Lensed Quasar Hosts*

Chien Y. Peng\textsuperscript{a}, Chris D. Impey\textsuperscript{b}, Hans-Walter Rix\textsuperscript{c}, Emilio E. Falco\textsuperscript{d}, Charles R. Keeton\textsuperscript{e}, Chris S. Kochanek\textsuperscript{f}, Joseph Lehár\textsuperscript{d}, & Brian A. McLeod\textsuperscript{d}

\textsuperscript{a}Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
\textsuperscript{b}Steward Observatory, Univ. of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721
\textsuperscript{c}Max-Planck-Institut für Astronomie, Königstuhl 17, Heidelberg, D-69117, Germany
\textsuperscript{d}Harvard-Smithsonian Center for Astroph., 60 Garden St., Cambridge, MA 02138
\textsuperscript{e}Department of Physics & Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854
\textsuperscript{f}Department of Astronomy, The Ohio State University, 4055 McPherson Lab, 140 West 18th Avenue, Columbus, OH 43210

Abstract

Gravitational lensing assists in the detection of quasar hosts by amplifying and distorting the host light away from the unresolved quasar core images. We present the results of \textit{HST} observations of 30 quasar hosts at redshifts $1 < z < 4.5$. The hosts are small in size ($r_e \lesssim 6$ kpc), and span a range of morphologies consistent with early-types (though smaller in mass) to disky/late-type. The ratio of the black hole mass ($M_{BH}$, from the virial technique) to the bulge mass ($M_{bulge}$, from the stellar luminosity) at $1 \lesssim z \lesssim 1.7$ is broadly consistent with the local value; while $M_{BH}/M_{bulge}$ at $z \gtrsim 1.7$ is a factor of 3–6 higher than the local value. But, depending on the stellar content the ratio may decline at $z \gtrsim 4$ (if E/S0-like), flatten off to 6–10 times the local value (if Sbc-like), or continue to rise (if Im-like). We infer that galaxy bulge masses must have grown by a factor of 3–6 over the redshift range $3 \gtrsim z \gtrsim 1$, and then changed little since $z \sim 1$. This suggests that the peak epoch of galaxy formation for massive galaxies is above $z \sim 1$. We also estimate the duty cycle of luminous AGNs at $z \gtrsim 1$ to be $\sim 1\%$, or $10^7$ yrs, with sizable scatter.

Key words:
quasar, host galaxy, gravitational lensing, evolution, supermassive black hole

* Observations presented in this paper were obtained using the Hubble Space Telescope, operated by the Space Telescope Science Institute under contract to NASA.
1 Introduction

Elsewhere in these proceedings the reader can find summaries of previous work on quasar hosts. We concentrate here on the benefits and challenges of using gravitational lensing as a technique for measuring the host galaxy, especially in regimes where traditional direct imaging methods are difficult – at high redshift, or when the host is either sub-luminous or compact. The context for this work is the coevolution of galaxies and supermassive black holes. In the local universe, a tight relation is observed between bulge mass ($M_{\text{bulge}}$) and black hole mass ($M_{\text{BH}}$) measured with stellar kinematics (Gebhardt et al., 2000; Ferrarese & Merritt, 2000). We now extend the relation to $z \gtrsim 1$ using the virial technique to estimate $M_{\text{BH}}$ (e.g. Kaspi et al., 2000; Vestergaard & Peterson, 2006), and the stellar luminosity to estimate $M_{\text{bulge}}$ (Kormendy & Richstone, 1995; Magorrian et al., 1998). The existence, slope, and scatter of a $M_{\text{BH}}/M_{\text{bulge}}$ relation at high redshift can be used to analyze the relative growth rates of galaxies and their (presumably ubiquitous) central engines.

The CfA-Arizona Space Telescope Lens Survey (CASTLES) is a project to image all known, multiply-imaged, quasars in a homogeneous set of optical and near infrared passbands using the Hubble Space Telescope (HST). With the number of lens systems now near 100, data are in hand for 80 targets. The observations are shallow, 1-2 orbits per filter, but the excellent surface brightness sensitivity of the HST leads to a host detection in most cases. The overall CASTLES project is described by Falco et al. (2001); early results in the lensed host search are given by Rix et al. (2001) in the same conference proceedings; and detections and models of the hosts of several individual quasars have been published (Impey et al., 1998; Kochanek et al., 2000; Keeton et al., 2000).

