension of the host light makes it much more detectable and yields a map (through a lens model) of many independent resolution elements in the host galaxy.

1.2 Sample

The data sample of quasars comes from the CASTLES survey (CfA-Arizona-Space Telescope Lens Survey). CASTLES is an ongoing project to obtain images of multiply imaged quasars with HST, where the lensing is primarily caused by a single foreground galaxy. The majority of objects are observed using shallow, 1-orbit, images in H, I and V-filters. As shown in Figure 1.1, the majority of the quasars in our sample lie above $z \approx 2$. This is a particularly interesting regime to study the properties of the hosts because it corresponds to the peak of the quasar luminosity function and space density.

1.3 Technique

While the lensing distortion facilitates detection and detailed studies of the host galaxies, the arcs/Einstein rings must be de-projected via lens model to measure their intrinsic properties. We developed an algorithm, LENSFIT, to fit all objects in the observed images directly, while simultaneously accounting for the lensing distortion. To fit the host arcs/Einstein ring, we represent the host galaxy as one or more Sérsic functions placed in the background (source plane). Given a lens model with adjustable parameters, light from the host model is ray-traced into the foreground (image plane) to construct an image, which is matched to the data by varying the Sérsic parameters and the lens model. The quasar images can also be modeled in the same way. Figures 1.2 – 1.5 illustrate the technique applied to 4 examples.

The lens deflector models we use are the singular or softened (i.e. non-singular) isothermal ellipsoids (SIE) with additional lens shear and higher-order deflection terms (Kochanek 1991). The SIE model is widely used because the deflection properties are simple, well known, and physically motivated. Empirically, galaxies have nearly singular density cusps (Lauer et al. 1995). Lens theory predicts that the number of quasar images observed will in general be odd. However, if the galaxy core is nearly singular, the central quasar image is suppressed, and an even number of quasar images are detected. SIE mass distributions also reproduce the flat rotation curves in galaxies at large radii. Finally, almost all gravitational lenses known are well fitted using an SIE+gamma model (e.g. Lehár et al. 2000; Muñoz, Kochanek & Keeton 2001).

Because the gravitational lenses in the CASTLES survey are generally “clean,” i.e. the background quasar is lensed mostly by a single foreground galaxy, the lens model is relatively simple to determine. However, foreground galaxy groups in the vicinity of the lens can affect the image geometry. When needed, LENSFIT fits an arbitrary number of SIE lenses to reproduce complicated image geometries.

Whenever possible, the quasar image positions, their flux ratios, the shapes of the host arcs, and the light profile of the lensing galaxy are all fitted simultaneously to constrain the lens model and measure the host galaxy. The light profiles of foreground lensing galaxies are also fitted with one or more Sérsic or exponential functions, just like the host galaxy. Complications arise when the quasar images have anomalous flux ratios compared to what lens theory predicts. This may be caused, for example, by microlensing due to sub-structures in the lensing galaxy halo or differential extinction in different lines of sight through the lens galaxy (Falco et al. 1999, Motta et al. 2002). Because bad subtraction of the quasar images will compromise the fitting of the host (which is not affected by microlensing), we relax the brightness ratio constraint, and determine the lens model only using the quasar image positions. Once we find a suitable lens model, we hold it fixed while all the light distributions (lensing galaxy, quasar images, host galaxies) are simultaneously fitted. We fit the quasar images as foreground objects to produce better PSF subtractions, but the host image is distorted by the lens model. More detailed discussion on the technique will be presented in Peng et al. (2004a).

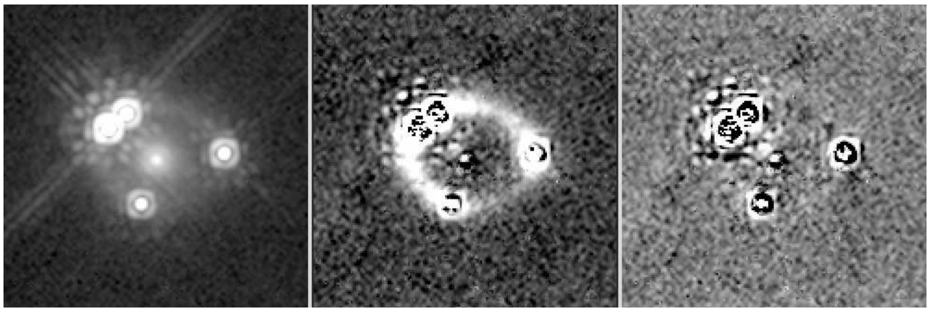

Fig. 1.2. An example of image decomposition of PG1115+080 (z_{QSO} = 1.72) – Left: original NICMOS H-band image. Middle: Quasar images and the lensing galaxy light profile removed, showing just the Einstein ring of the quasar host galaxy. Right: Residuals after all objects were removed.