Gravitational lensing is a large and growing field of astrophysics so only the rudiments can be given here; a number of excellent book and reviews are available for the full formalism and diverse applications (Blandford & Narayan, 1992; Schneider, Ehlers, & Falco, 1992; Claeskens & Surdej, 2002). About one in 500 quasars has a sight-line passing close enough to the central potential of a massive galaxy for multiple image formation. It has taken surveys of tens of thousands of radio and optically selected quasars to yield the sample of $\sim 100$ objects (see the CASTLES web site\(^1\) and that of Liége group\(^2\)). Even though adaptive optics techniques from the ground are improving, stable point spread functions, obtained with HST, are still essential for reliable modeling.

In gravitational lensing, the AGN is magnified into multiple images, but remains unresolved, whereas the extended light from the host galaxy maps into arcs or Einstein rings (ER). A lens model is needed to extract the full infor-

---

\(^1\) http://www.cfa.harvard.edu/castles

\(^2\) http://vela.astro.ulgc.ac.be/themes/extragal/gravlens
Fig. 1. An example of the lens modeling technique. (a) Original NIC2 image of PG 1115+080 (z_{QSO} = 1.72). (b) The host galaxy Einstein ring, after removing the best fit lensing galaxy and quasar point sources. (c) The best fitting residuals. (d) The parametric model of the host galaxy in the source plane.

Information content of the lensed host light. In principle, a typical ER having a radius \( \sim 1 \) arcsec means that HST imaging potentially yields 50-100 resolution elements in the host galaxy in the deep images from the survey.

2 Modeling

The image modeling (Fig. 1) uses a custom-built program called LENSFIT (Peng et al. 2006, in prep.), which is based on a methodology that has been well-tested with the GALFIT algorithm (Peng et al. 2002). The model for the light profiles of the host and foreground (lens) galaxy uses a Sérsic model with a concentration index \( n \) that is often used to quantify the gross morphology of galaxies (e.g., \( n = 1 \) for late-type, while \( n = 4 \) for early-type). Both the quasar point source and the host galaxy light profile are propagated through the lens model to produce the image distortion, and multiple images. External shear is included to model the tidal influence due to neighbors. All the parameters are simultaneously varied to reduce the \( \chi^2 \) on a pixel-by-pixel basis. The models are often very robust in well resolved systems (\( \theta \geq 1 \) arcsec), due to the spatial separation between the host and the lens, and their different shapes.
3 Results

Here we present a summary of our findings, which are detailed along with a description of our analysis techniques elsewhere (Peng et al. 2006, in prep.). We select on lensing geometry size ($\theta \gtrsim 0.7$ arcsec), which does not a priori bias the intrinsic AGN luminosity selection, or the host luminosities. Therefore, we expect the sample of the AGNs to be randomly drawn from the AGN luminosity function, where the lower limits are determined by various lensing search programs. The heterogeneity of different surveys, however, will not affect our primary conclusions about the relationships between $M_{\text{BH}}$ and $M_{\text{bulge}}$, since both quantities are measured in the same objects.

3.1 General Properties

Figure 2 shows the $H$-band host galaxy luminosities (lensing distortion removed) versus redshift. Overall, the host luminosities from CASTLES appear to agree well with non-lensing studies [Kukula et al. 2001; Ridgway et al. 2001]. The host luminosities range from 1 to 20 times $L_*^V$ today, while the AGNs are 0 to 3 magnitudes brighter than the host in restframe $B$ to $V$ band. Despite their brightnesses, the host galaxies appear to be fairly small in...
size (typical \( r_e \lesssim 6 \) kpc) for their central AGNs. As we shall see later, when coupled with information about their \( M_{BH} \), both the host luminosities and sizes lead to the conclusion that the bulges may be undermassive compared to present-day normal galaxies. Lastly, the Sérsic index values suggest that while a number of quasar hosts at \( z \gtrsim 1.5 \) have steep central concentrations consistent with the presence of a bulge, many (30% – 50%) also have low Sérsic values \( (n \leq 2) \) more analogous to later-type galaxies today. Even those galaxies with high Sérsic indices may not qualify as bona fide – fully formed and passively evolving – ellipticals, given their small sizes and black hole masses.

**Radio-loud (RLQ) vs. Radio-quiet (RQQ) hosts**  
Quantifying differences between RLQ and RQQ hosts has historically been controversial. Figure 2 shows that there is not a clear difference in the host luminosities between RLQ (open) and RQQ (closed) AGNs in the lensing sample. The diverse selection criteria from disjointed surveys are, however, hard to quantify. It is worth to keep in mind, however, that in a study by Kukula et al. (2001) RLQs were drawn from the rare and extreme radio-loud sources which may require atypically large BHs to produce. Consequently, the finding of luminous hosts in those RLQs may reflect a correlation between \( M_{BH} \) and \( M_{bulge} \) at high redshifts. The issue of radio correlation with host properties remains unsettled.

**AGN Duty Cycle**  
We can estimate the duty cycle of nuclear activity for each object with a host detection. A rough estimate of the duty cycle is:

\[
D \sim \Phi_Q(L_{QSO}, z)/\Phi_G(L_{Gal}, z),
\]

where \( \Phi_Q \) and \( \Phi_G \) are the luminosity functions of quasars and galaxies, respectively, appropriate to a given redshift. At \( z \gtrsim 1 \), the median duty cycle is 1%, or \( 10^7 \) years, with a sizable scatter.

### 3.2 Black Hole vs. Bulge Evolution

Based on quasar and host luminosities we can study the \( M_{BH} \) vs. bulge properties at \( z \gtrsim 1 \) (see Peng et al. 2005 for details), where \( M_{BH} \)'s are obtained using the virial technique (Kaspi et al. 2000; Vestergaard, & Peterson, 2006).

1.7 \( \lesssim z \lesssim 4.5 \)  
Fig. 3 shows the \( M_{BH} \) vs. the restframe \( R \)-band bulge luminosity \( (L_R) \) for the host galaxies at 1.7 \( \lesssim z \lesssim 4.5 \). Determining \( L_R \) requires \( K \)-corrections, computed using an Sbc SED; the dashed lines shows the small systematic effect of using an E/S0 (right) or Im (left) SED. It is clear that a correlation between \( M_{BH} \) and bulge luminosity was already present at a lookback time of 10–12 Gyr. Remarkably, the high-redshift hosts appear to lie on the same relation as \( z = 0 \) normal galaxies, implying that the high-z hosts are undermassive in comparison. To explain why, Fig. 3b shows the host luminosities after we account for passive evolution of \( dM_R/dz = -0.8 \) mag; specifically, we hold \( M_{BH} \) fixed and shift the color points in Fig. 3a to the left.
The relationship of the black hole mass, $M_{\text{BH}}$, vs. bulge absolute luminosity ($L_R$, bottom axis; $M_R$, top axis), at low $z$ (solid round points) and $z \gtrsim 1.7$ (open points). Solid lines: fit to $z \approx 0$ solid points. All open points assume a modern-day Sbc-type SED for $K$-correction and their average is represented by dotted lines. Dashed lines illustrate assumptions of bluer (Im, left)/redder (E, right) SEDs. Open circle: gravitationally lensed quasar hosts. Open triangles: Ridgway et al. (2001). Open squares: Kukula et al. (2001). Vertical line in points: a possible lower limit in $M_{\text{BH}}$ due to AGNs being broad absorption line QSOs. Criss-crossed points: potential problem with lens identification, host detection, radio-loud quasar, or narrow line AGN. Panel (a): The observational data. Panel (b): The same data in (a), but the open points are shifted horizontally by assuming that the hosts evolve passively with $z_f = 5$ by $dM_R/dz = -0.8$ mag. See also Peng et al. (2005) for details.

Now the $z \gtrsim 1.7$ hosts are displaced from the local host relation (solid line) by a factor of $3–6$ in luminosity, which translates into a mass deficit of a factor of $3–6$ in the quasar hosts compared to local galaxies with the same $M_{\text{BH}}$.

In contrast, by $z \approx 1$, Fig. 4 shows that the mass deficit of the hosts is mostly reduced (to within a factor of unity in mass), after accounting solely for passive evolution. Thus, massive bulges that correspond to luminous E/S0 galaxies today may have been nearly assembled by $z \approx 1$.