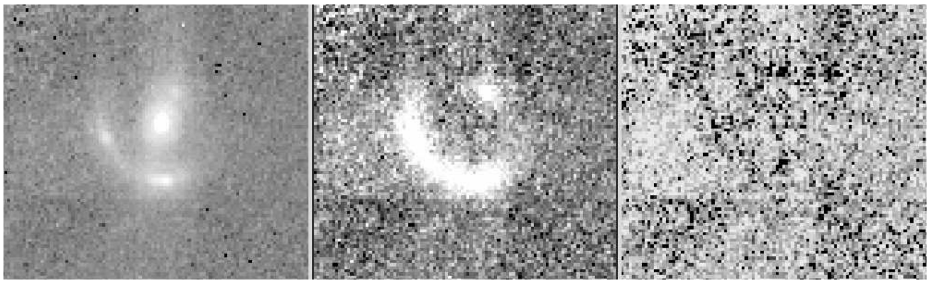

Fig. 1.3. Similar to above, image decomposition of B0712+472 (z_{QSO} = 1.34) in the H-band.

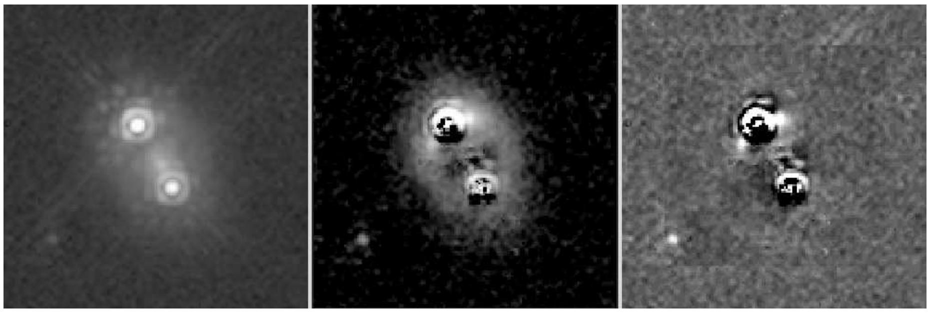

Fig. 1.4. Image decomposition of CTQ414 (z_{QSO} = 1.29) in the H-band.

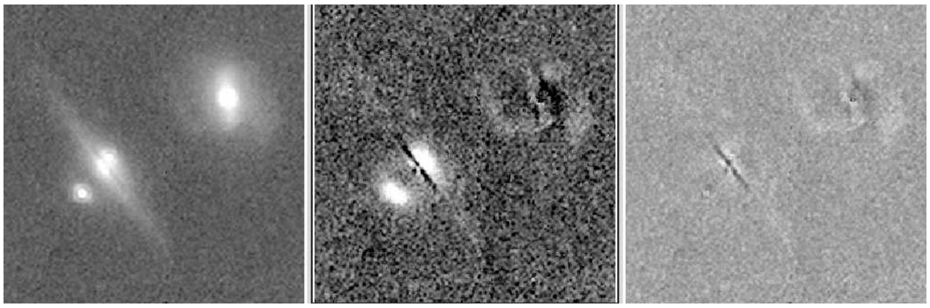

Fig. 1.5. Image decomposition of B1600+434 (z_{QSO} = 1.59) in the H-band.

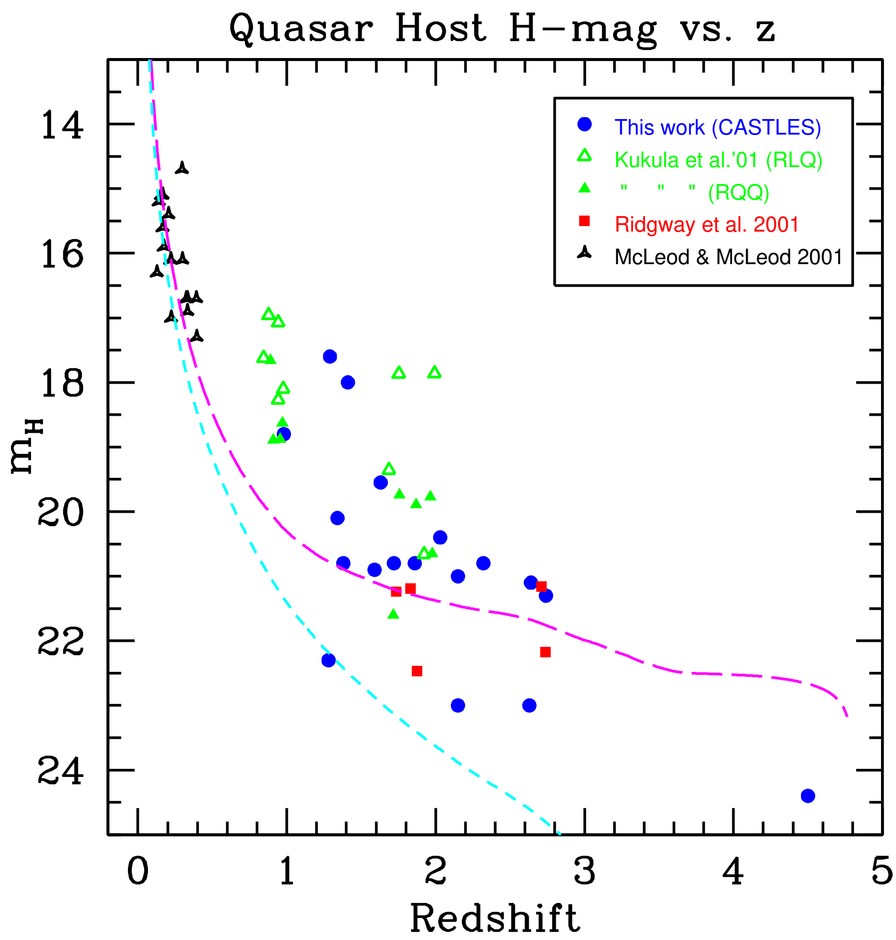

Fig. 1.6. Apparent H-band magnitude for quasar host galaxies as a function of z. The long-dashed line is a theoretical passively evolving track for an E/S0 type galaxy, and the short-dashed line is that of an Sb-type star formation history, both normalized to McLeod & McLeod (2001) points. The tracks undergo a burst of star formation at $z = 5$. The cosmology is $H_0 = 65$ km/s/Mpc, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

1.4 Host Luminosity

Analysis of large arcs found in the CASTLES H-band images shows that many of the host galaxies are in fact intrinsically more luminous than passively evolving L* galaxies. This is illustrated in Figure 1.6 where we also plot HST NICMOS observations published by Kukula et al. (2001) and Ridgway et al. (2001). The two lines overplotted are stellar synthesis tracks based on Bruzual-Charlot models as published in Keeton, Kochanek, & Falco (1998), showing passively evolving stars (long dashes) and an Sb-type star formation history (short dashes), both with $z_f = 5$. The assumed cosmology for the synthesis model is an $H_0 = 65$ km/s/Mpc, $\Omega_m = 0.3$, flat universe. The model lines, normalized to the McLeod & McLeod (2001) host observations at $z \sim 0.2$, show that a large number of the hosts at $1 \leq z \leq 2$, even undergoing passive evolution, would reach several times L^* by $z = 0$. Thus,

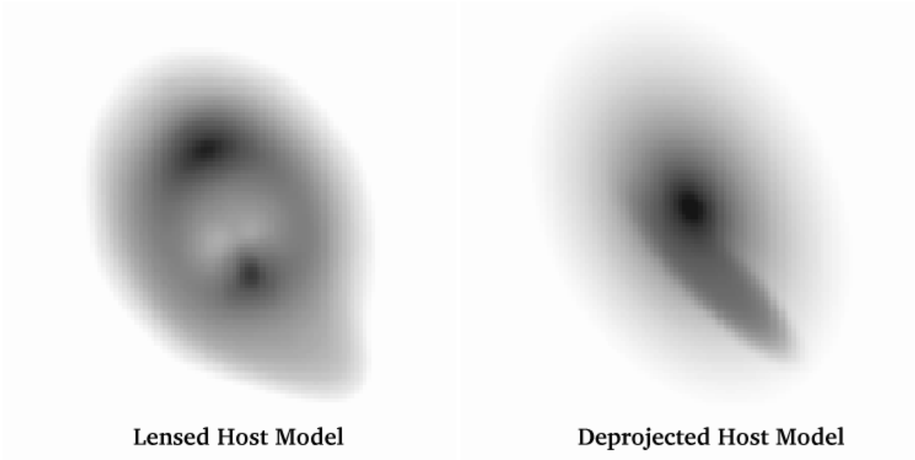

Fig. 1.7. The lensed model of the host galaxy CTQ414 (left) and the deprojected host galaxy model (right), showing the host appears to be an interacting system.

many of the hosts at high-z may in fact be analogous to the rare and brightest galaxy members in a cluster we see today. Furthermore, it is intriguing that even though we ought to easily detect comparably luminous hosts above $z > 2$, the ones we find are much fainter. If this trend is real, the steep drop off in average host luminosity would naively imply that the hosts undergo a dramatic increase in mass or star formation after $z = 2$. The details of the sample will be presented in Peng et al. (2004b), along with more marginal detections that are not shown here.