By requiring that the hosts evolve onto the local $M_{\text{BH}}$ vs. $L_R$ of Figs. 3 and 4, we can illustrate a growth in the $M_{\text{BH}}/M_{\text{bulge}}$ ratio with redshift relative to today, shown in Figure 5. We find that the ratio of $M_{\text{BH}}/M_{\text{bulge}}$ increases roughly to a factor of $10$ higher than today (assuming an Sbc-type SED) out at $z = 4$. This conclusion depends somewhat on the assumption of the SED and evolutionary history: the ratio at earlier times would be higher than shown for a bluer SED than Sb/c, or for a faster fading rate than passive evolution.
Fig. 4. The same diagram as Figure 3, except for redshift of $1 \lesssim z \lesssim 1.7$ quasar hosts. The vertical line in the square points indicates that the AGN either has a strong narrow Mg II line component or is strongly absorbed in the wings, causing a potentially low $M_{\text{BH}}$ estimate. The dotted line is displaced from the solid line, representing the local $M_{\text{BH}}-L_R$ relation, by $-0.5$ (Fig. a) and $+0.5$ (Fig. b) magnitude. Note the very slight bias between the non-lensed and lensed datasets, which might be explained by the difference in the median redshift of $\langle z \rangle_{\text{med}} = 1.45$ for the lens sample and $\langle z \rangle_{\text{med}} = 0.94$ for the non-lenses. However, three of the non-lensed data points may also have a lower limit on the $M_{\text{BH}}$ estimate, as noted above.

Fig. 5. The growth of the $M_{\text{BH}}/M_*$ ratio as a function of (a) redshift and (b) age of the universe in Gyrs. Circles are gravitational lens data points, while triangles are from direct imaging of hosts using HST NICMOS $H$-band ([Ridgway et al., 2001; Kukula et al., 2001]). Point styles are the same as Fig. 3. The $M_{\text{BH}}/M_*$ ratio appears to rise quickly beyond $z \approx 1$ and may slow, and perhaps flatten, to a factor of $6 - 10 \times$ local value by $z \approx 3$. A fading rate of $dM_R/dz = -0.8$ is assumed here (passive evolution since $z_{\text{form}} = 5$).
4 Conclusions

Detailed modeling of 30 well-observed systems from a total sample of 80 lensed quasars has provided new insights into the properties of host galaxies at $1 < z < 4.5$. About half have Sérsic model fits indicative of early type galaxies. However, combined with their small sizes of $r_e < 6$ kpc, luminosities, and $M_{\text{BH}}$, it appears that luminous, fully-formed, ellipticals are in a minority as hosts of luminous quasars at $z \gtrsim 2$. No difference is seen between the luminosities of radio-loud and radio-quiet quasars in the sample, with a caveat on sample selection. Even at $z \gtrsim 2$, the host galaxies follow nearly the same relationship between $M_{\text{BH}}$ and luminosity as at low redshifts, but the bulges must gain in mass by a factor of 3-6 between $1 \lesssim z \lesssim 4.5$. However, by $z \approx 1$, the mass deficit is mostly gone. Thus massive bulges at $z \approx 1$ may be consistent with being passively evolving, or may still grow by at most a factor of 1. Our estimate of the AGN duty cycle is $\approx 1\%$, or $10^7$ years. Ongoing work includes using color information to constrain the host star formation histories, obtaining sub-millimeter data to measure star formation rate, and characterizing detailed host morphology with deeper HST imaging.

References

Blandford, R.D. & Narayan, R. 1992, ARAA, 30, 311
Claeskens, J.-F. & Surdej, J. 2002, AARv, 10, 263
Falco, E.E., et al. 2001, in Gravitational Lensing: Recent Progress and Future Goals, eds. T. Brainerd & C. Kochanek, ASP Volume 237, p.25
Ferrarese, L. & Merritt, D. 2000, ApJ, 539, L9
Gebhardt, K., et al. 2000, ApJ, 539, L13
Impey, C.D., et al. 1998, ApJ, 509, 551
Kaspi, S., et al. 2000, ApJ, 533, 631
Keeton, C.R., et al. 2000, ApJ, 542, 74
Kochanek, C.S., et al. 2000, ApJ, 535, 692
Kormendy, J., & Richstone, D. 1995, ARAA, 33, 581
Kukula, M., et al. 2001, MNRAS, 326, 1533
Magorrian, J., et al. 1998, AJ, 115, 2285
Peng, C.Y., Ho, L.C., Impey, C.D. & Rix, H.-W. 2002, AJ, 124, 266
Peng, C.Y. et al. 2005, ApJ in press, astro-ph/0509155
Ridgway, S. E., et al. 2001, ApJ, 550, 122
Rix, H.-W., et al. 2001, in Gravitational Lensing: Recent Progress and Future Goals, eds. T. Brainerd & C. Kochanek, ASP Volume 237, p.169
Schneider, P., Ehlers, J. & Falco, E.E. 1992, Gravitational Lenses, Berlin: Springer-Verlag
Vestergaard, M., & Peterson, B.M. 2006, ApJ accepted, astro-ph/0601303