1.5 Host Morphology and Structure

In some lensed systems, the highly extended lens arcs allow a robust measure of the galaxy profile. We model the lensed hosts with one or more Sérsic profiles, depending on the complexity of the host structure. The Sérsic concentration index $n = 4$ corresponds to a de Vaucouleurs profile, while $n = 1$ is an exponential disk, and $n = 0.5$ is a Gaussian. Analysis of PG1115+080 (Fig. 1.2) shows that a single Sérsic component can fit the arc well. The concentration index is in between a pure exponential disk and de Vaucouleurs profile, which may happen if a de Vaucouleurs bulge is embedded inside an exponential disk. However, this interpretation is complicated by a poor PSF subtraction. Despite the fact we use observed PSFs, there is a mismatch caused by platescale "breathing" of the NICMOS camera. Using other PSFs, which produce worse residuals, give similar results.

In the second example (Fig. 1.3), the host galaxy of B0712+472 also has an intermediate index $n = 2$. The residuals are clean because of the relatively low signal to noise.

Figure 1.4 shows the image decomposition of CTQ414. Because the PSF mismatch makes it hard to fit the quasar images and the host galaxy simultaneously, we fit the host after subtracting the PSFs. The host image itself is an elliptical Einstein ring, fit by two Sérsic components. The moderately eccentric ring can be reproduced if one component of the host is significantly off-centered from the main body, as shown in Figure 1.7. The long extension may indicate that the host is either an interacting system, or a spiral galaxy. The residual image in Fig. 1.4 reveals a strong arc around the top quasar image, which indicates yet a third galaxy component. It is difficult to fit because it is very near the PSF artifacts. But analysis shows that a highly eccentric, bar-like, component in the host would be able to reproduce the feature. More examples will be shown in Peng et al. (2004c).

1.6 Host Color

Gravitational lensing magnification makes it much easier to measure the color of the host galaxy than in unlensed quasars. Figure 1.4 shows an example of B1600+434, whose red colors $V-H = 2.9 \pm 0.3$, $V-I = 1.9 \pm 0.3$ and roughly L^* luminosity at $z = 1.59$ indicate the host is very likely to be an elliptical galaxy, based on the Bruzual-Charlot stellar synthesis model with $z_f = 5$ (Keeton et al. 1998). The $V-I$ color is redder than that predicted by the $z_f = 5$ model, which may be caused by dust reddening in the host galaxy itself, or if the stars were formed earlier than $z = 5$. The reddening is not likely to be caused by the lensing galaxy, given that the lens model accurately predicts the flux ratios, the positions of the quasar images and the host arcs simultaneously. Deeper H-band images will be needed to better constrain the morphology of the host galaxy and the lens models simultaneously. A number of such examples will be published in Peng et al. (2004d).

1.7 Conclusions

We have detected both luminous and faint hosts at redshifts as large as 4.3. Results using a modest sample of hosts (both lensed and unlensed) show that the $1.0 \leq z \leq 2$ host population may be massive, passively evolving, galaxies. This statement is mostly based on RLQ hosts published by Kukula et al. (2001), and RQQ hosts at $1 \lesssim z \lesssim 1.5$. There is not yet radio data on all objects in the CASTLES sample to make a similar comparison. At $z > 1.5$ the RQQ hosts are on average fainter than what would be expected of a passively evolving sample. Hence, hosts may gain a significant amount of mass at around $z = 2$.

The study of high-z quasar hosts is currently limited by both quantity and quality of the data because of observational challenges. Gravitational lensing offers an avenue around some of the difficulties, and has nearly doubled the sample size at $z > 1.5$ compared to non-lenses. We show that lensing can be used to study the morphology of the host galaxies. We find that some hosts have shallow nuclear profiles, e.g. PG1115+080, while some other examples in our data may have a de Vaucouleurs profile (e.g. Q0957+561). In at least one object, CTQ414, we have detected substructure within the host galaxy itself. Obtaining higher S/N HST NICMOS images in the current sample of shallow CASTLES data would greatly aid the study of host morphology at $z > 1$.

Finally, gravitational lensing provides a strong constraint on the host colors. In B1600+434, we find that the host color and luminosity are consistent with a passively evolving L* galaxy. Early analysis of other lensed hosts at $z > 2$ indicates they have blue colors, which indicates active star formation in the quasar rest frame.

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